Modern Applied Mathematics in Bioelectromagnetism – Part I

IBB:

Prof. Dr. rer. nat. Carsten Wolters (Coordinator and main responsibility)

Prof. Dr. rer. nat. Joachim Gross (one lecture in SS)

Radiology:

Dr. rer. nat. Jochen Bauer (one lecture in WS and one lecture in SS)

Epilepsy Center Münster-Osnabrück:

PD. Dr. med. Christoph Kellinghaus (one lecture in WS)

Dr. med. Gabriel Möddel (one lecture in SS)

Lecture, Oct.8, 2024


anonym anrufen
oder mitmachen
nightline
MÜNSTER e.V
Zuhörtelefon
von Studierenden für Studierende
0251 83 45400
So–Fr: 21–1 Uhr

Outline

- General planning for this lecture (language? required knowledge? Participants-email-list! target group!)
- Literature for this lecture
- Introduction to the lecture

Target group

The course will be offered over two semesters (winter semester 2024/25 and summer semester 2025).

The following applications are available:
- MSc Mathematics, PO 2020, Specialization "Scientific Computing", Type I
- MSc Mathematics, PO 2020, broadening (area of applied mathematics)
- BSc Mathematics, PO 2020, broadening (specialization in modeling and analytical methods)
- BSC Mathematics, PO 2020, advanced supplement Modeling and Numerical Methods

In these cases, the lecture parts of both semesters (4 SWS in total) and the exercise parts of both semesters (2 SWS in total) must be completed, the exercises for both exercise parts must be passed and an oral exam on everything must be taken.

The following other possible uses exist:
- MSc Mathematics, PO 2020, specialization "Scientific Computing", type II.

In this case, the lecture parts of both semesters (4 SWS in total) have to be passed and a reduced course work (from the possibilities of the examination regulations) has to be done, whose form and extent will be announced by Prof. Dr. Carsten Wolters at the beginning of the course.

The QISPOS registrations will not take place until the summer semester 2025, when the respective supplementary parts to the lecture and the exercises are also offered.

Lecture planning for Part I

Program for the lecture "Modern Applied Mathematics in Bioelectromagnetism, Part I"

Oct.8: **Wolters:** Preliminary discussion, introduction and motivation

Oct.15: **Wolters (per Zoom from Tampere/FIN):** Basics of Electro- (EEG) and Magnetoencephalography (MEG), EEG/MEG source analysis

Oct.22: **Wolters:** Maxwell equations and physical modeling in bioelectromagnetism

Oct.29: **Wolters:** Basic mathematics for bioelectromagnetism (EEG/MEG, TES/TMS): Scriptum chap 6.1.1 – 6.1.4

Nov.5: **Wolters:** Basic mathematics for bioelectromagnetism (EEG/MEG, TES/TMS): Scriptum chap 6.1.5 – 6.1.6

Nov.12: **Wolters:** Finite element method (FEM) based forward modeling for bioelectromagnetism (EEG/MEG, TES/TMS), Part I: Source models, potential approaches, convergence analysis

Nov.19: **Wolters:** FEM-based forward modeling for bioelectromagnetism (EEG/MEG, TES/TMS), Part II: Part I: Source models, potential approaches, convergence analysis
6.5.2-6.5.4, 6.5.7, 6.2 (Analytical solutions in simplified geometries),
6.5.8-6.5.10 (Validation of numerical procedures in simplified geometries)

Nov.26: **Wolters**: FEM-based forward modeling for bioelectromagnetism (EEG/MEG, TES/TMS), Part III: FEM source models/potential approaches and accuracies

Dec.3: **Wolters:** Linear complexity and fast iterative solver techniques for FEM-based forward modeling (EEG/MEG, TES/TMS):
Scriptum chap 6.5.1, 6.5.5-6.5.6, 7

Lecture planning for Part I

Dec.10: **Wolters:** Different FEM approaches (Continuous and Discontinuous Galerkin FEM (CG-, DG-FEM), unfitted FEM such as Unfitted DG (UDG) and CutFEM, mixed FEM in tetrahedral and hexahedral meshes

Dec.17: **Wolters:** Further topics in EEG and MEG forward modeling, Part I: Complete electrode model (CEM); Uncertainty/sensitivity analysis of EEG and MEG source analysis and combined EEG/MEG calibration; model error

Jan.7: **Wolters**: Further topics in EEG and MEG forward modeling, Part II: Integral equation method, boundary element method (BEM)

Jan.14: **Kellinghaus**: Basics of epilepsy and EEG

Jan.21: **Bauer:** Introduction to MRI

Jan.28: **Wolters**: Parametric registration of MRI

Further links/literature:
This
http://www.sci.utah.edu/~wolters/LiteraturZurVorlesung/
is the basic link to our lecture.
Please find
http://www.sci.utah.edu/~wolters/LiteraturZurVorlesung/Vorlesungen/
always the newest lecture-notes/slides and the tutorial material.
Please find
http://www.sci.utah.edu/~wolters/LiteraturZurVorlesung/Vorlesungsskriptum/
the newest version of the lecture scriptum.
Please find
http://www.sci.utah.edu/~wolters/LiteraturZurVorlesung/Literatur/
further interesting literature.

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Literature for this lecture

- **Lecture webside:**

http://www.sci.utah.edu/~wolters/LiteraturZurVorlesung/


https://www.sci.utah.edu/~wolters/LiteraturZurVorlesung/Vorlesungen/

Index of /~wolters/LiteraturZurVorlesung/Vorlesungen

Name	Last modified	Size	Description
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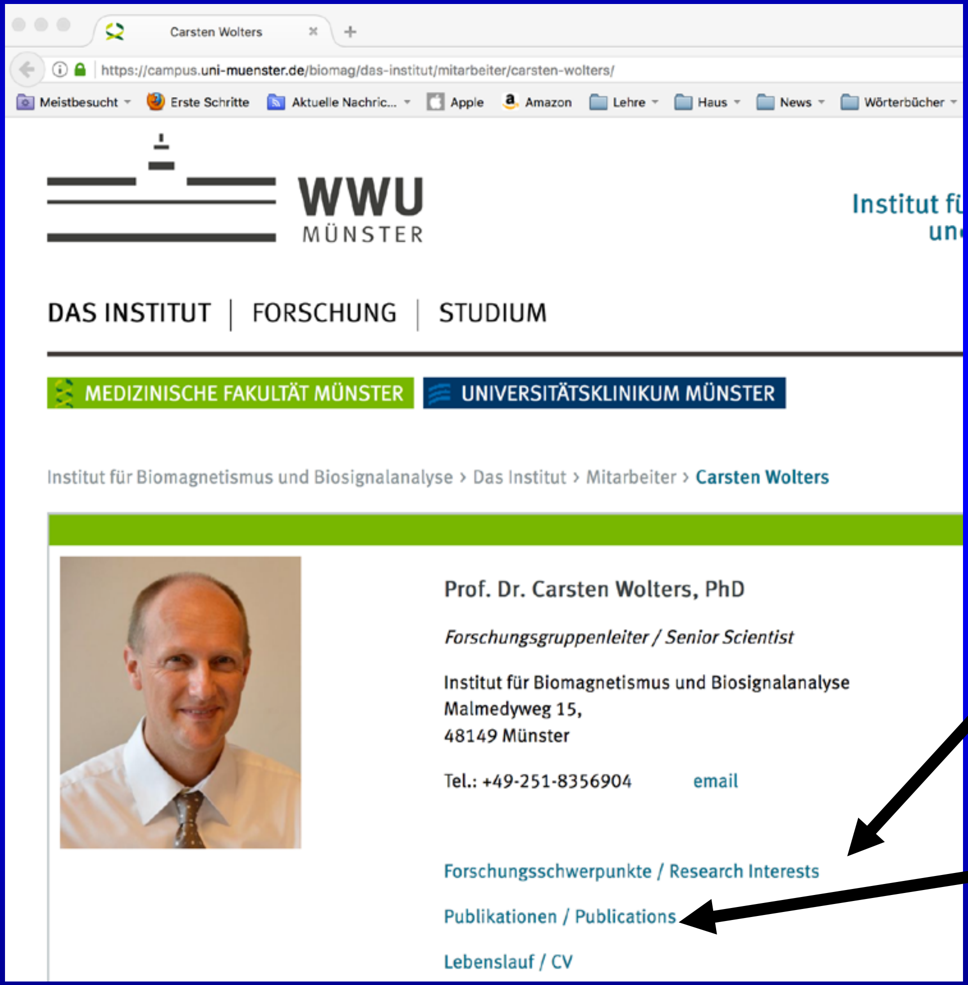
Tutorial/	2023-10-10 01:12	-	
WS2024-2025-Lectures/	2024-10-07 01:39	-	

Link for literature to own work:

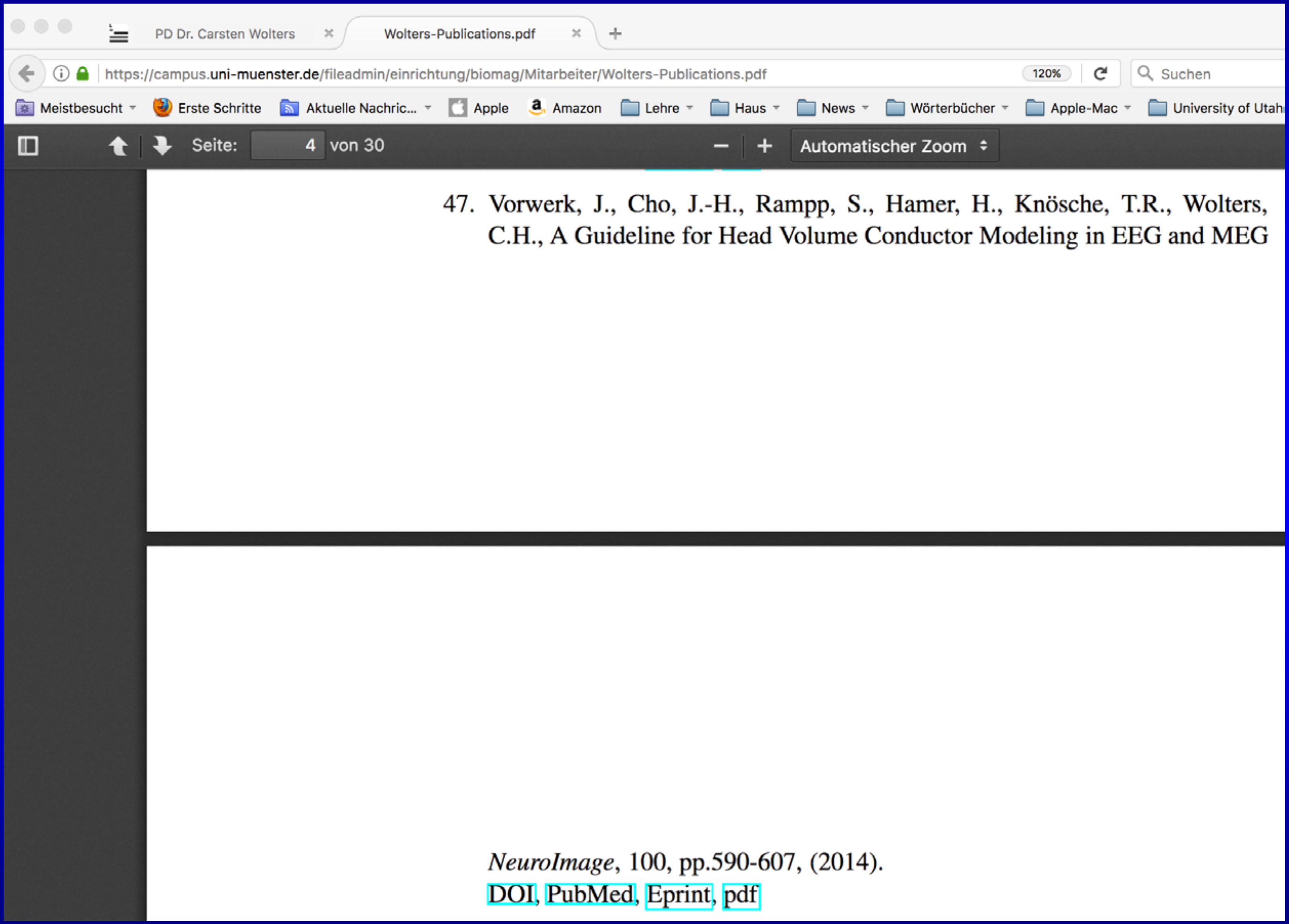


Links to all PhD, Master and Bachelor theses and to lecture scriptum

All own publications

[Vorwerk, Cho, Rampp, Hamer, Knösche & Wolters, *NeuroImage*, 2014]

Link for literature to own work:



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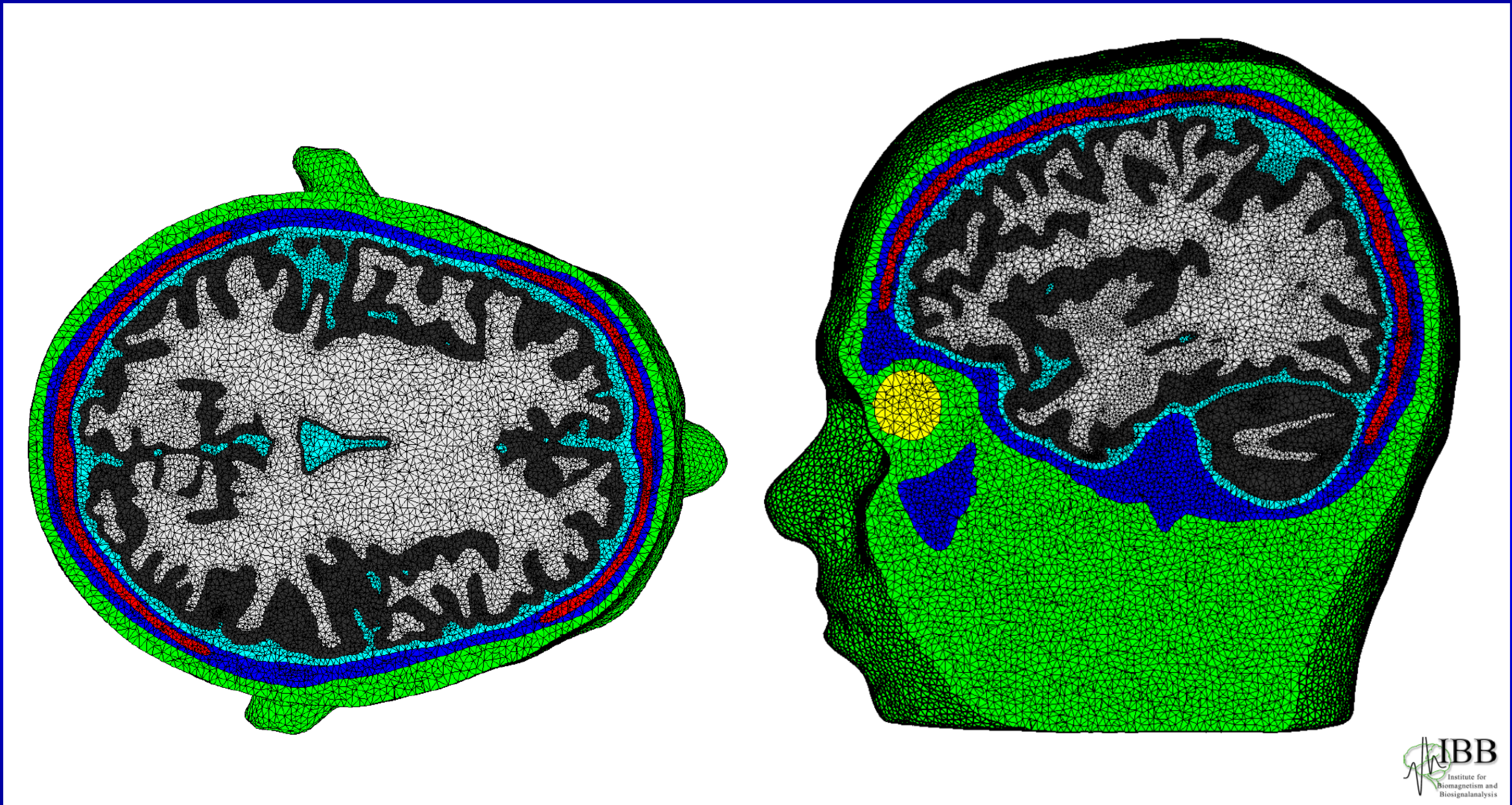
Introduction to the lecture: Part I

- Main steps for brain stimulation: Setup of head model, targeting, optimization of stimulation

- Part I will focus on head modeling and EEG/MEG neuroimaging (non-invasive targeting):
  - Short history of important bioelectromagnetism- or neuroimaging-methods
  - Evoked responses and non-invasive source analysis

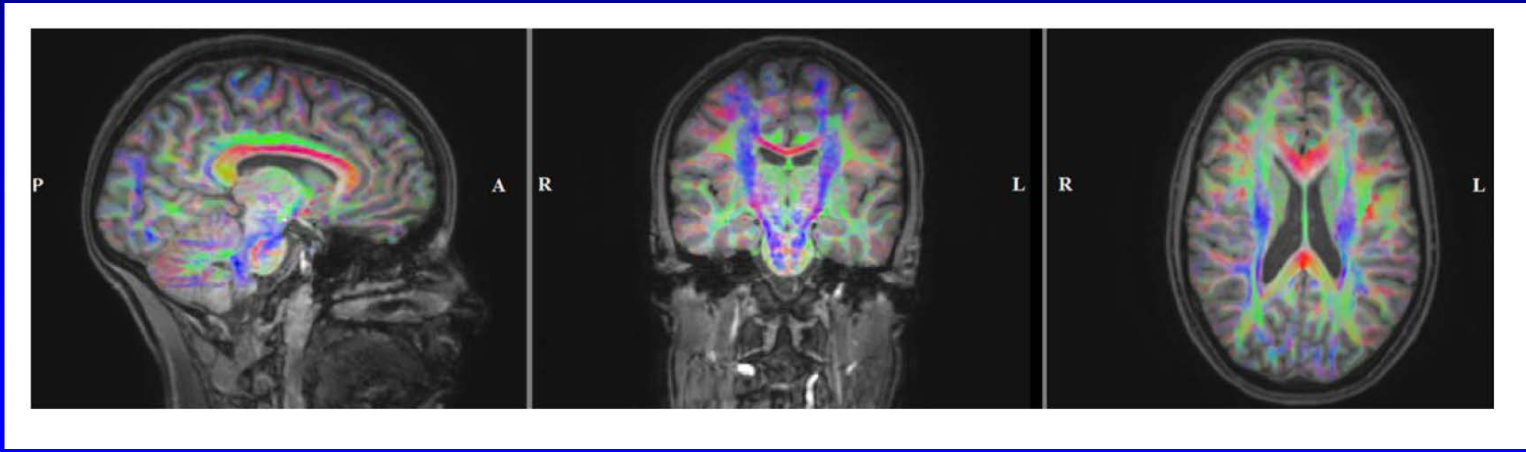
[Vorwerk, Cho, Rampp, Hamer, Knösche & Wolters, *NeuroImage*, 2014]

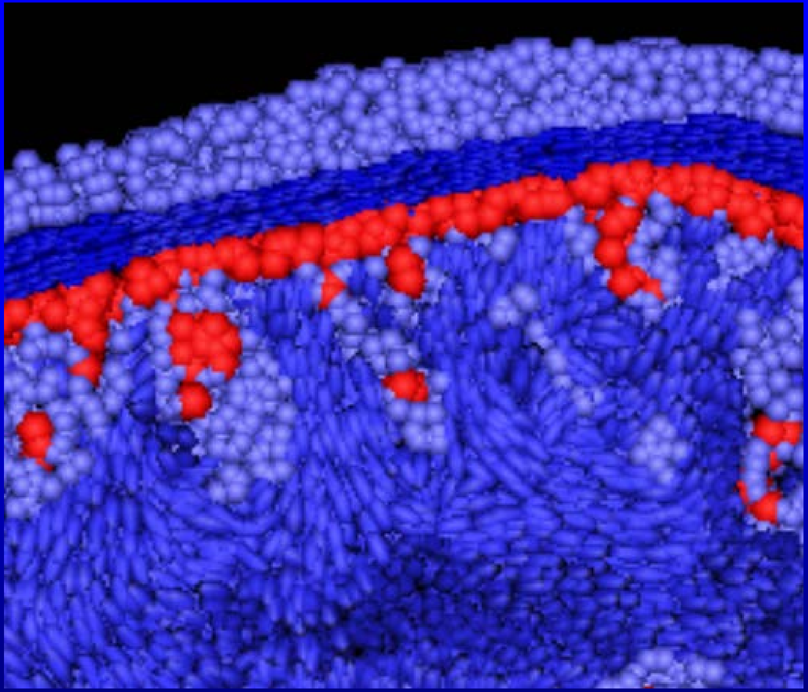
Setup of head model



[Vorwerk, Cho, Rampp, Hamer, Knösche & Wolters, *NeuroImage*, 2014]
[Wolters, Anwander, Tricoche, Weinstein, Koch & MacLeod, *NeuroImage*, 2006]

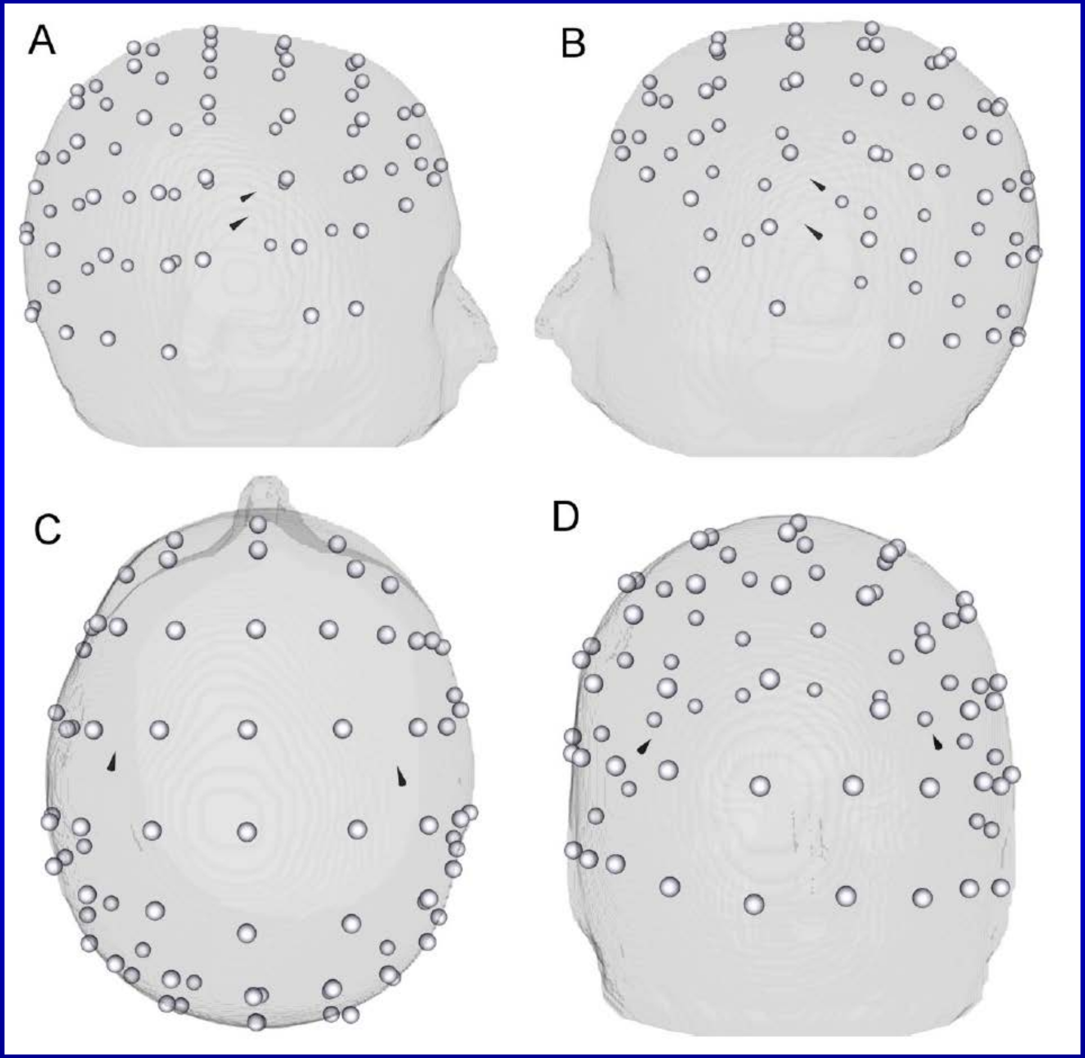
Setup of head model





[Wagner, Burger & Wolters, *SIAM J. Appl. Math.*, 2016]
[Schmidt, Wagner, Burger, van Rienen & Wolters, *J. Neur. Eng.*, 2015]
[Wagner, PhD thesis in Mathematics, *WWU Münster*, 2015]

Targeting



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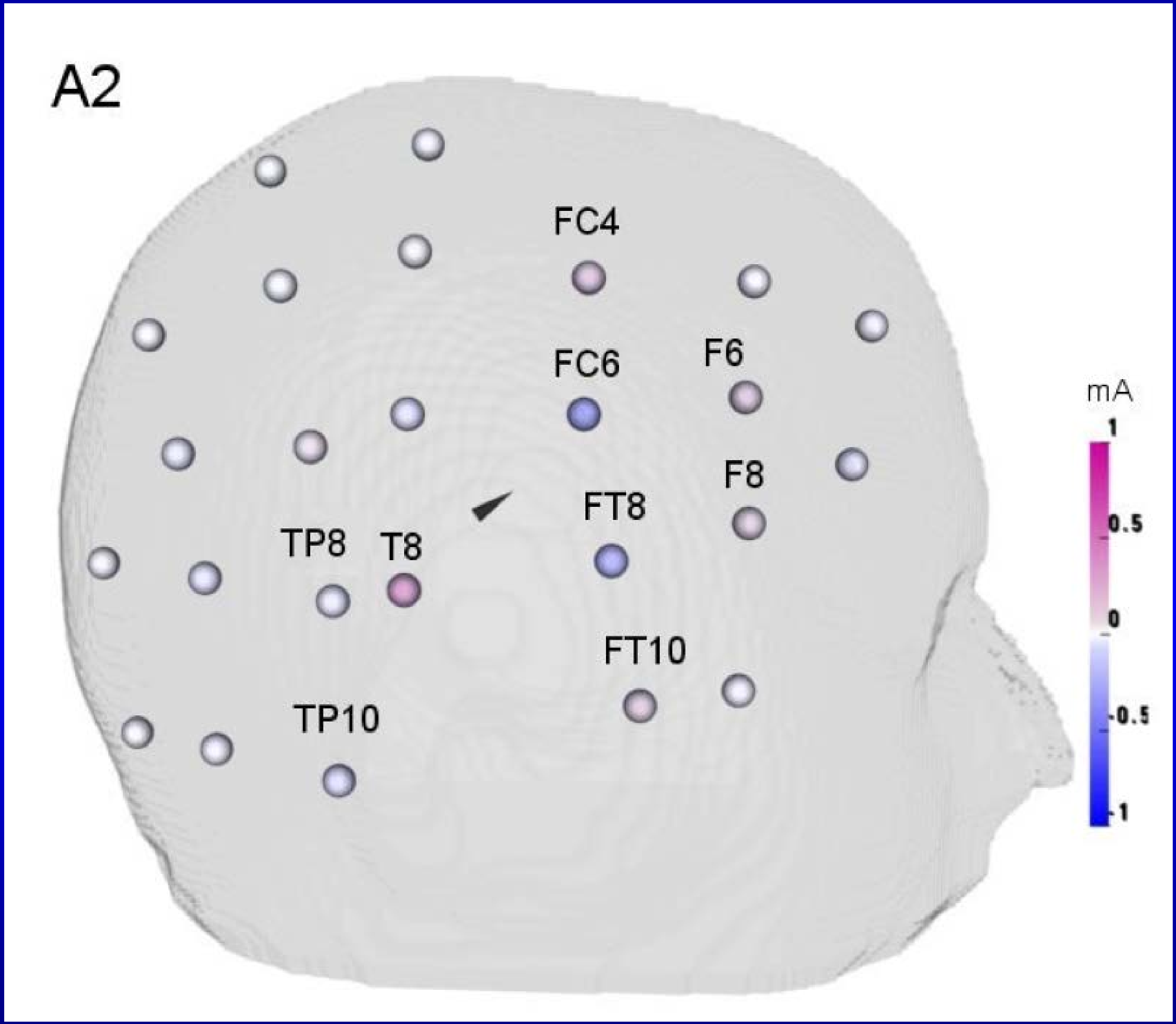
[Schmidt, Wagner, Burger, van Rienen & Wolters, *J. Neur. Eng.*, 2015]
[Wagner, PhD thesis in Mathematics, *WWU Münster*, 2015]

Optimization of stimulation



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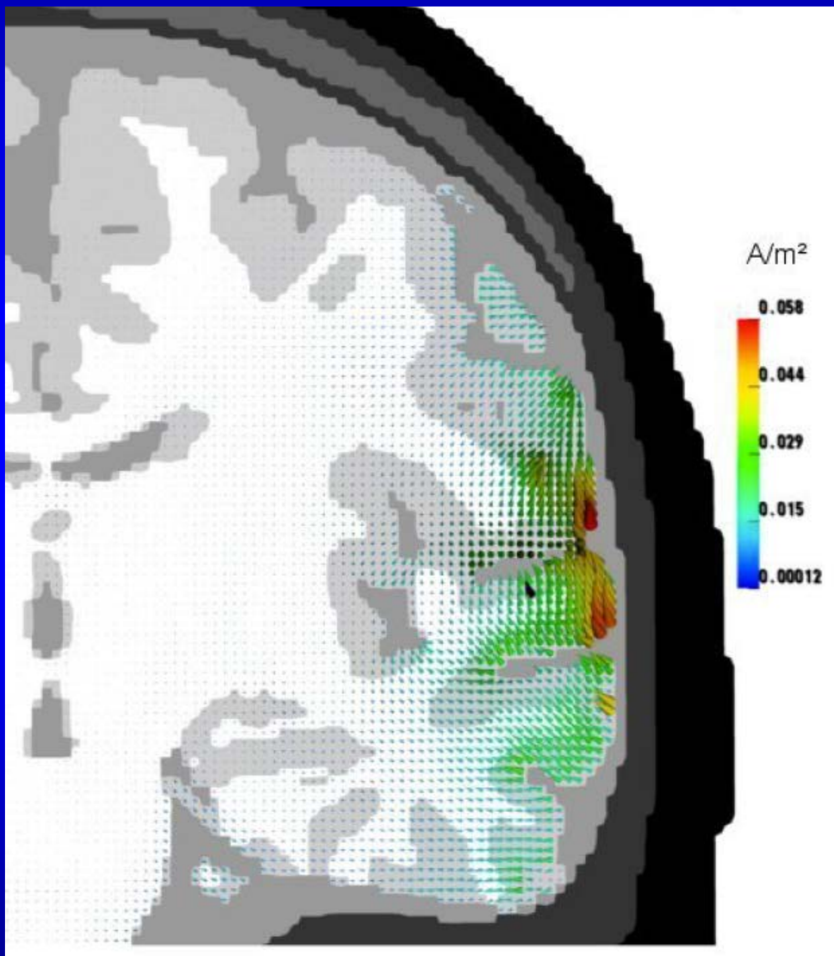

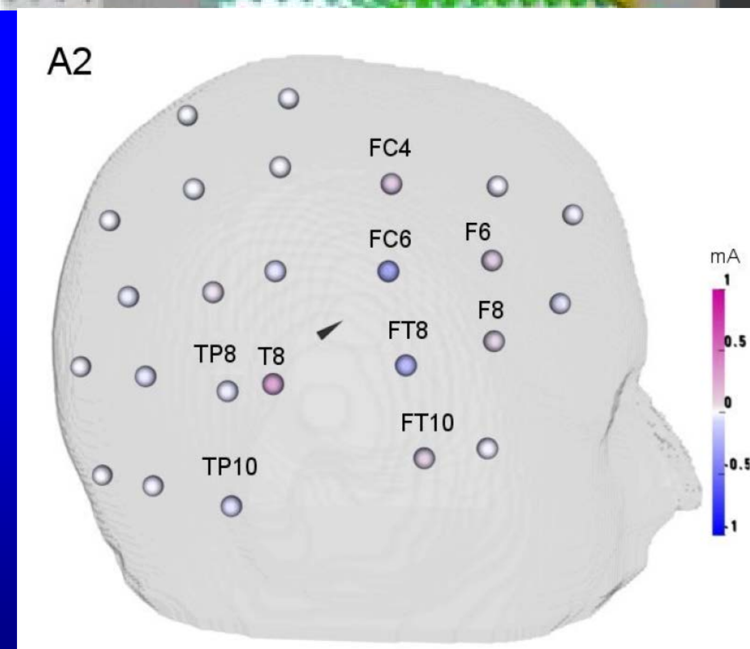

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Introduction to the lecture: Part I

- **Main steps for brain stimulation: Setup of head model, targeting, optimization of stimulation**
- **Part I will focus on head modeling and non-invasive targeting:**
  - **Short history of important bioelectromagnetism- or neuroimaging-methods**
  - **Evoked responses and non-invasive source analysis**

Institute for Biomagnetism and Biosignalanalysis (IBB)

Bioelectromagnetism-research:

- Electroencephalography (EEG)
- Magnetoencephalography (MEG)
- Magnetic Resonance Imaging (MRI)
- Transcranial Electric Stimulation (TES)
- Transcranial Magnetic Stimulation (TMS)

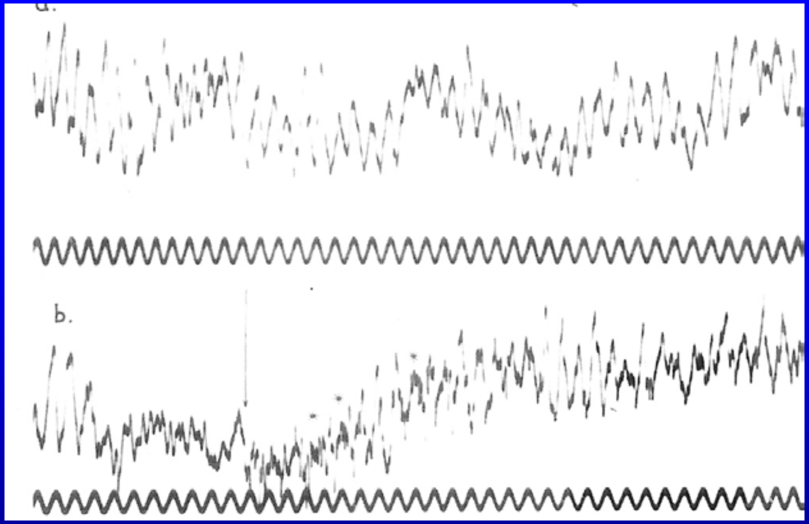
Measurement and analysis of EEG/MEG and MRI data

304 channel MEG
128 channel EEG

3Tesla Research-MRI

Short history of electroencephalography (EEG)

- Hans Berger
  - 1873-1941
  - Neurologist and psychiatrist
  - 3 times nominated for Nobel-price
- 1924: First EEG in Jena



Short history of magnetoencephalography (MEG)

- David Cohen (Physiker)

2010 in Boston/USA

Short history of magnetoencephalography (MEG)

- David Cohen (Physicist)
- 1968: Measured the first MEG at MIT in Boston/USA

Short history of magnetoencephalography (MEG)

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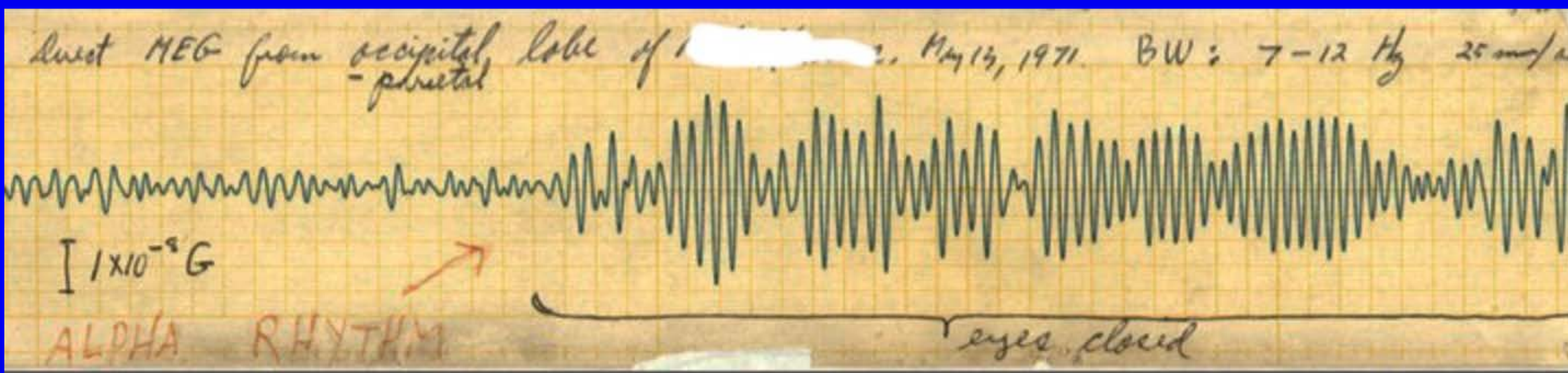
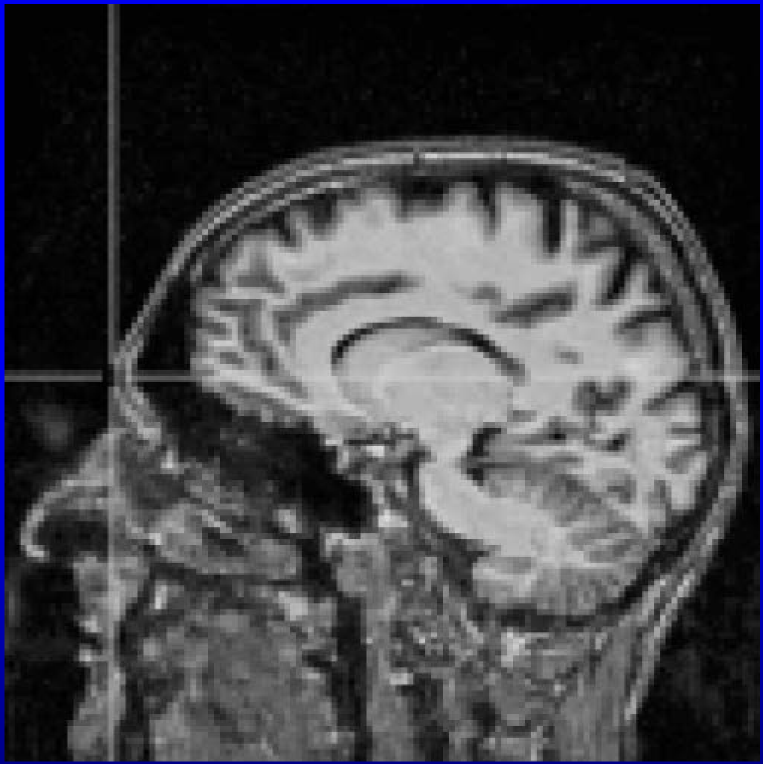


Short history of magnetic resonance imaging (MRI)

- Peter Mansfield (Physicist), Paul Lauterbur (Chemist)
- 1971: developed MRI as imaging modality
- Nobel-price of physiology/medicine (2003) for MRI work



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The concept of evoked potentials and fields using the example of somatosensory evoked potentials (SEP) and fields (SEF)

Somatosensory evoked potentials (SEP) and fields (SEF)

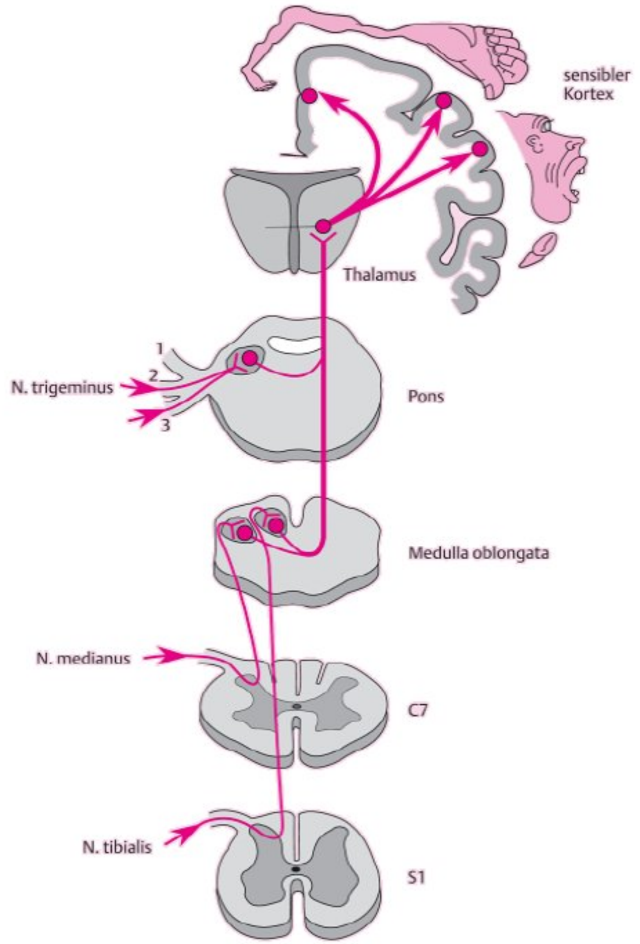


Abbildung 2.3: Erregungsleitung bei einer Stimulation des Nervus medianus, des Nervus tibialis und Nervus trigeminus. Aus: Vogel [5]

[Grottke, Bachelor thesis in Physics, *WWU Münster, 2015*]

Somatosensory evoked potentials (SEP) and fields (SEF)

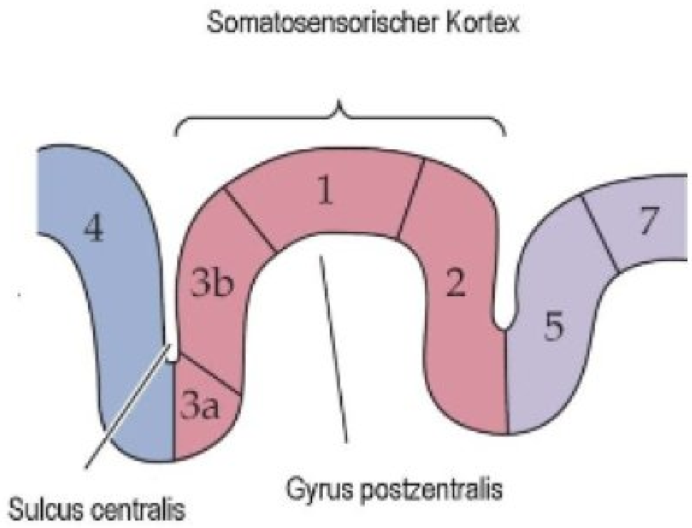


Abbildung 2.4: Darstellung der Brodmann-Areale 1, 2, 3a und 3b im somatosensorischen Kortex. Das Brodmann-Areal 4 gehört zum somatomotorischen Kortex im Gyrus precentralis. Die Gyri werde durch den Sulcus centralis getrennt. Aus: Purves u. a. [6]

S1 and M1 homunculi

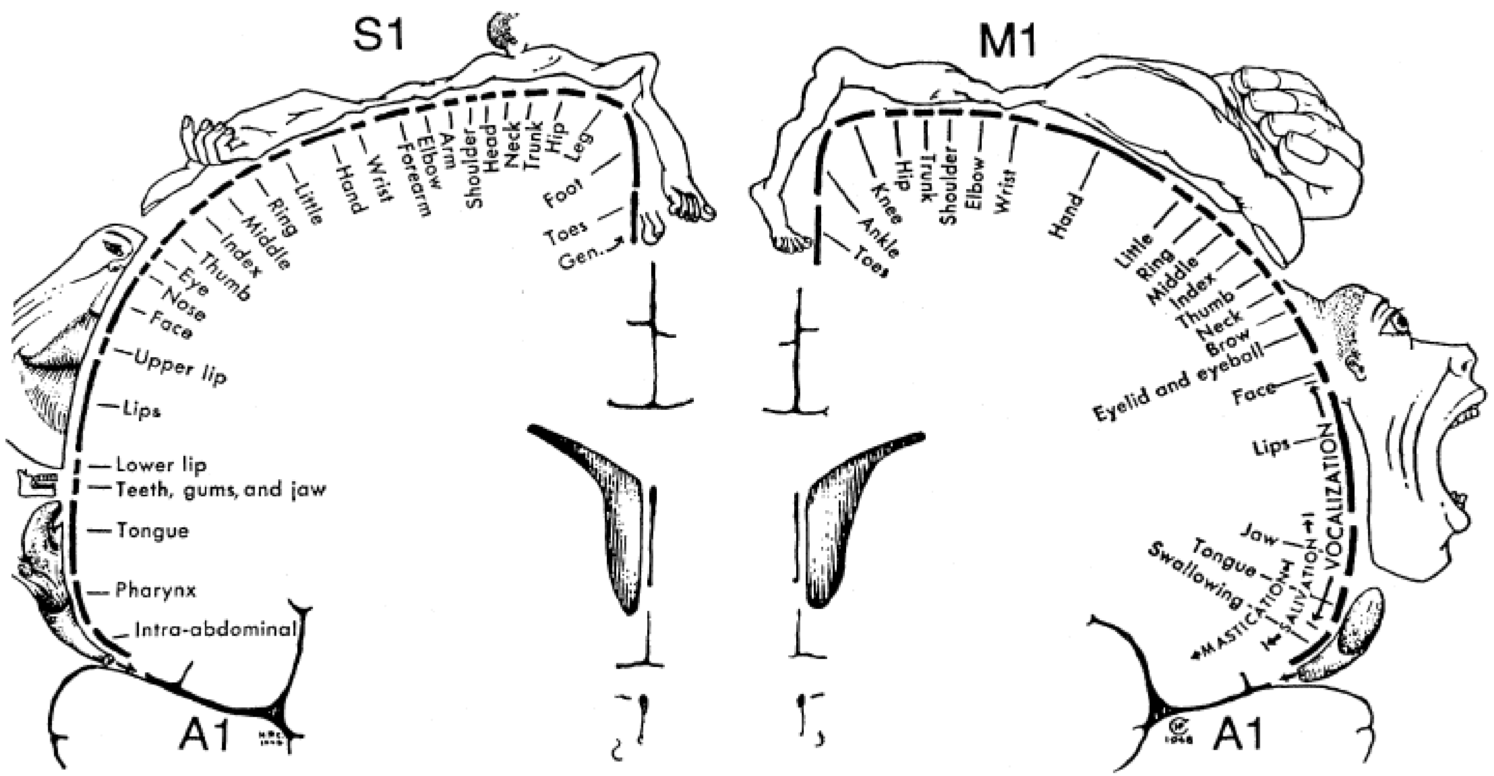
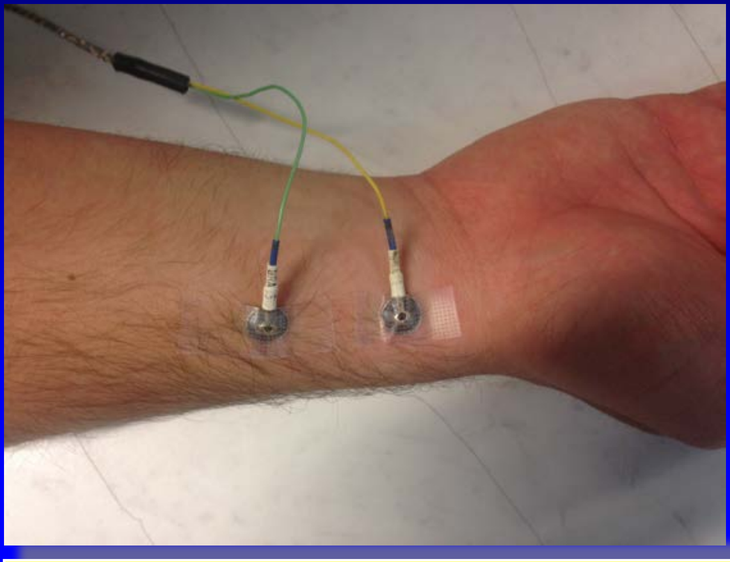


FIG. 3. Representations of different body parts on the somatosensory (S1) and motor (M1) cortices. These "homunculi" are based on direct cortical stimulation of awake humans during brain surgery. The picture illustrates a transsection of the brain in a plane parallel to the face [see Fig. 13(a)]. The two halves are separated by the longitudinal fissure, which has been widened here for clarity. The locations of the left and right primary auditory cortices A1 in the upper surface of the temporal lobe are shown as well. Modified from Penfield and Rasmussen (1950).

[Piastra, *PhD thesis*, 2019]

Somatosensory evoked potentials (SEP) and fields (SEF)

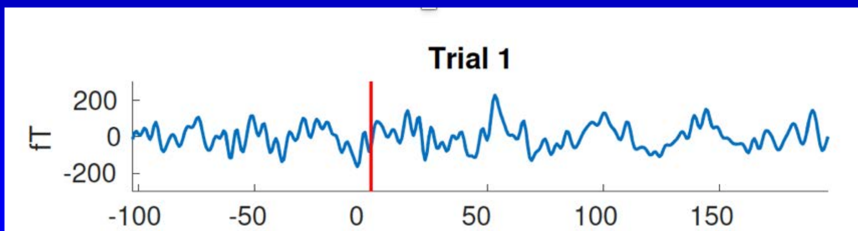
Combined MEG/EEG



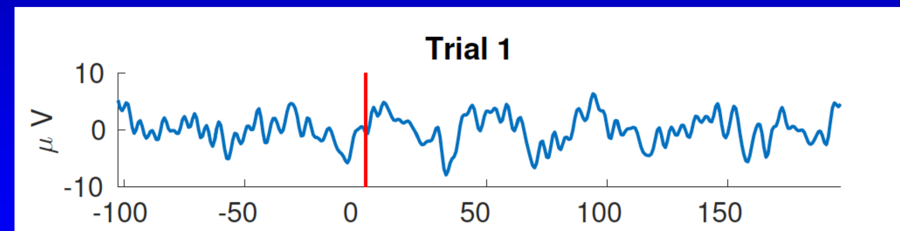
Electric stimulation of the medianus nerve

Somatosensory evoked potentials (SEP) and fields (SEF)

MEG sensor MLP33: Field strength over time



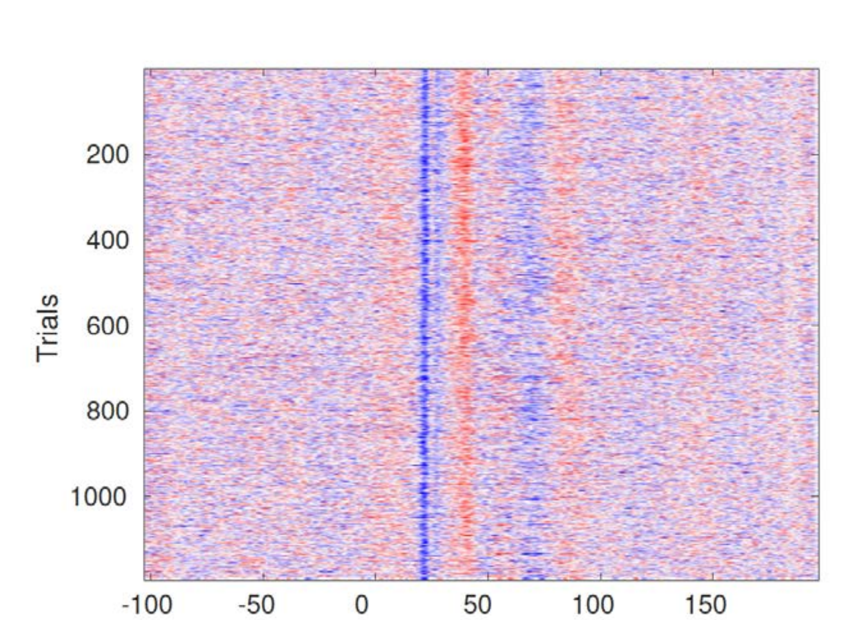
EEG electrode CP3: Potential difference to reference electrode at Cz over time

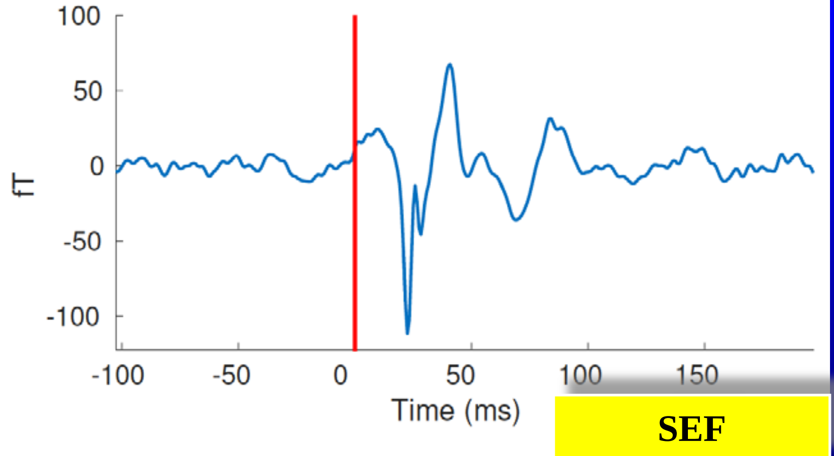


[Piastra, *PhD thesis*, 2019]

Somatosensory evoked potentials (SEP) and fields (SEF)

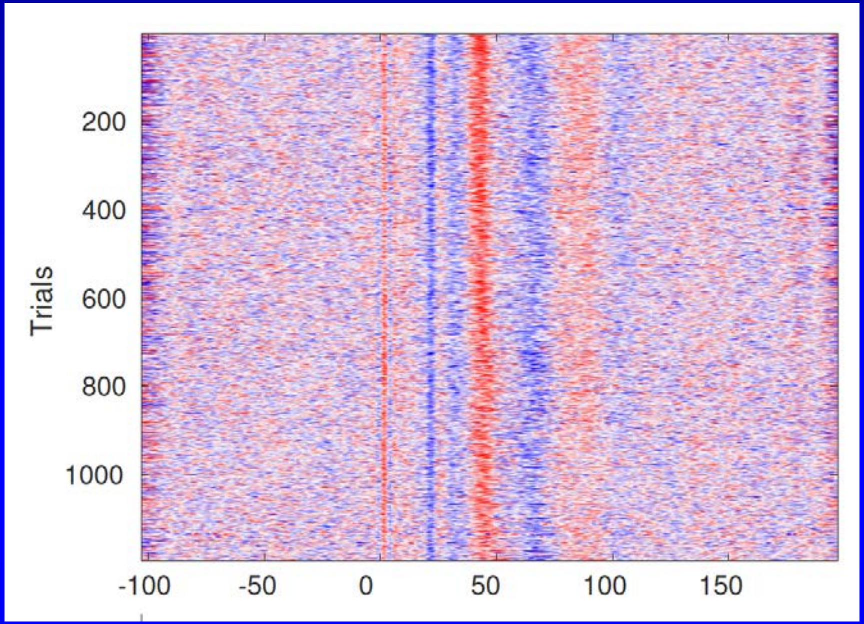
MEG sensor MLP33: Field strength over time

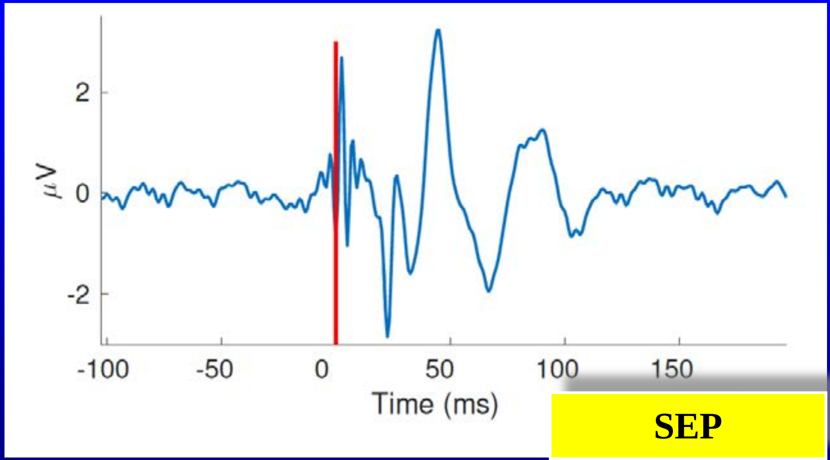




SEF

EEG electrode CP3: Potential difference to reference electrode at Cz over time

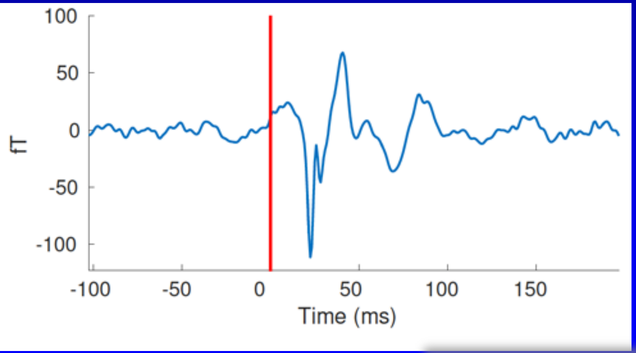




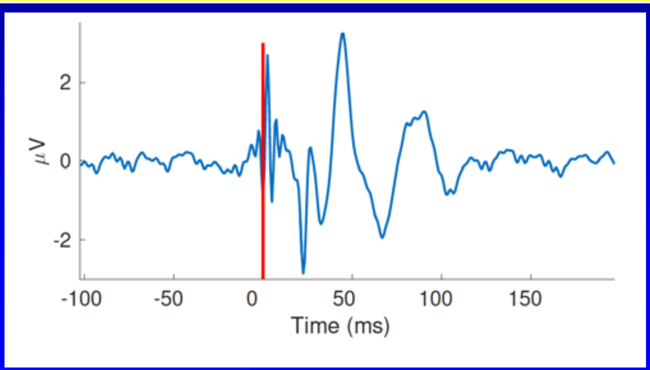
SEP

Somatosensory evoked potentials (SEP) and fields (SEF)

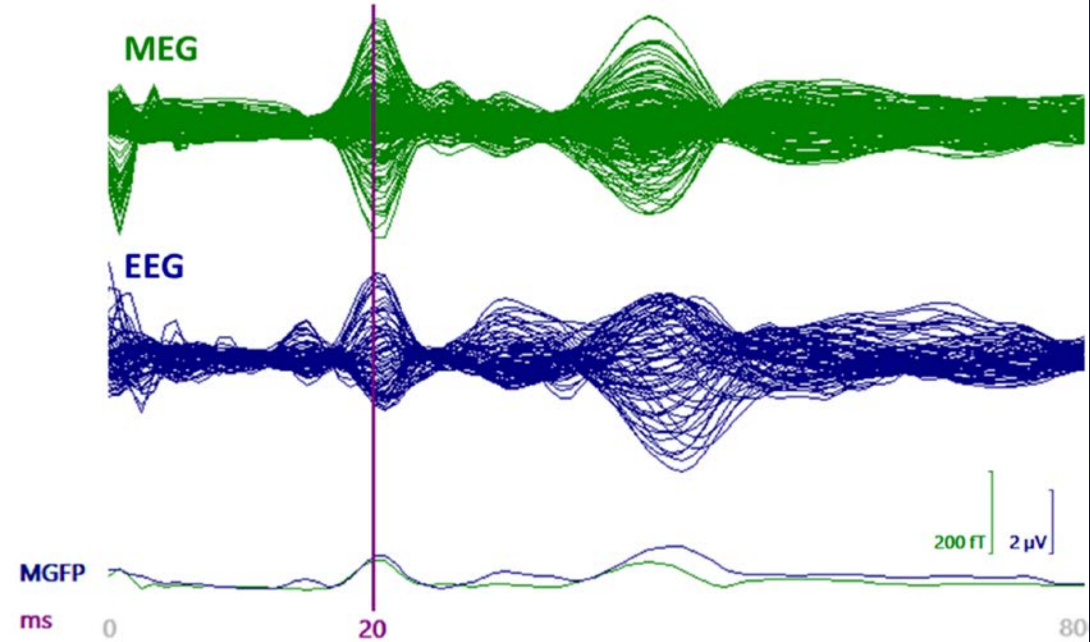
SEF at sensor MLP33: Field strength over time



SEP electrode CP3: Potential difference to reference electrode at Cz over time



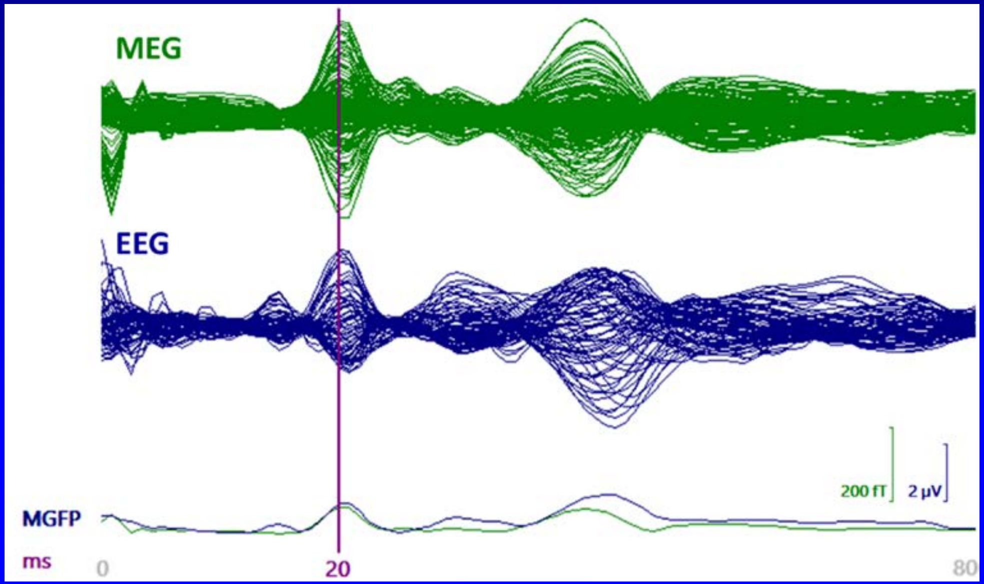
SEF and SEP butterfly plots over all sensors



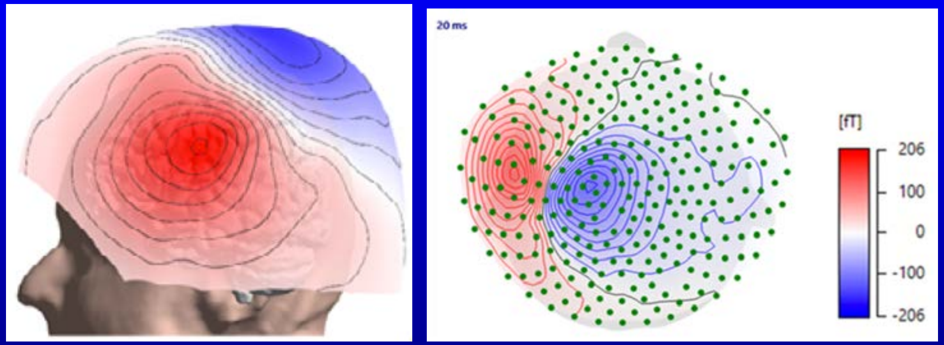
[Piastra, *PhD thesis*, 2019]

Somatosensory evoked potentials (SEP) and fields (SEF)

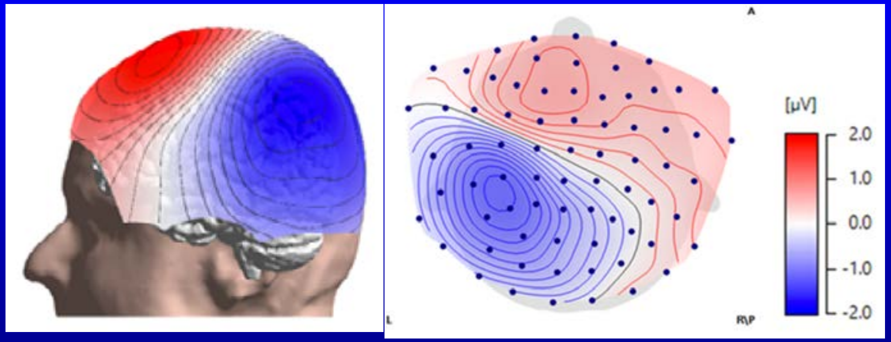
SEF and SEP butterfly plots over all sensors



SEF topography at 20 ms post-stimulus: N20m component



SEP topography at 20 ms post-stimulus: P20/N20 component



The concept of evoked potentials and fields using the example of auditory evoked potentials (AEP) and fields (AEF)

Evoked responses

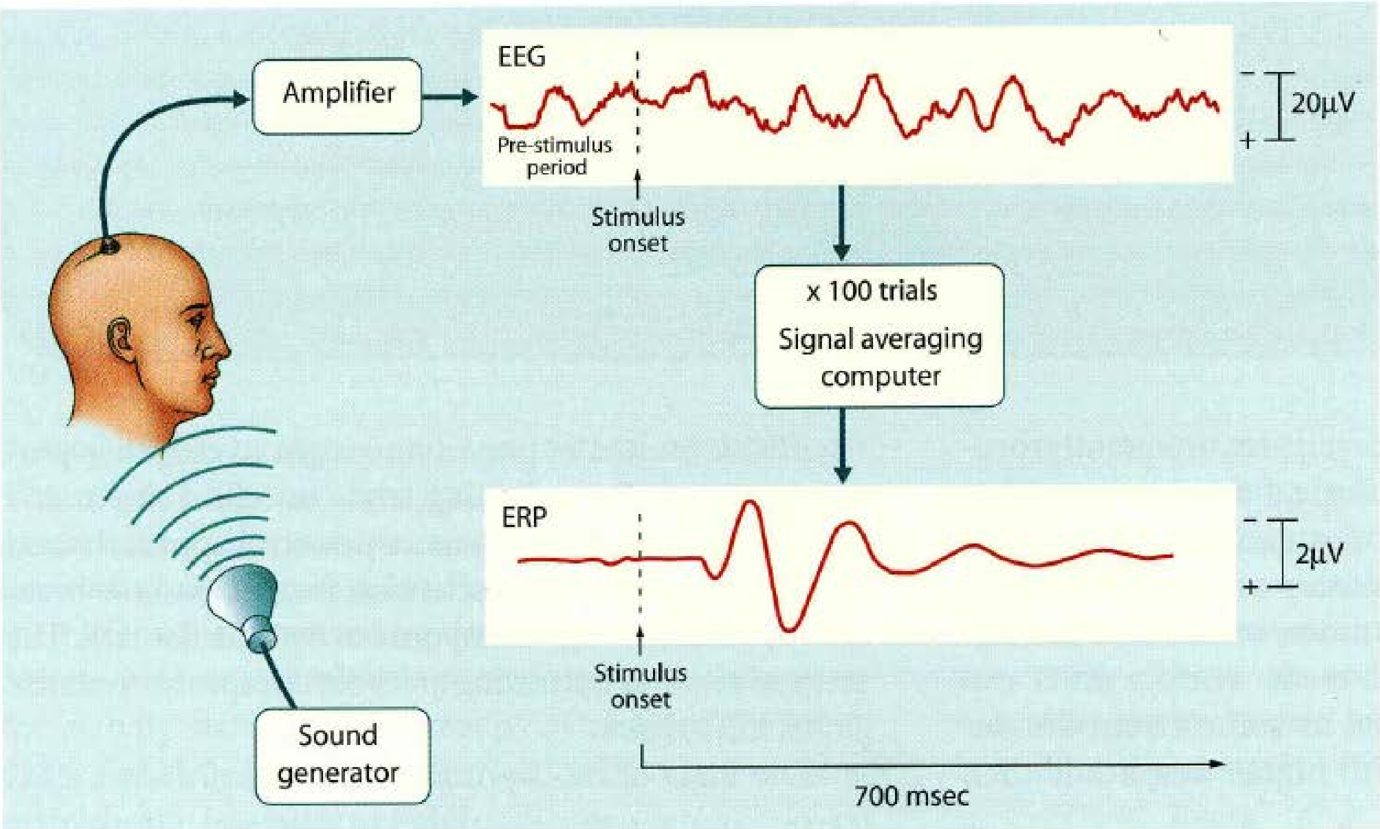


Figure 4.25 The relatively small electrical responses to specific events can only be observed by averaging the EEG traces over a series of trials. The large background oscillations of the EEG trace make it impossible to detect the evoked response to the sensory stimulus from a single trial. However, by averaging across tens or hundreds of trials, the background EEG is removed, leaving the event-related potential (ERP). Note the difference in scale between the EEG and ERP waveforms.

[Gazzaniga, Ivry & Mangun, Cognitive Neuroscience, 2nd ed., *W.W.Norton & Company*, 2002]

Auditory evoked potential (AEP)

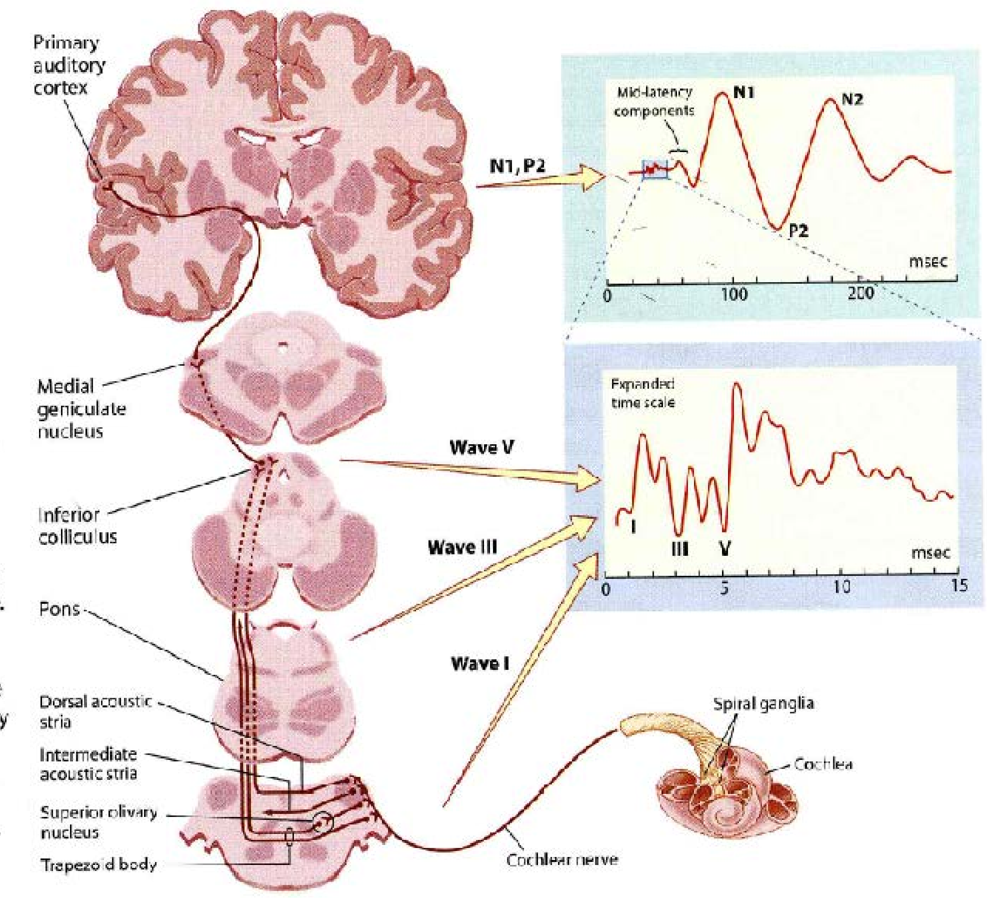
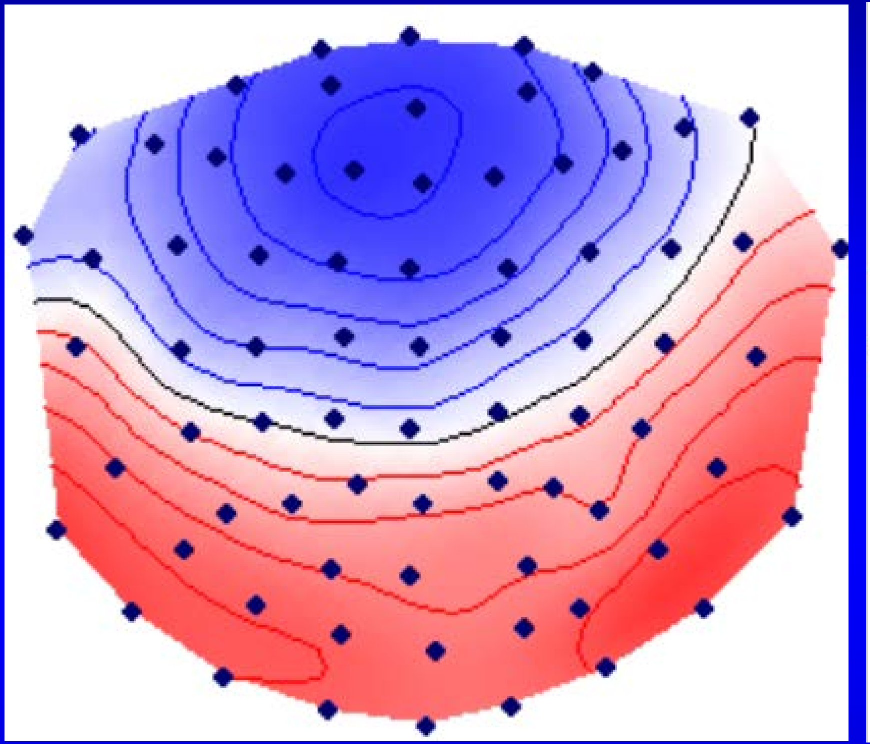


Figure 4.26 The evoked potential shows a series of positive and negative peaks at predictable points in time. In this auditory evoked response potential, the early peaks are invariant and have been linked to neural activity in specific brain structures. Later peaks are task dependent, and localization of their source has been a subject of much investigation and debate.

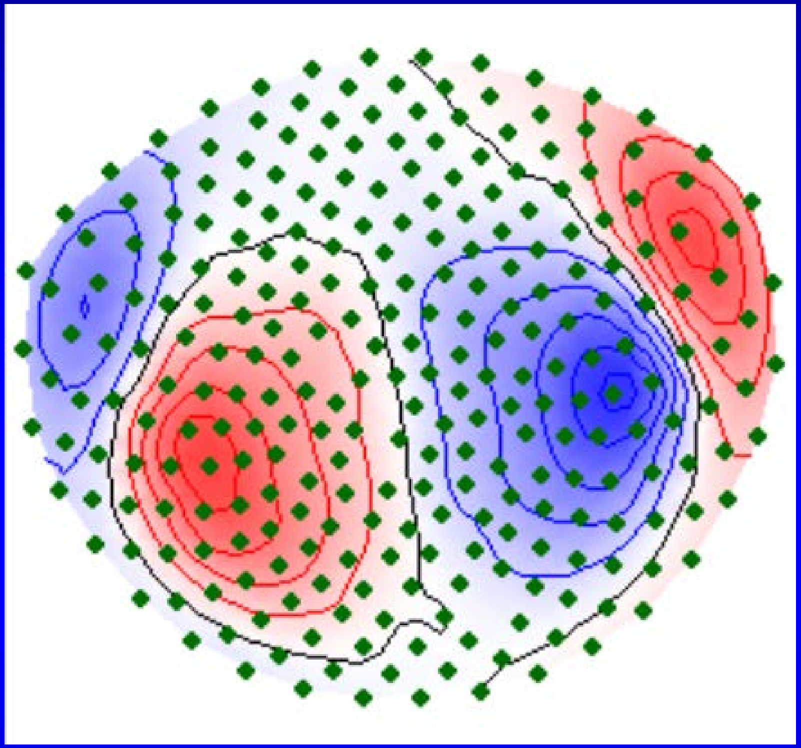
Only contralateral path is shown.

[Okamoto, Stracke, Wolters, Schmael & Pantev, *J Neurosci*, 2007]

N100 component of AEP/AEF



AEP-N1 component

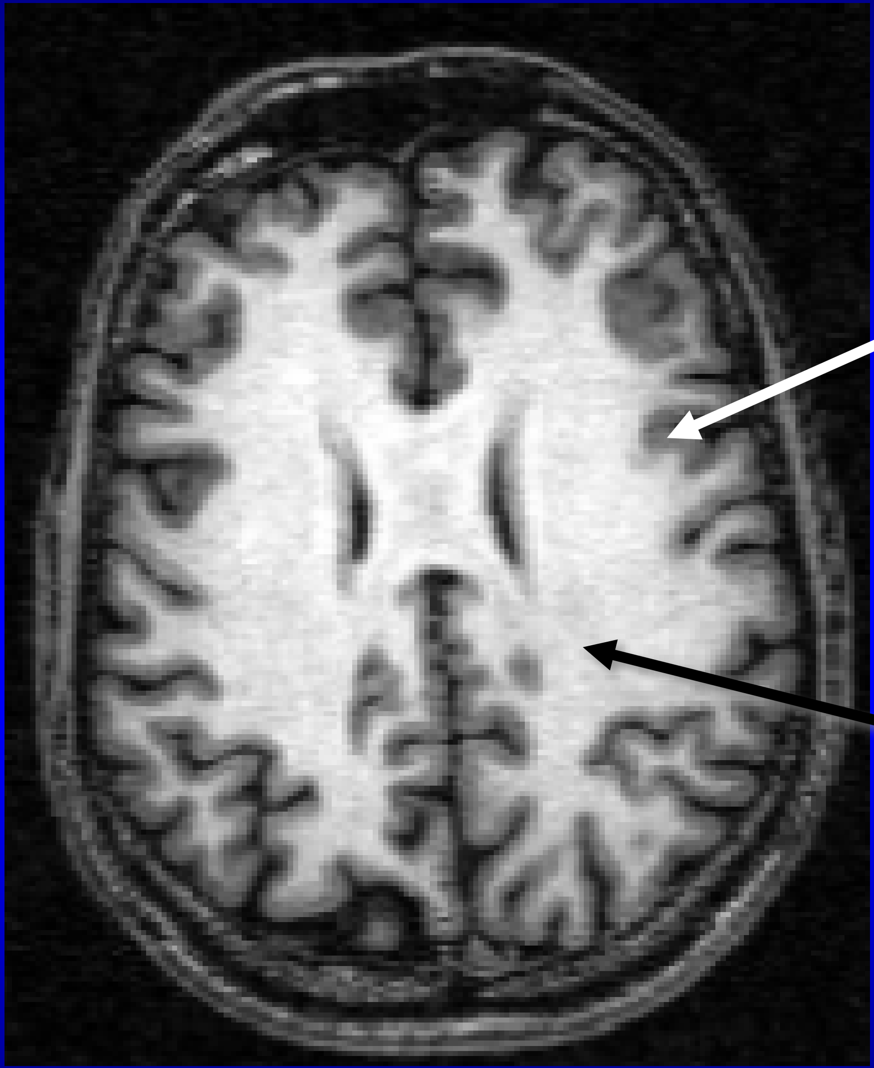


AEF-N1 component

Reconstruction of neuronal networks using EEG and MEG source analysis

- Model for the sources
- The forward problem
- The inverse problem

Gray and White Matter

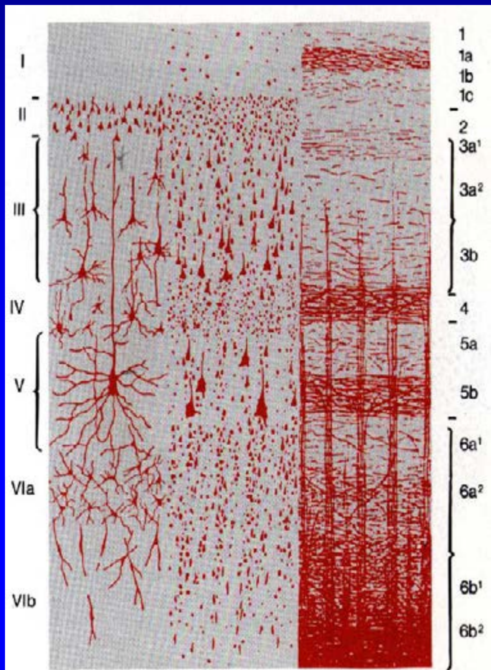


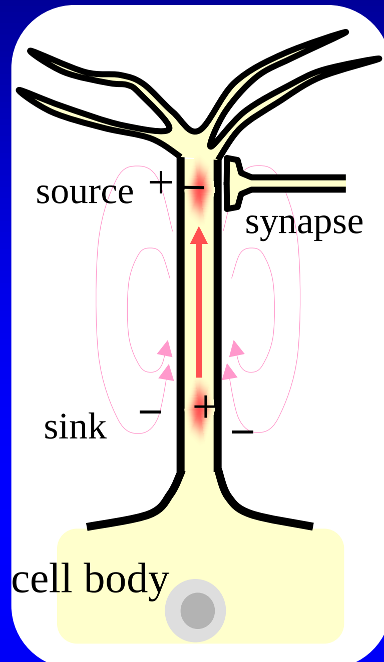
Gray matter (GM)

White matter (WM)

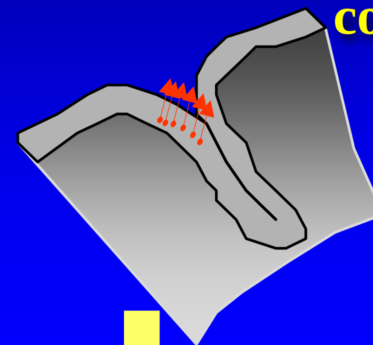
T1 weighted Magnetic Resonance Image (T1-MRI)

The source model





Microscopic current flow (~5×10^{-5} nAm)

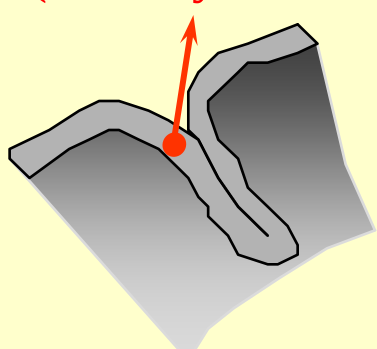


Equivalent Current Dipole (Primary current) (~50 nAm)

parameters:

position : x_0

moment : M



Size of Macroscopic Neural Activity

~30 mm^2 = **5.5×5.5 mm^2**

Reconstruction of neuronal networks using EEG and MEG source analysis

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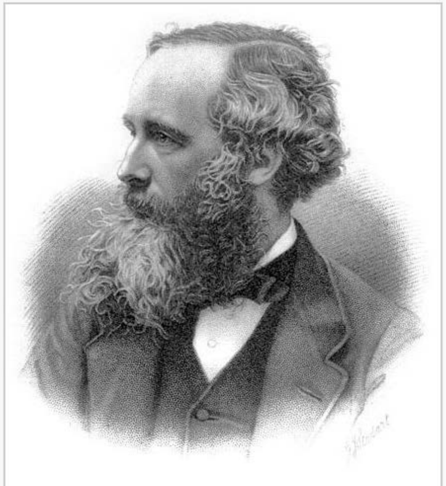
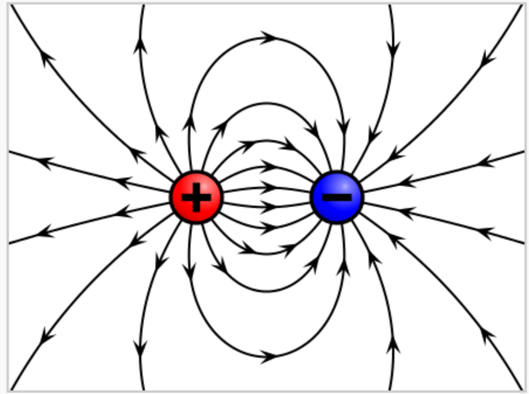
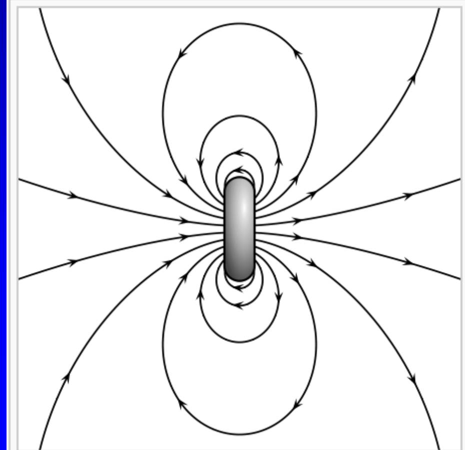
Maxwell equations



James Clerk Maxwell



Feldlinien des elektrischen Feldes zwischen positiven und negativen Ladungen



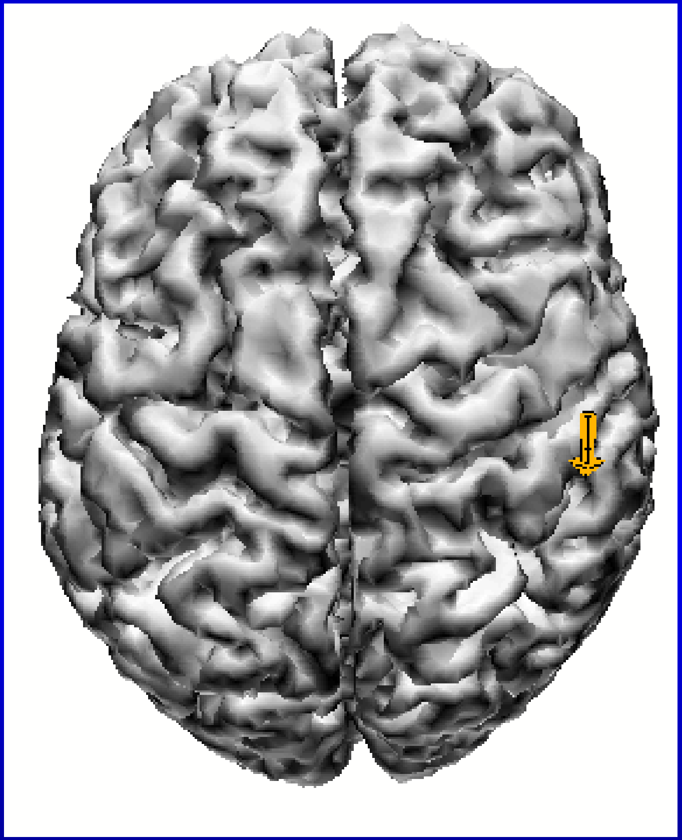
Die Feldlinien der magnetischen Flussdichte $\vec{B}$ sind stets geschlossen.

Name	SI	Physikalischer Inhalt
Gaußsches Gesetz	$\vec{\nabla} \cdot \vec{D} = \rho_{\text{frei}}$	Die Ladung ist Quelle des elektrischen Feldes.
Gaußsches Gesetz für Magnetfelder	$\vec{\nabla} \cdot \vec{B} = 0$	Das Feld der magnetischen Flussdichte ist quellenfrei; es gibt keine magnetischen Monopole.
Induktionsgesetz	$\vec{\nabla} \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$	Änderungen des magnetischen Feldes führen zu einem elektrischen Wirbelfeld.
Erweitertes Durchflutungsgesetz	$\vec{\nabla} \times \vec{H} = \vec{j}_{\text{frei}} + \frac{\partial \vec{D}}{\partial t}$	Elektrische Ströme – einschließlich des Verschiebungsstroms – führen zu einem magnetischen Wirbelfeld.

[Wolters & de Munck, *Scholarpedia*, 2007]
[de Munck, Wolters & Clerc, *In: Handbook of neural activity measurement*, 2012]

EEG forward problem

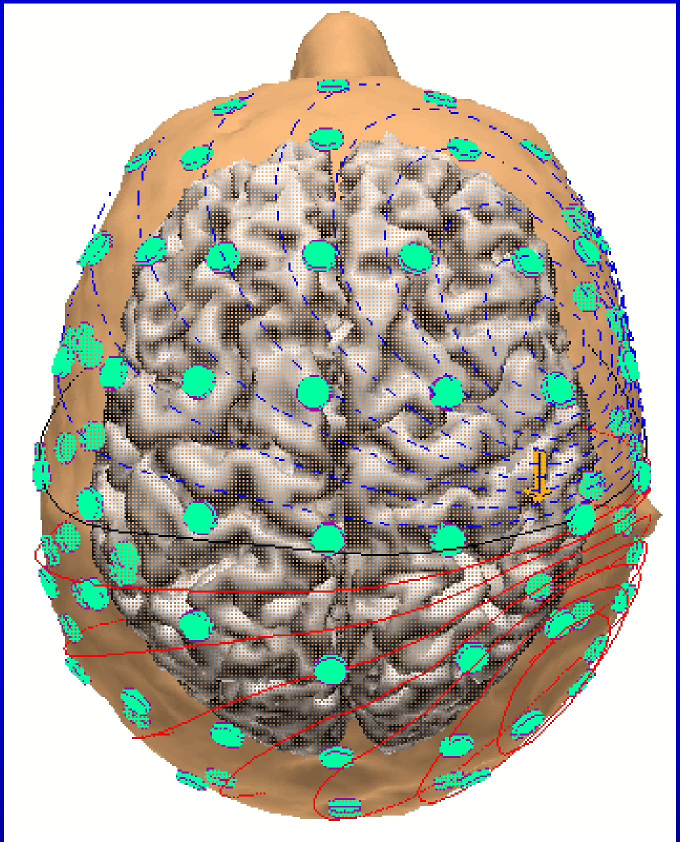
Place a dipole



Simulate quasistatic

Maxwell equations

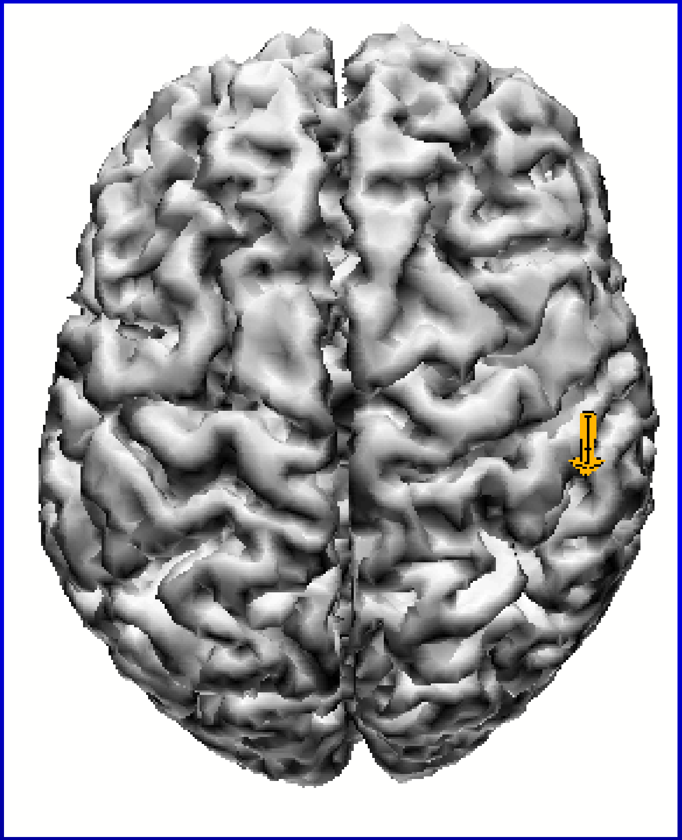
Compute the EEG



[Wolters & de Munck, *Scholarpedia*, 2007]
[de Munck, Wolters & Clerc, *In: Handbook of neural activity measurement*, 2012]

MEG forward problem

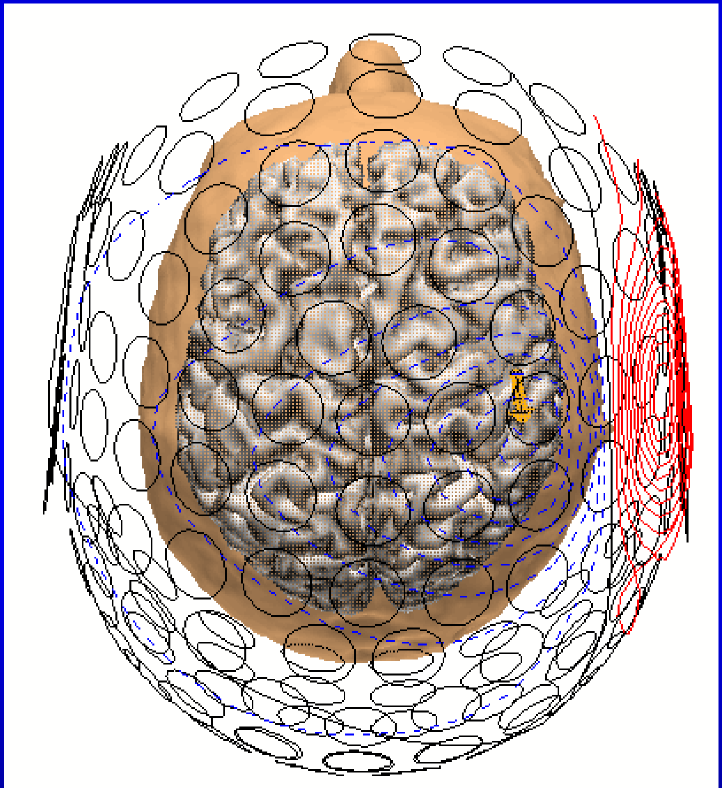
Place a dipole



Simulate quasistatic

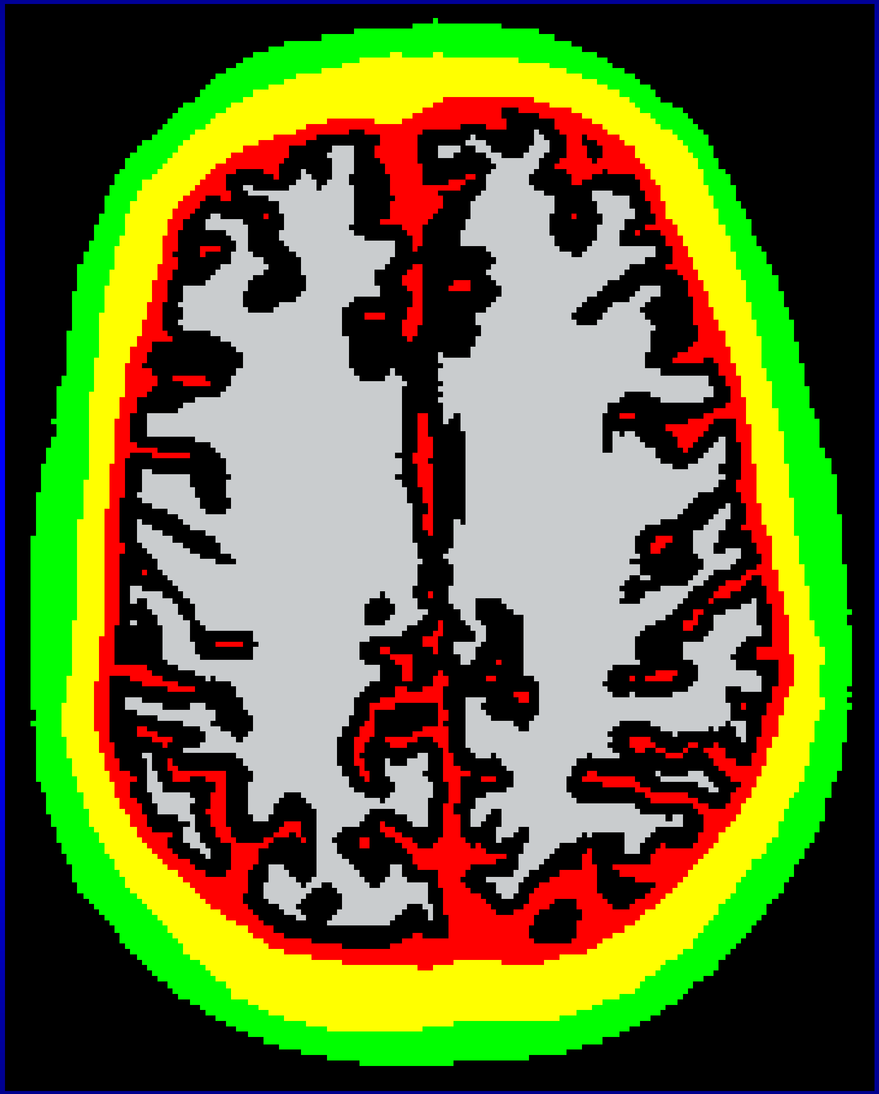
Maxwell equations

Compute the MEG



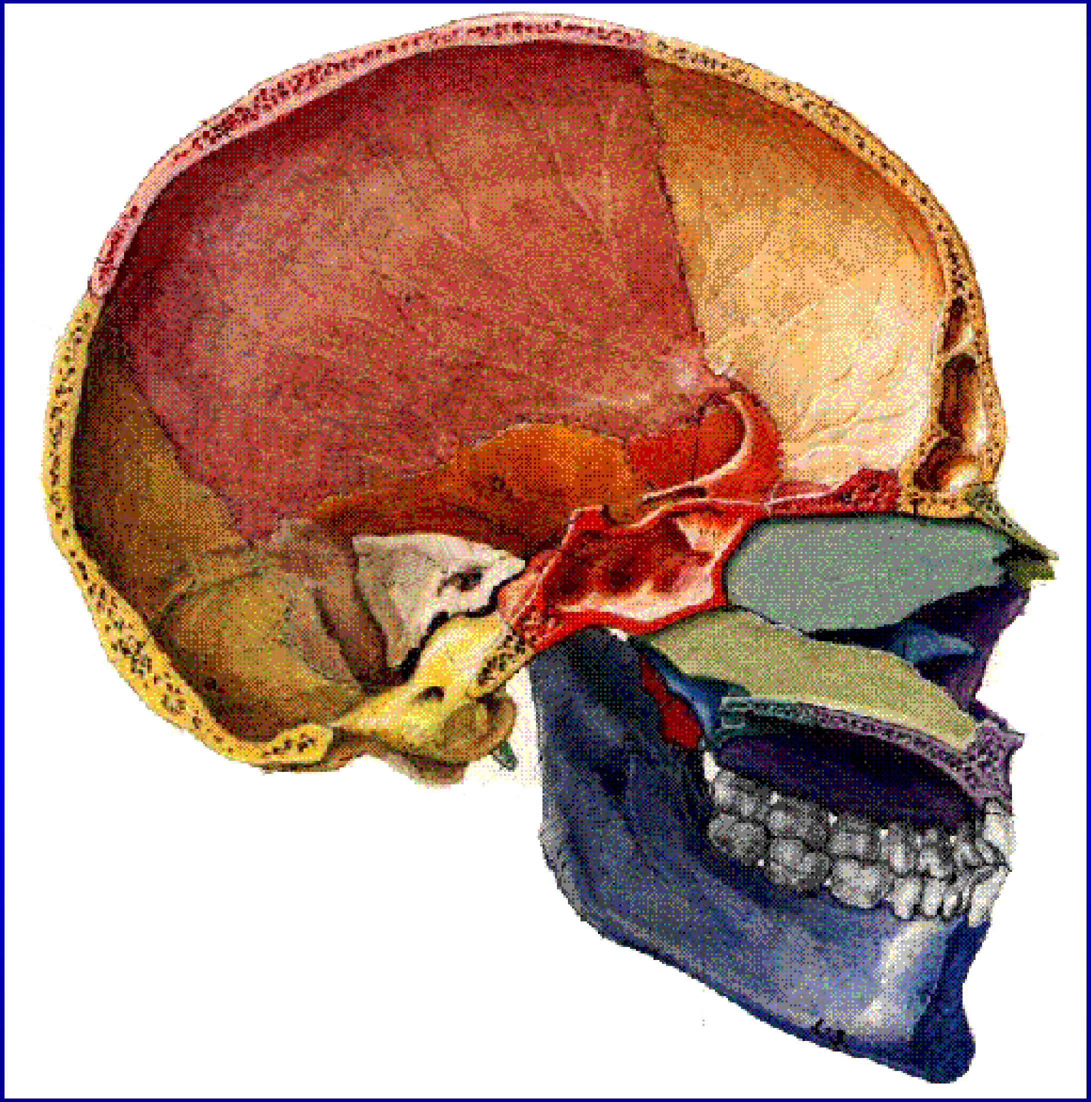
[Wolters & de Munck, *Scholarpedia*, 2007]
[de Munck, Wolters & Clerc, *In: Handbook of neural activity measurement*, 2012]

Multi-compartment volume conductor model

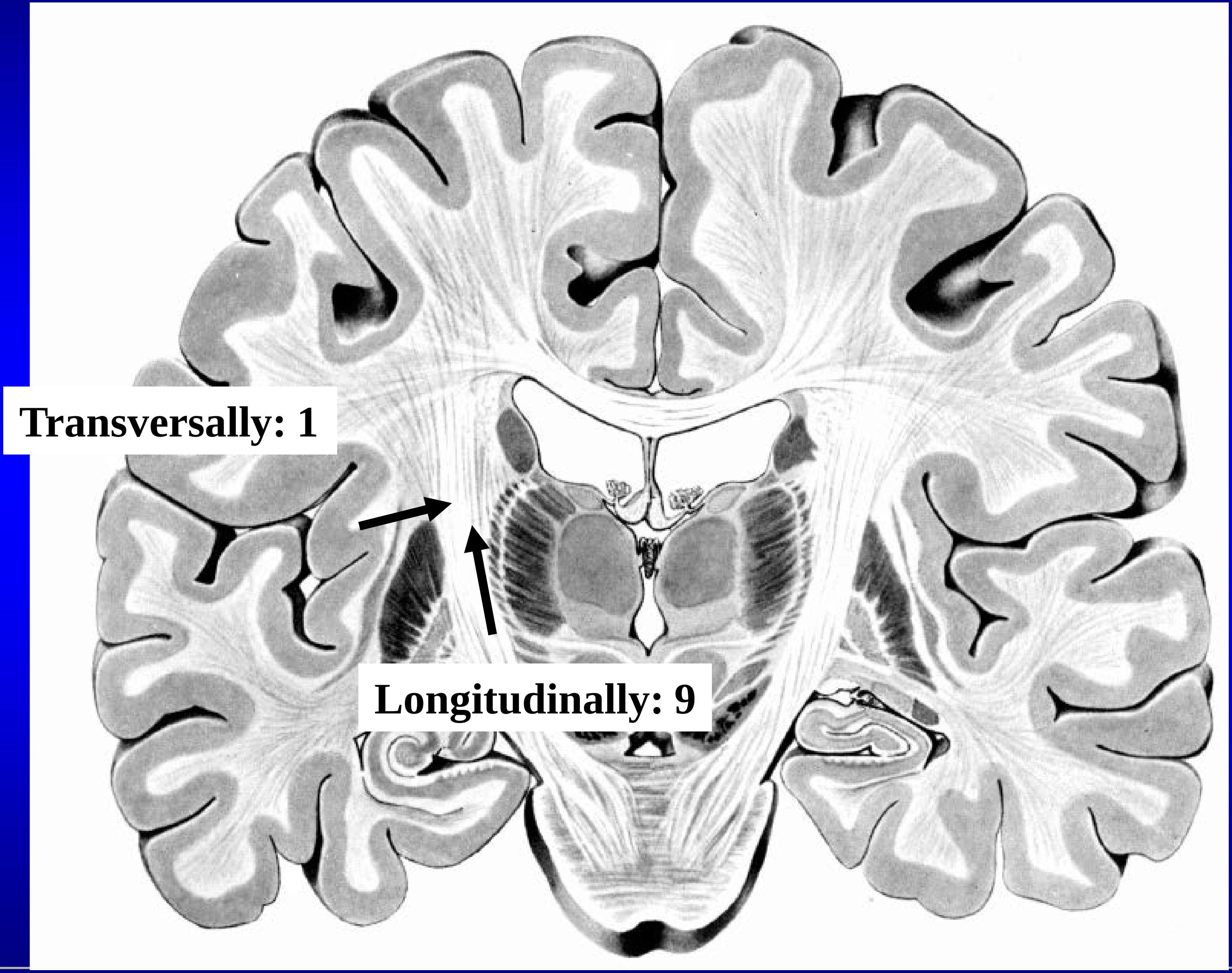


Skin	0.33 S/m
Skull	anisotropic/ 3-layer
CSF	1.79 S/m
Gray matter	0.33 S/m
White matter	anisotropic

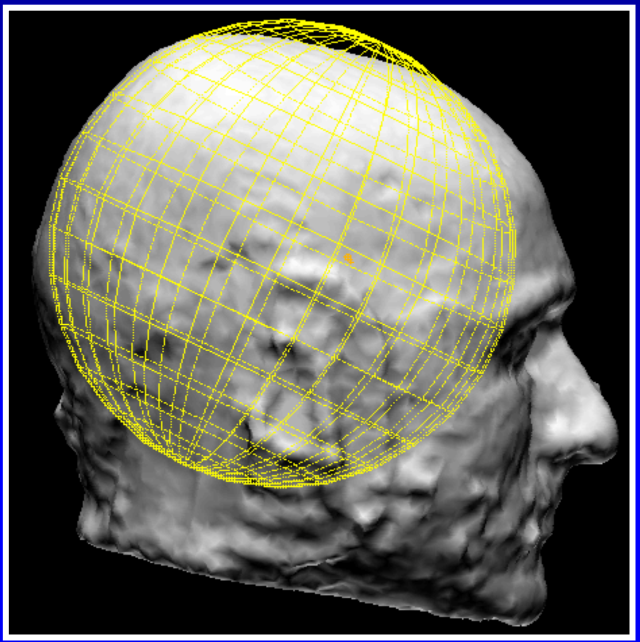
Three-layered human skull

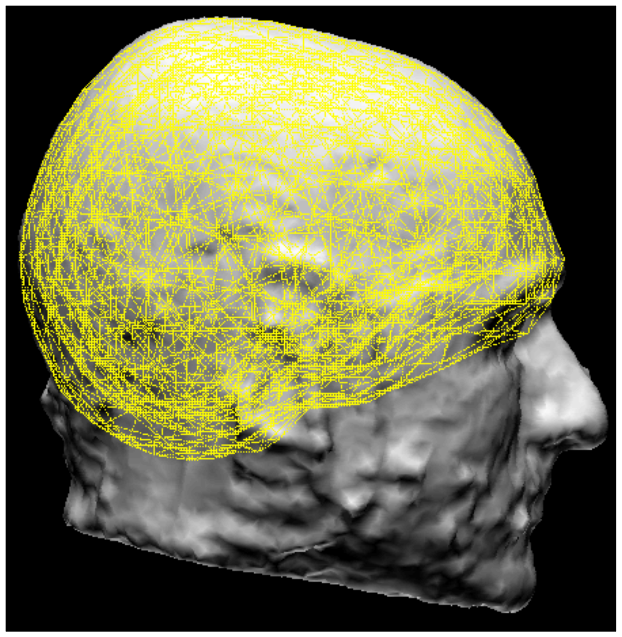


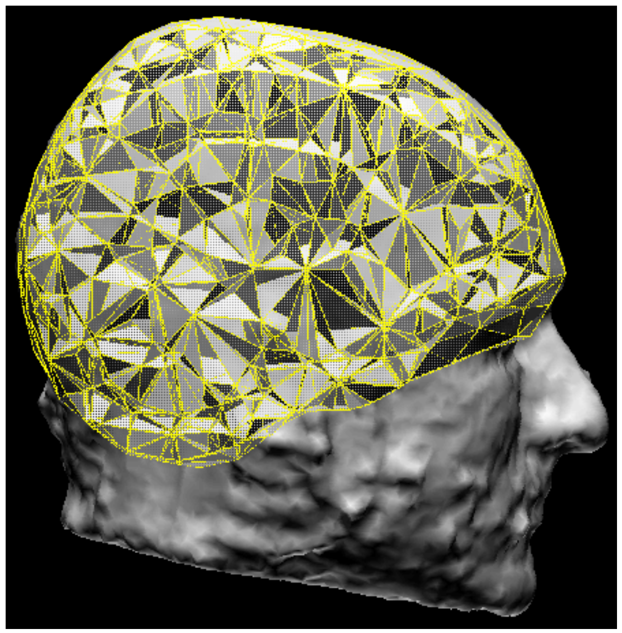
Anisotropy of white matter (WM)



Volume conductor modeling







Spherical shells

	Geometry	Conductivity
Skin	unreal.	unreal.
Skull	unreal.	unreal.
CSF	unreal.	unreal.
GM	unreal.	unreal.
WM	unreal.	unreal.

Boundary element

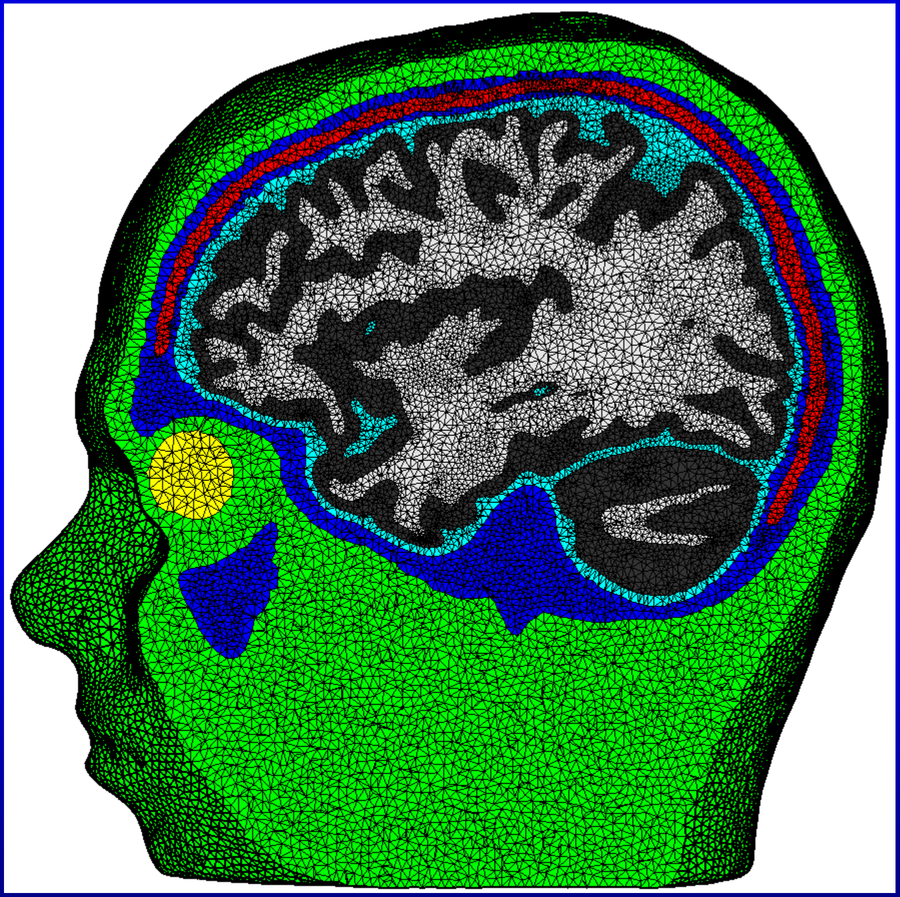
<table>
<tr><th></th><th>Geometry</th><th>Conductivity</th></tr>
<tr><td>Skin</td><td>realistic</td><td>realistic</td></tr>
<tr><td>Skull</td><td>realistic</td><td>unreal.</td></tr>
<tr><td>CSF</td><td colspan="2" rowspan="3">unrealistic
(1 isotropic value)</td></tr>
<tr><td>GM</td></tr>
<tr><td>WM</td></tr>
</table>

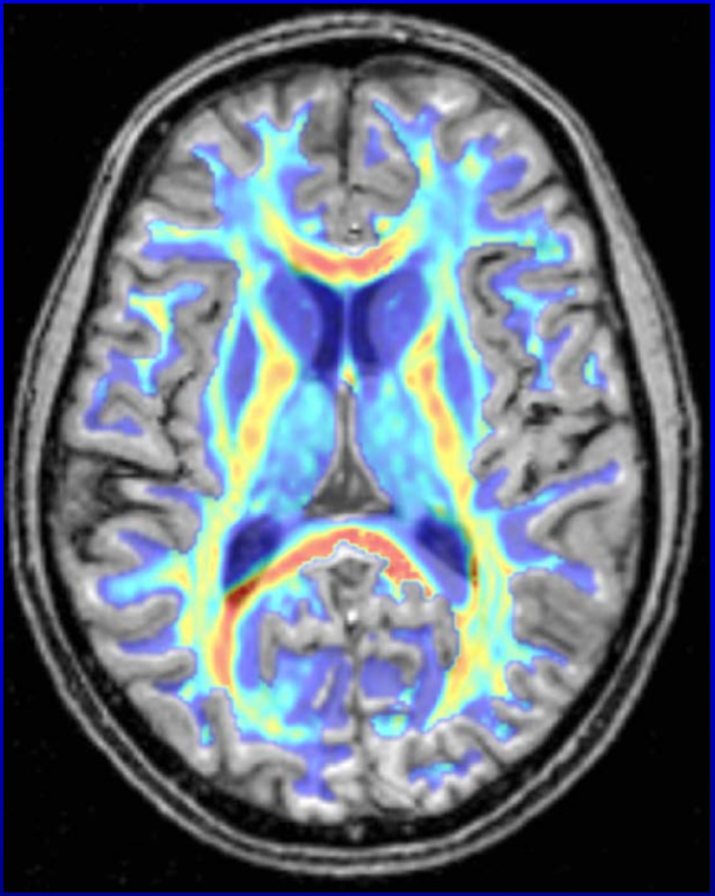
Finite Element (FE)

	Geometry	Conductivity
Skin	realistic	realistic
Skull	realistic	realistic
CSF	realistic	realistic
GM	realistic	realistic
WM	realistic	realistic

[Wolters, Anwander, Tricoche, Weinstein, Koch & MacLeod, *NeuroImage*, 2006]
[Vorwerk, Cho, Rampp, Hamer, Knösche & Wolters, *NeuroImage*, 2014]
[Wagner, Rampersad, Aydin, Vorwerk, Oostendorp, Neuling, Herrmann, Stegeman & Wolters, *J. Neur. Eng.*, 2014]

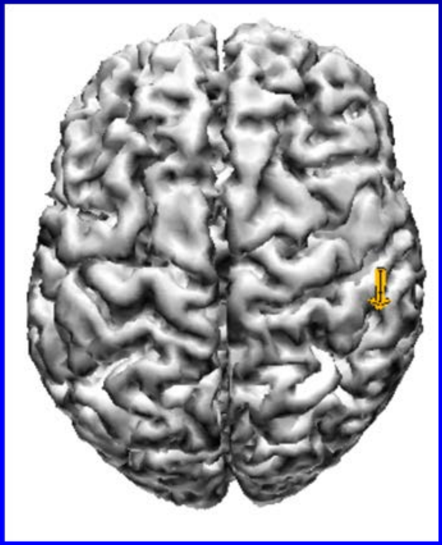
Realistically shaped multi-compartment anisotropic head volume conductor modeling for accurate simulation in EEG/MEG and tCS/TMS

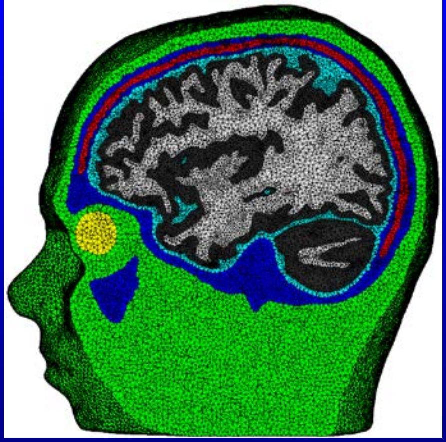




[Wolters & de Munck, *Scholarpedia*, 2007]
[de Munck, Wolters & Clerc, *In: Handbook of neural activity measurement*, 2012]

The forward problem in EEG/MEG

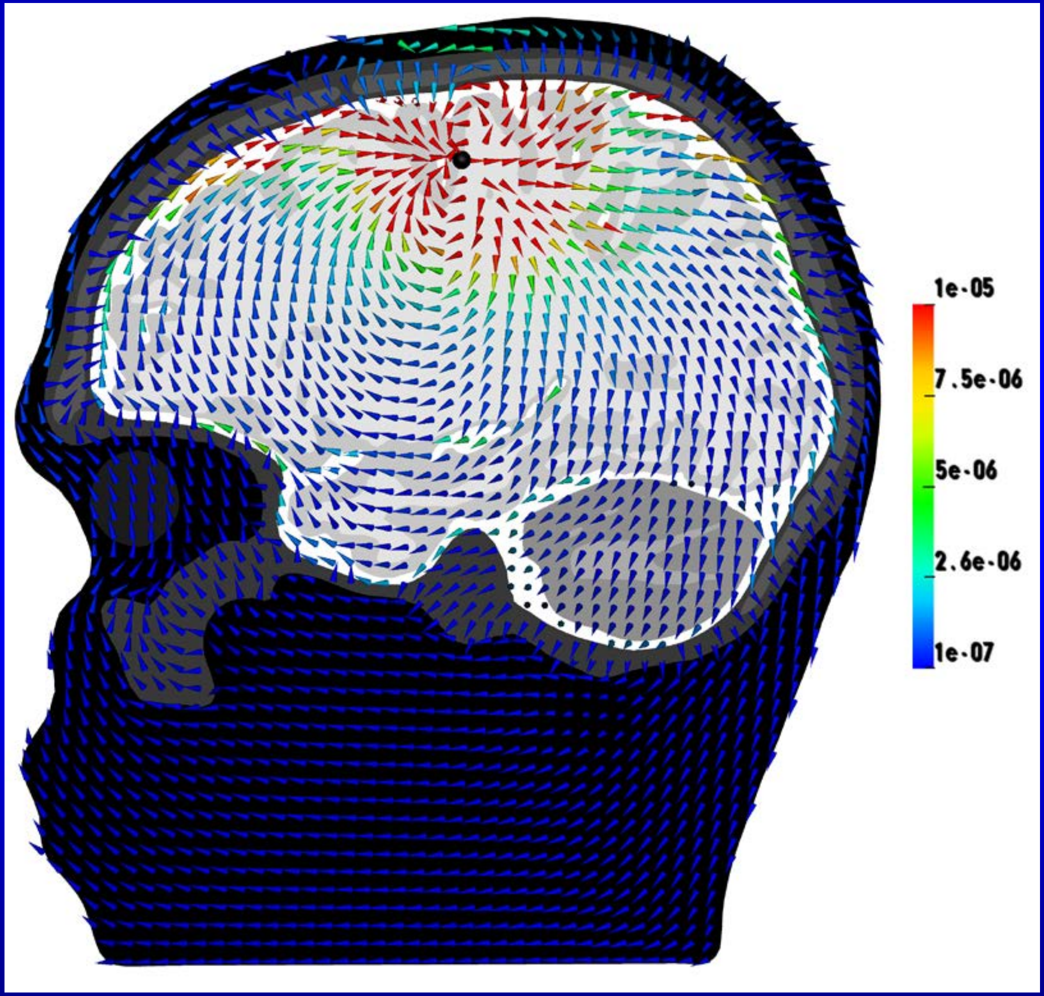




Simulate

➡

potential distribution or current



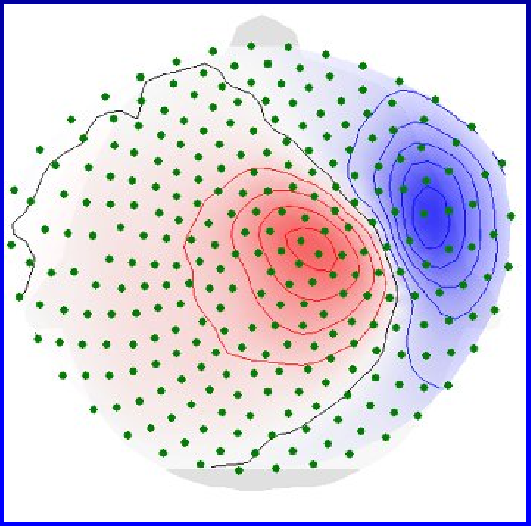
Reconstruction of neuronal networks using EEG and MEG source analysis

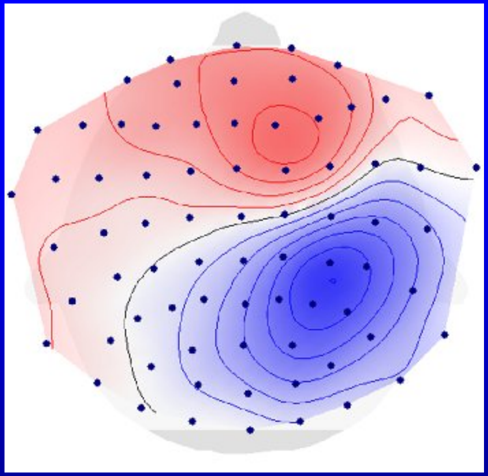
- Model for the sources
- The forward problem
- The inverse problem

[Antonakakis, Schrader, Wollbrink, Oostenveld, Rampp, Haueisen & Wolters, *HBM*, 2019]

Source analysis: The inverse Problem

SEF-P20

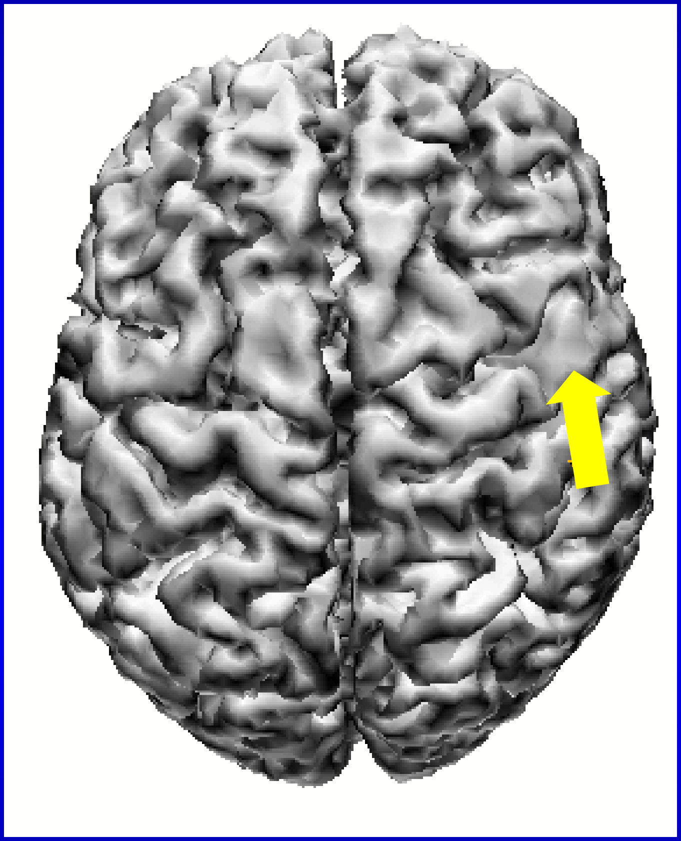




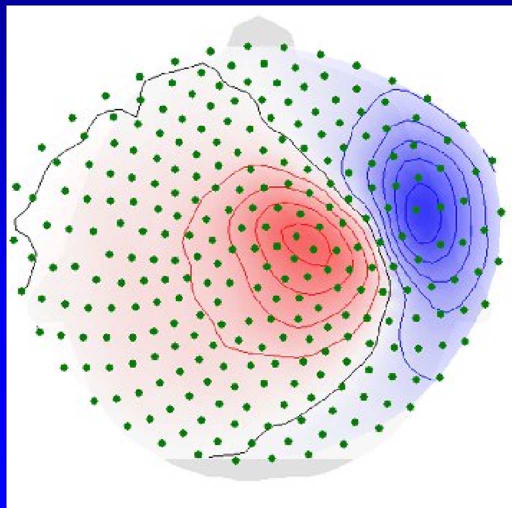
SEP-P20

Reconstruct

source



Source analysis: The inverse Problem



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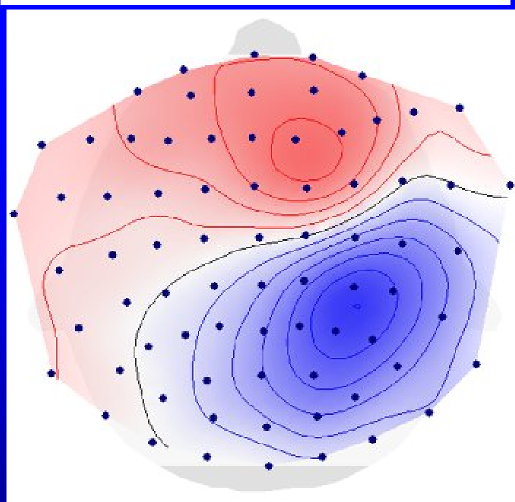
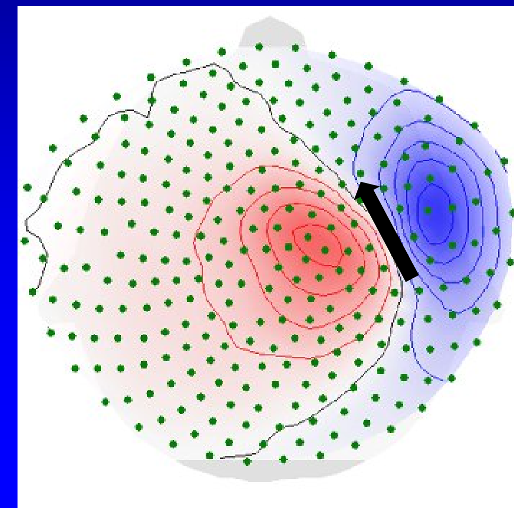
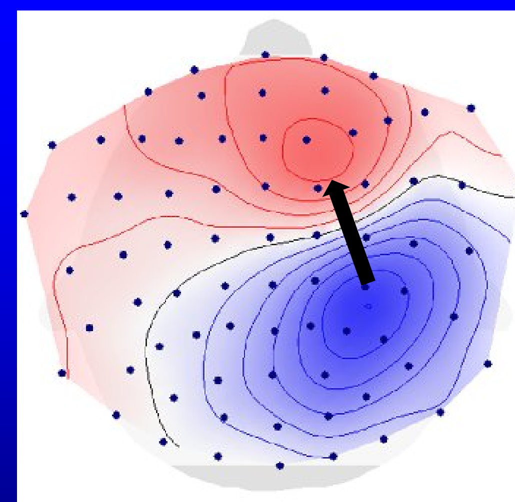


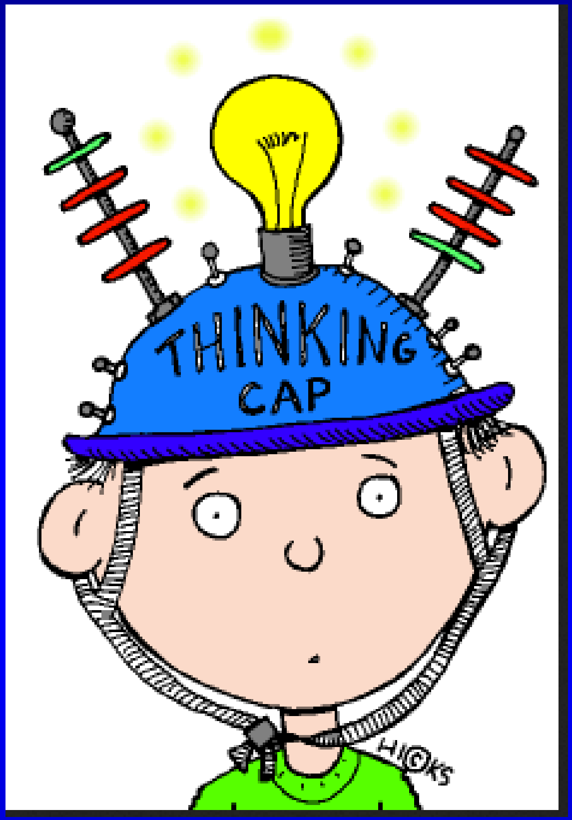
SEP-P20

Reconstruct

source







Thank you for your attention!