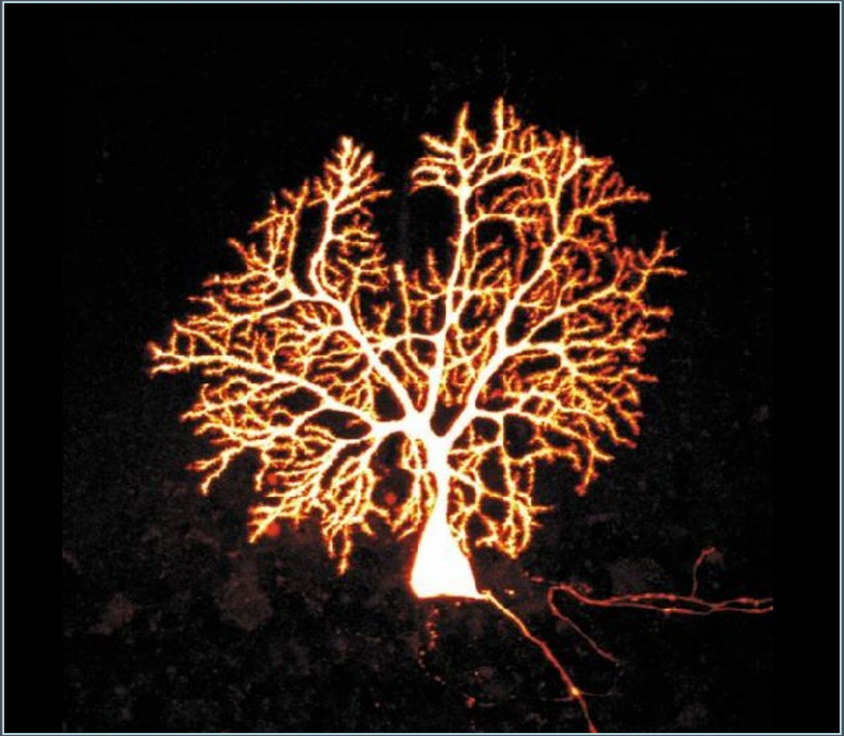
Introduction to electroencephalography and magnetoencephalography (M/EEG)

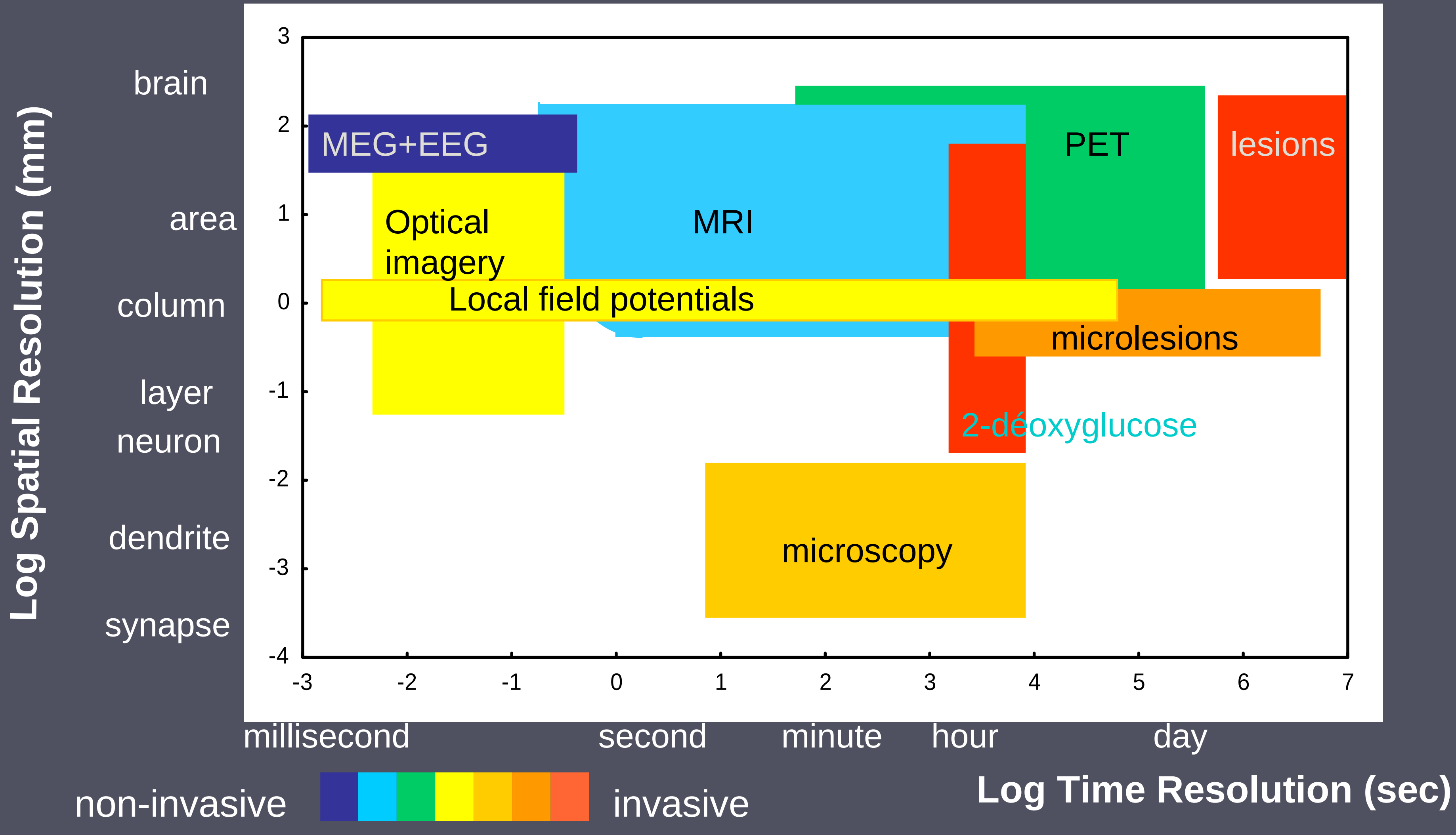
Théo Papadopoulo

INRIA

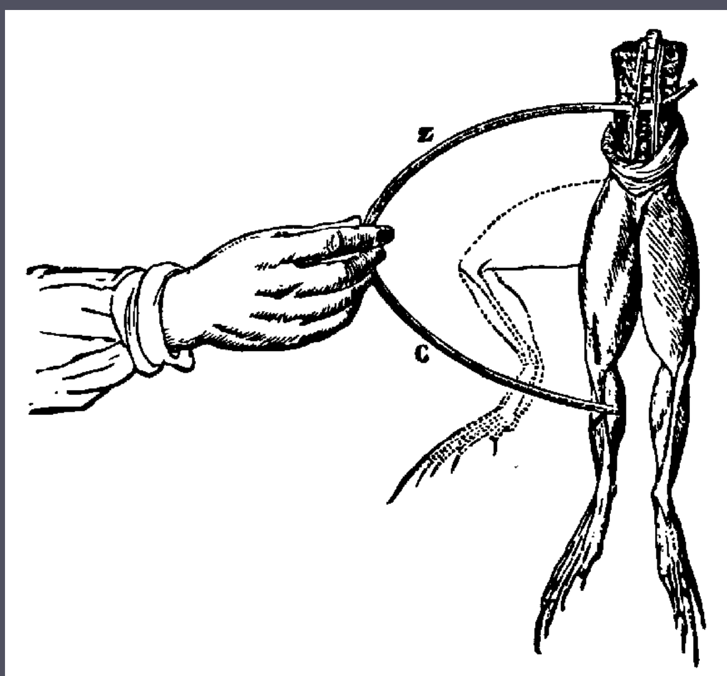


Master DSAI, October 2023

Spatio-temporal properties of various brain functional imagery modalities



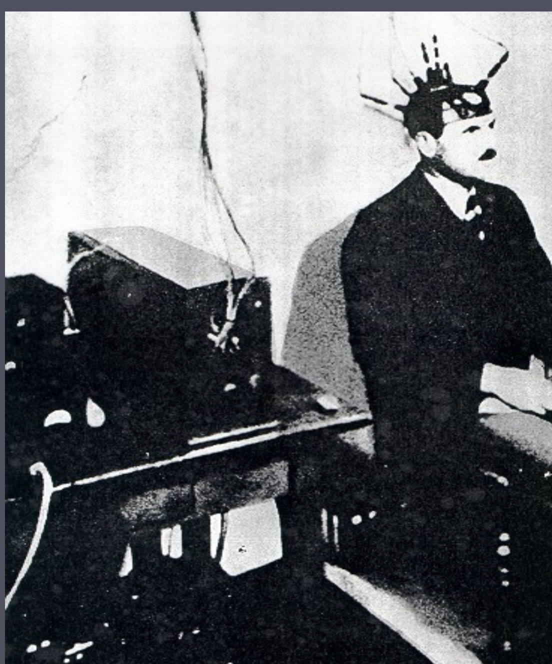
1791: Galvani dicovers bio-electricity.

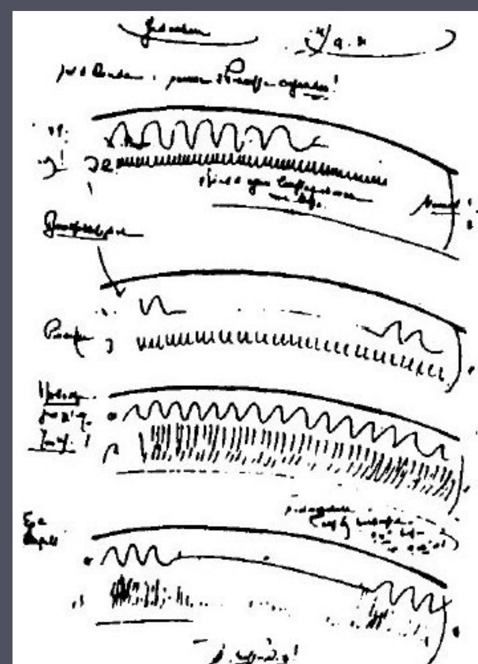


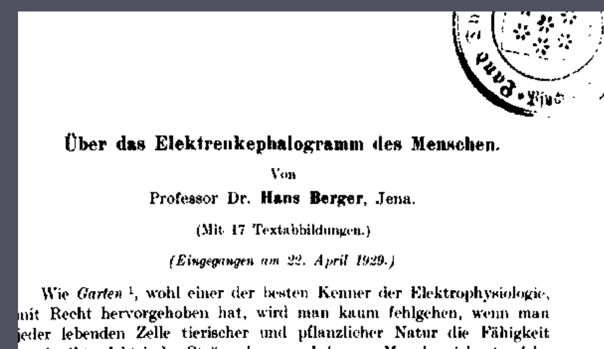
- Experiment of “galvanic paw”.
- Two metalic stalks of different metals (copper & zinc) cause an ionic current flow.

1924: Hans Berger invents electroencéphalography

- Demonstration of electrical activity of the brain at the surface of the scalp.
- This raises the question of the precise origin of this signal.







Über das Elektrenkephalogramm des Menschen.

Von

Professor Dr. **Hans Berger**, Jena.

(Mit 17 Textabbildungen.)

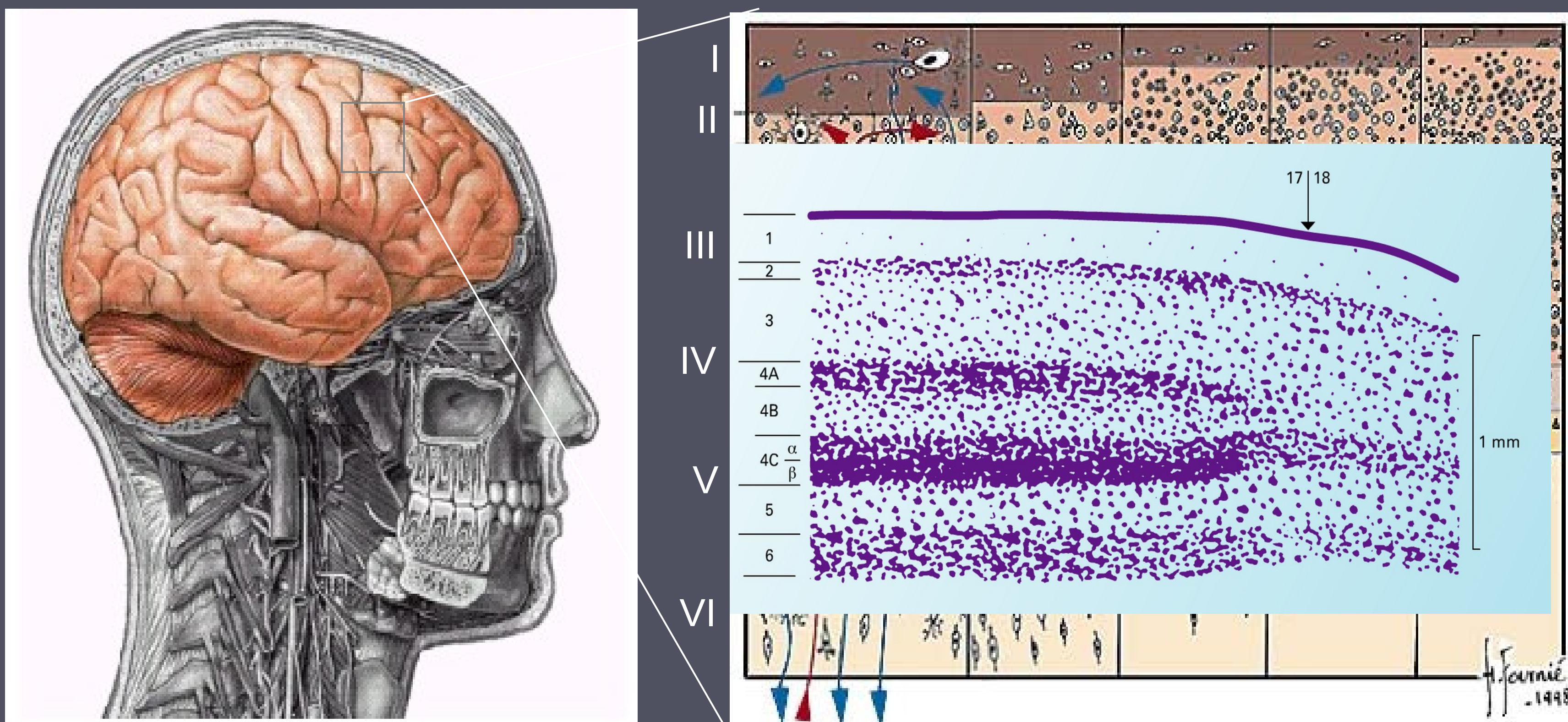
(Eingegangen am 22. April 1929.)

Wie *Garten* [1], wohl einer der besten Kenner der Elektrophysiologie, mit Recht hervorgehoben hat, wird man kaum fehlgehen, wenn man jeder lebenden Zelle tierischer und pflanzlicher Natur die Fähigkeit zuschreibt, elektrische Ströme hervorzubringen. Man bezeichnet solche

- First publication: 1929
- Discovery of two types of rythms/oscillations
  - alpha: 10Hz
  - beta: 15Hz
  - Up to 200µV

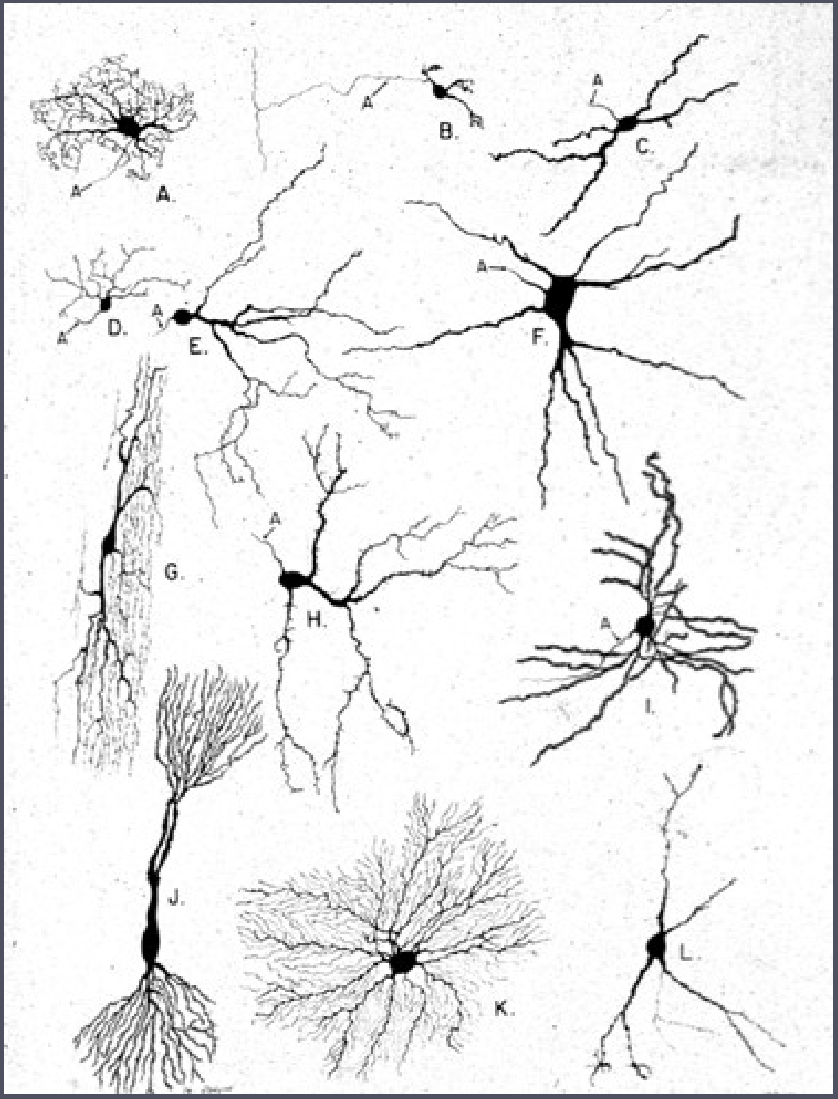
Bases of Neuroanatomy

- Cerebral cortex & cellular organisation
- Cortical layers :
    - Up to 6, variable in thickness, density and neuronal cell types



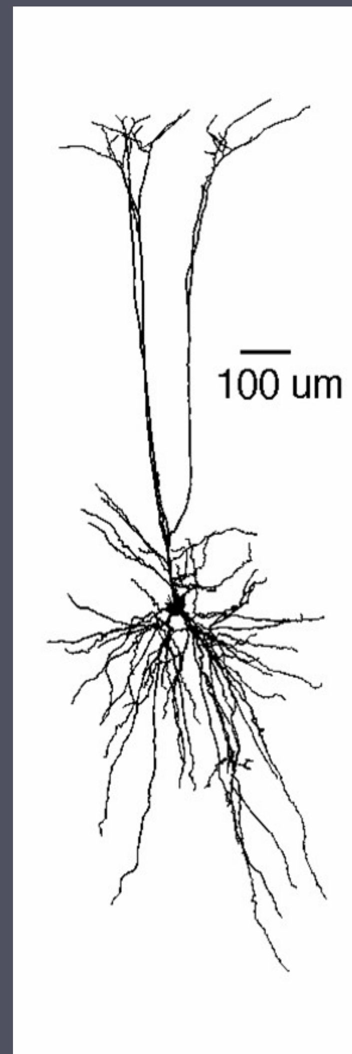
Neuroanatomy bases

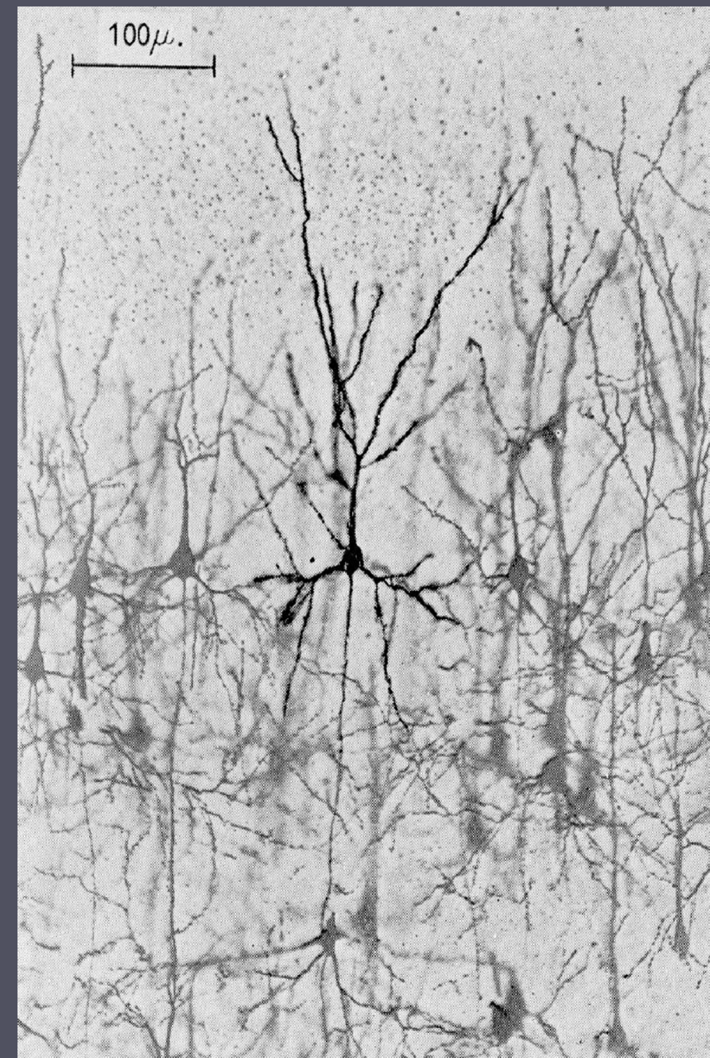
- The neuron
  - Basic building block of the nervous system.
    - Discrete organization.
    - Cajal 1889 & Waldeyer 1891
  - Many different neuron types across the central nervous system (CNS).



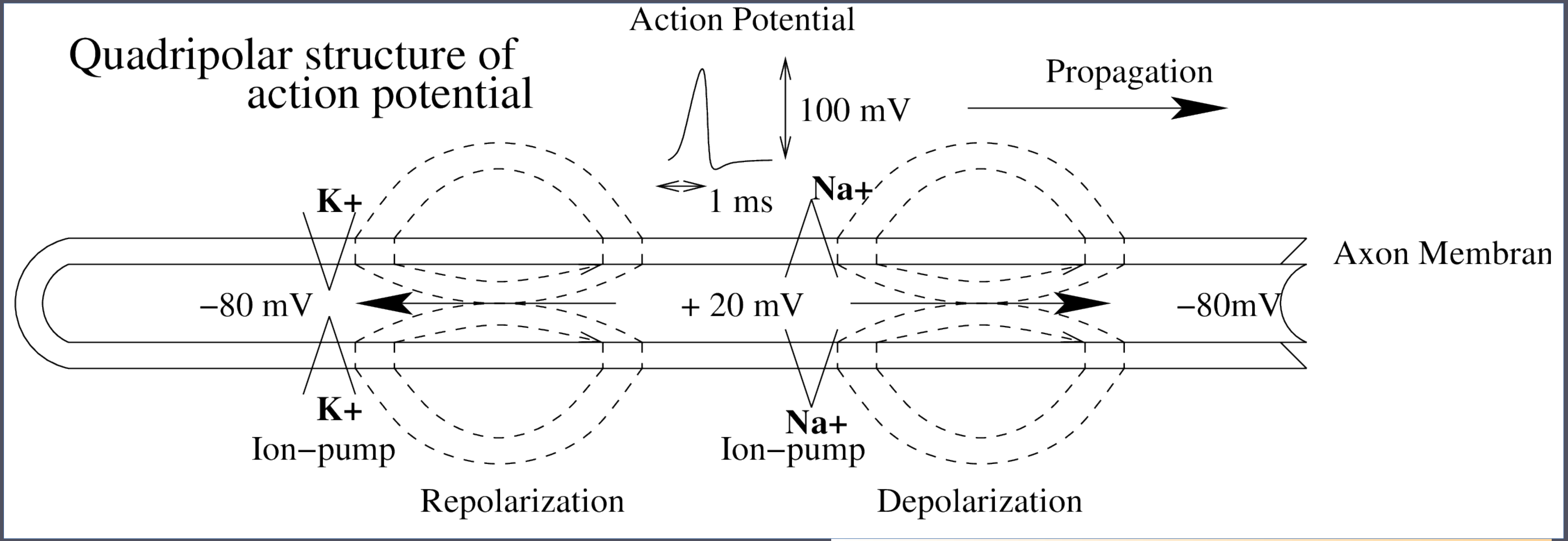
Elements of neural electrophysiology

- The pyramidal neuron case
  - Big cell
  - Organized into macro-assemblies
  - Superposition of elementary currents
    - « traces » visibles at distance, at the scalp surface

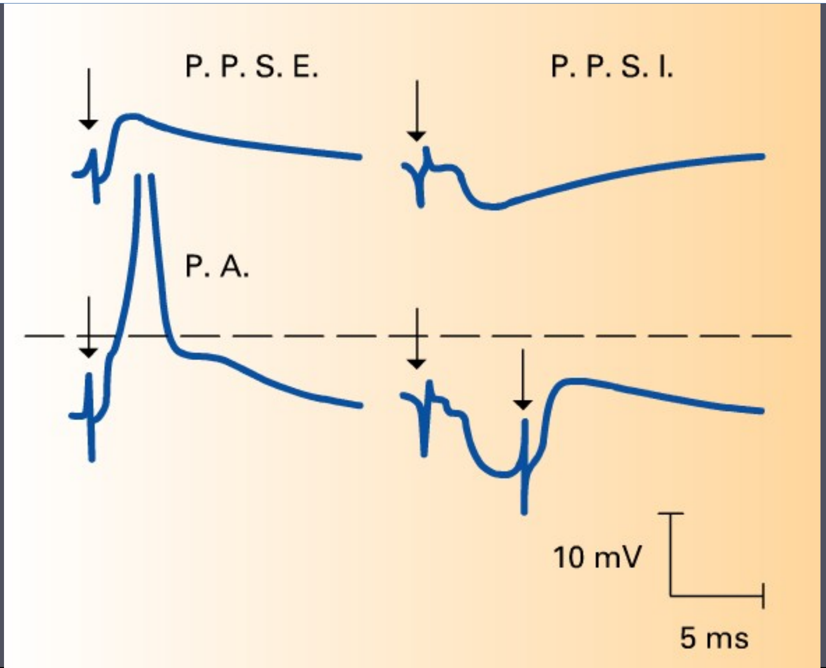




Elements of neural electrophysiology



- Post-Synaptic Potentials
  - Evoked by action potentials (AP) of afferent cells.
  - Excitatory (EPSP) or inhibitory (IPSP)
  - Summation effect with eventual emission of an efferent AP.
  - Wider and slower than AP.
    - This reinforces superposition of PSPs of the same neural assemblies.

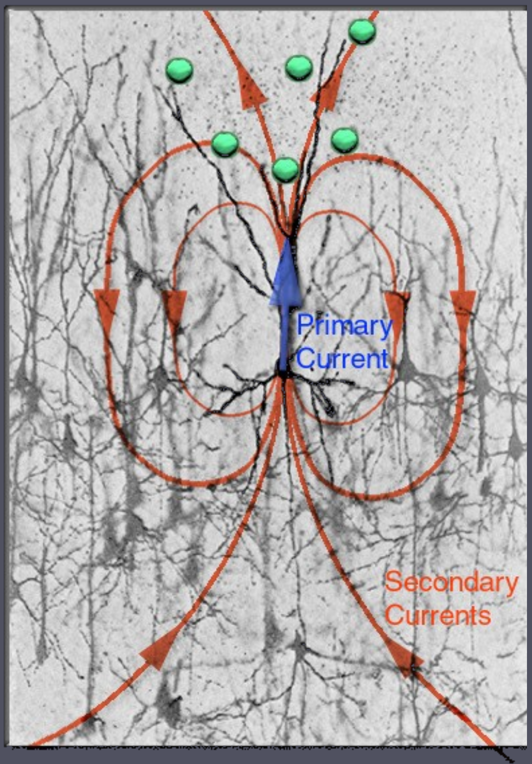


A question of scale

Excitatory post-synaptic potentials

Scale: micro

Pyramidal cell assembly



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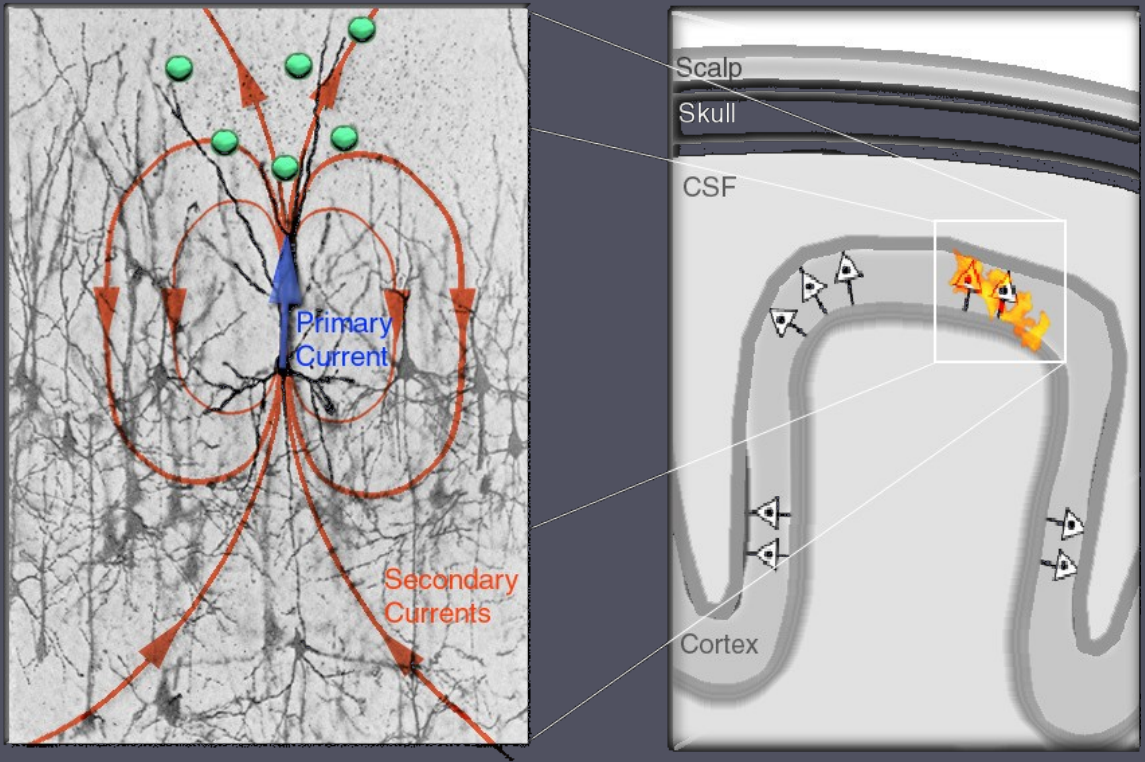
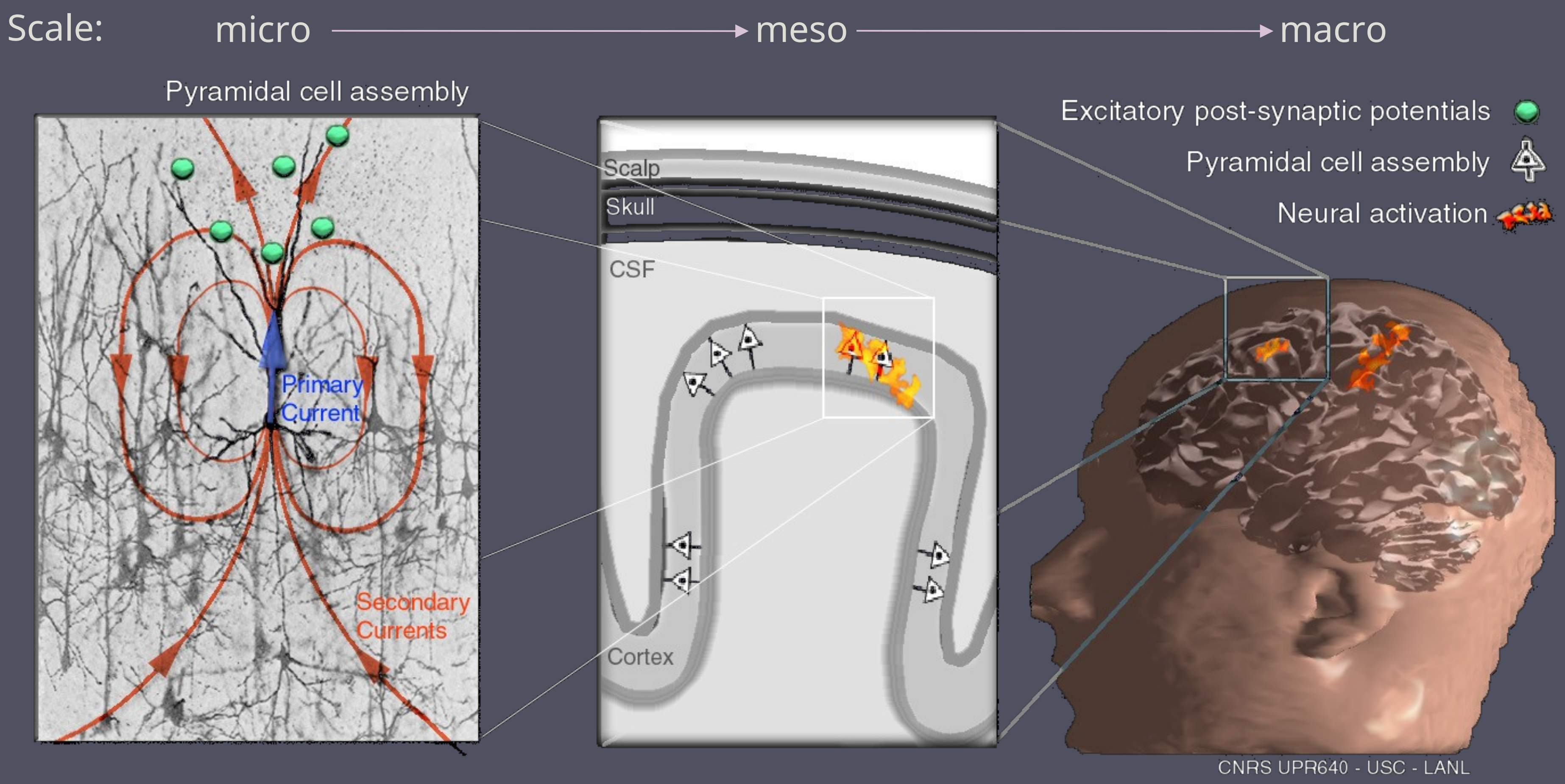
A question of scale

Scale: micro → meso

Pyramidal cell assembly



A question of scale



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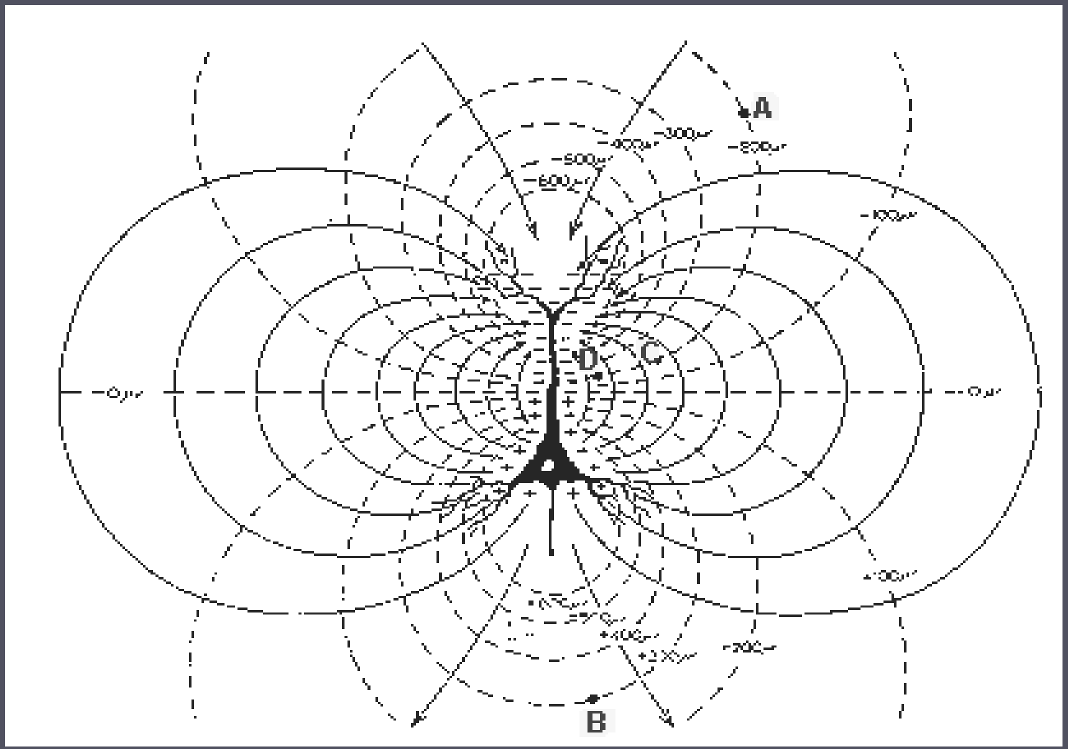
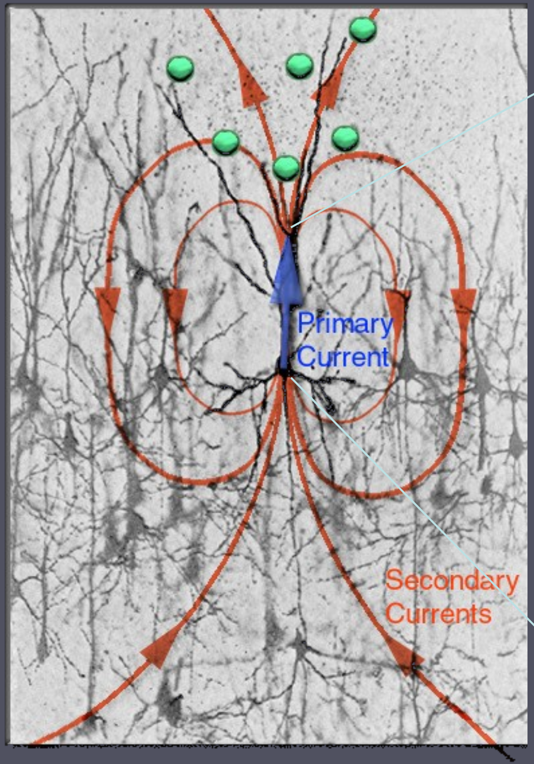
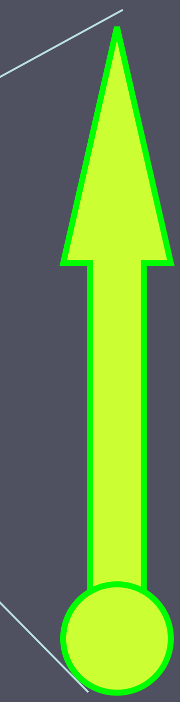
The current dipole: a simple model for electrophysiology of neural assemblies

Pyramidal cell assembly



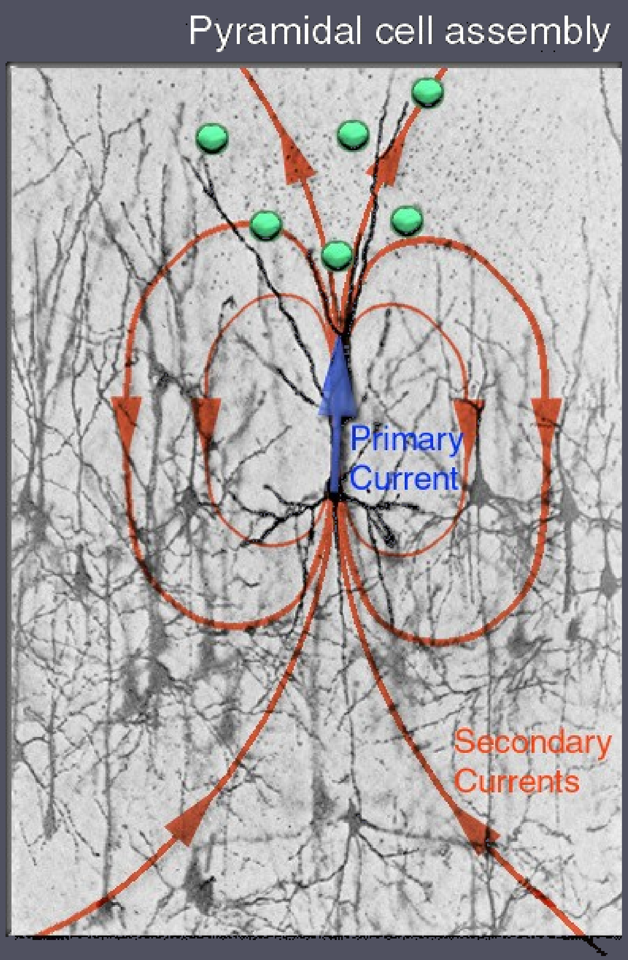




Current flow lines (-) and isopotential lines (--)

Excitatory post-synaptic potentials

Current dipole

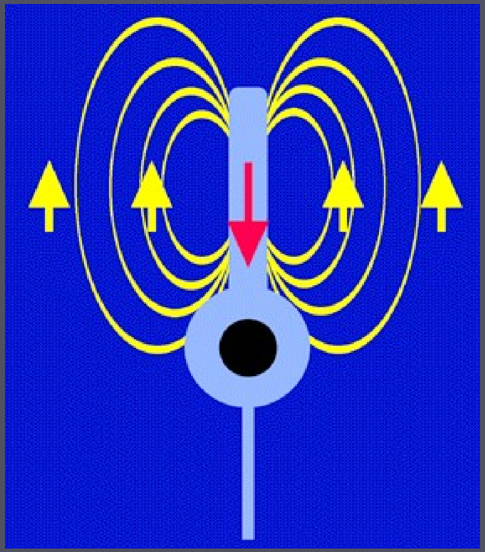


- Q = I x d = 10 fAm (20 fAm)
- Cortical macrocolumn
  - 10^6 neurons
  - Q =~10nAm
  - Homogeneous infinite domain:

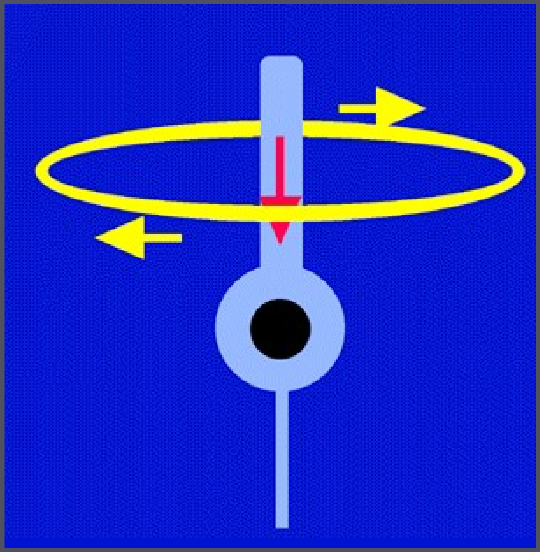
$$V = \frac{1}{4\pi\sigma}\frac{Q\cdot R}{\|R\|^3} \approx 2\,mV$$

From bio-electricity to bio-magnetism

- Magnetic field: dual of the neural electric potential.



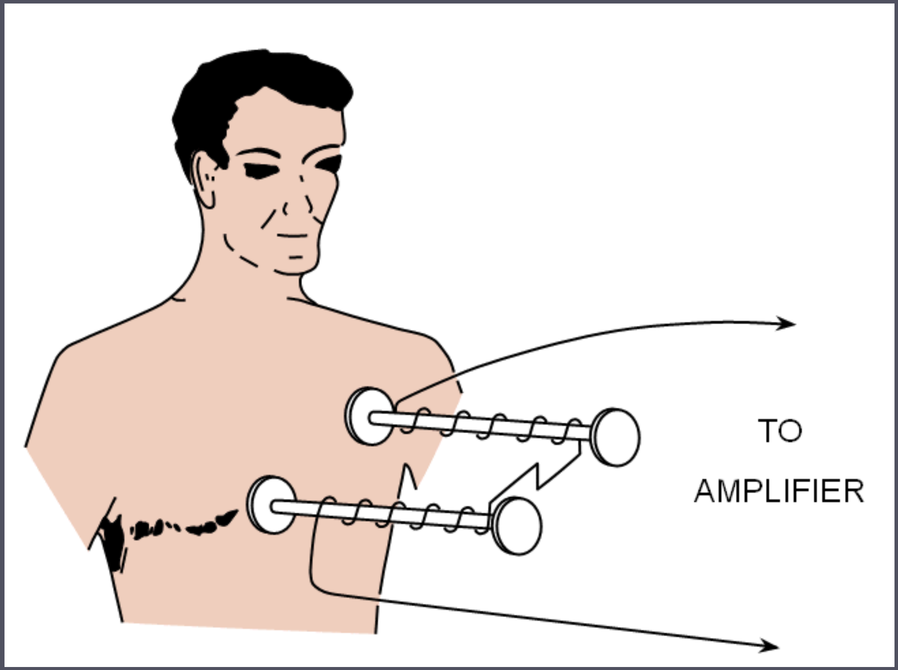
Electrical current flow lines



Magnetic field flow lines

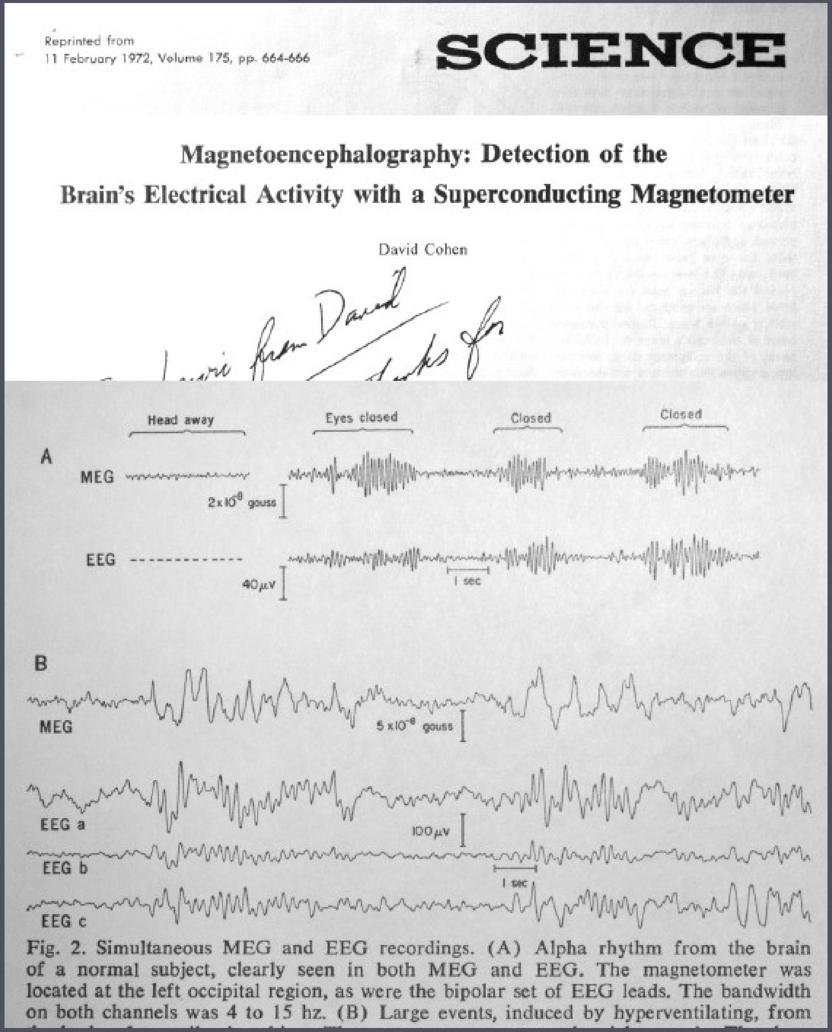
1963: First magnetocardiogram (MCG)

- Baul & McFee, 1963



1972: First magnetoencephalogram (MEG)

- David Cohen (MIT)
  - Oscillations of type alpha
  - As Berger with EEG about 40 years before.



Reprinted from
11 February 1972, Volume 175, pp. 664-666

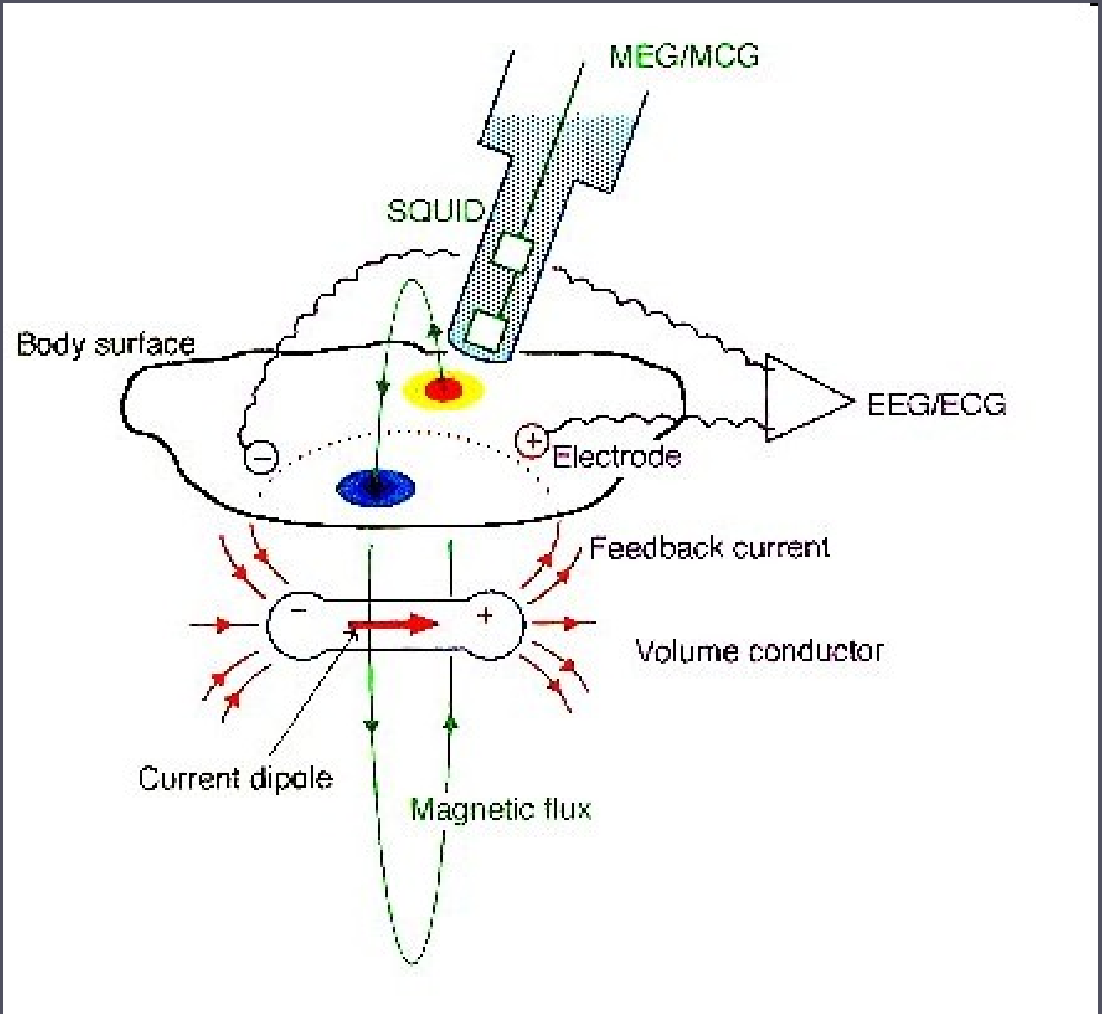
SCIENCE

Magnetoencephalography: Detection of the Brain's Electrical Activity with a Superconducting Magnetometer

David Cohen

Fig. 2. Simultaneous MEG and EEG recordings. (A) Alpha rhythm from the brain of a normal subject, clearly seen in both MEG and EEG. The magnetometer was located at the left occipital region, as were the bipolar set of EEG leads. The bandwidth on both channels was 4 to 15 hz. (B) Large events, induced by hyperventilating, from

Summary :



EEG:

- From 1 to 100 μV

MEG:

- About 100 fT
- Earth static magnetic field (50 μT)
- ~1 billion times weaker

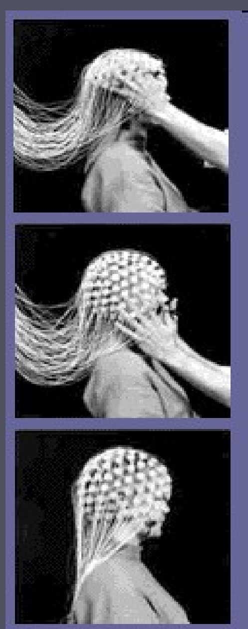
Instrumentation: EEG

1945

1955

Instrumentation: EEG

- Integration of more and more sensors.
- Up to 256.
- Faster and faster.
  - ++kHz
- Reliable and easy to setup.

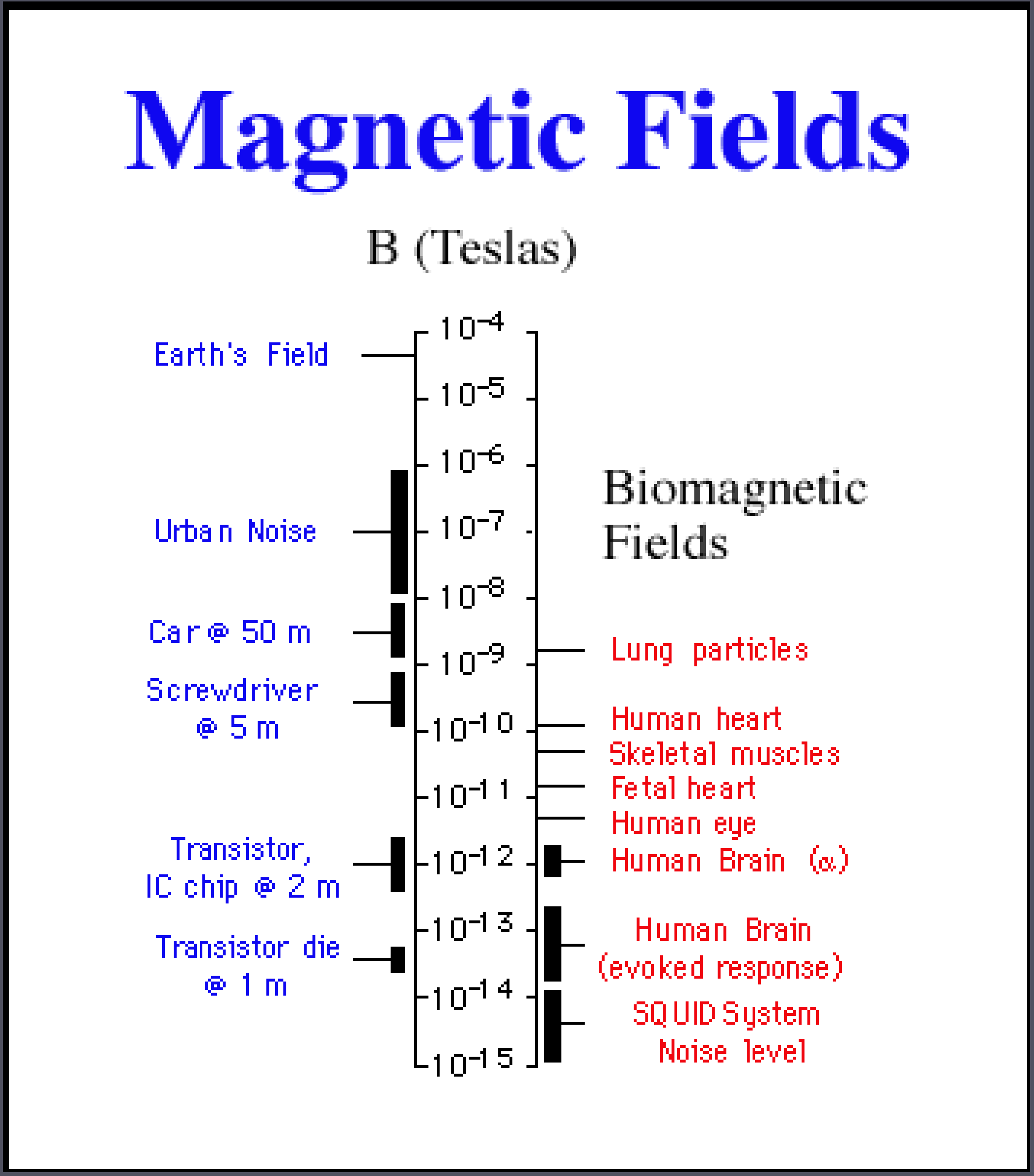


Electrical Geodesics

NeuroScan

MicroMed

Magnitude of cerebral magnetic fields

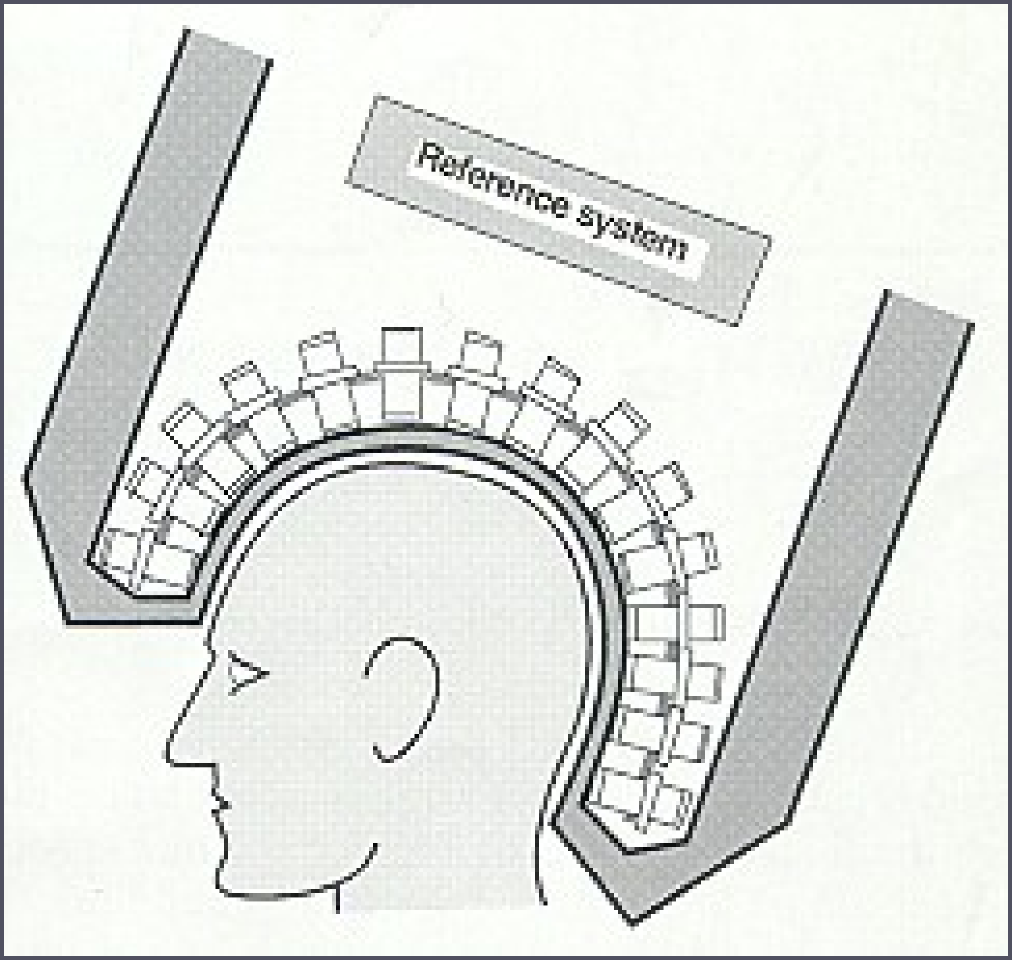


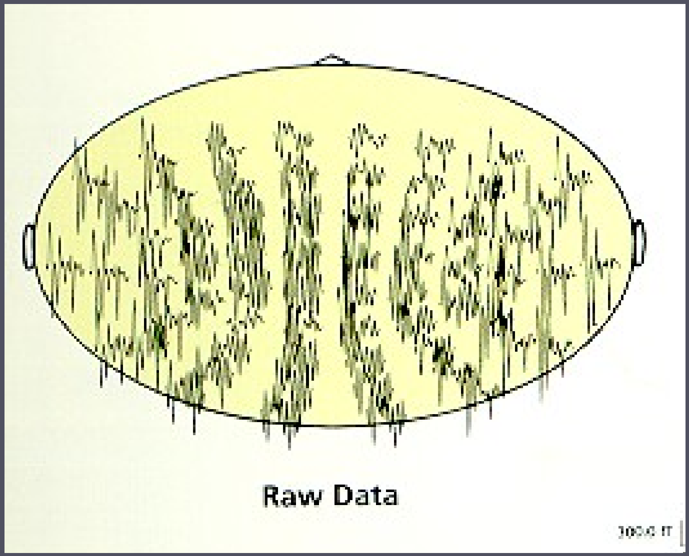
Instrumentation: MEG

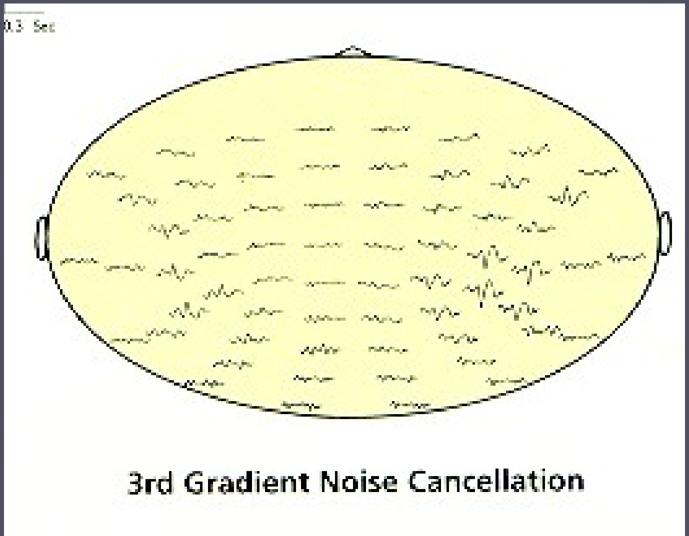
Instrumentation: MEG

MEG: improving the SNR

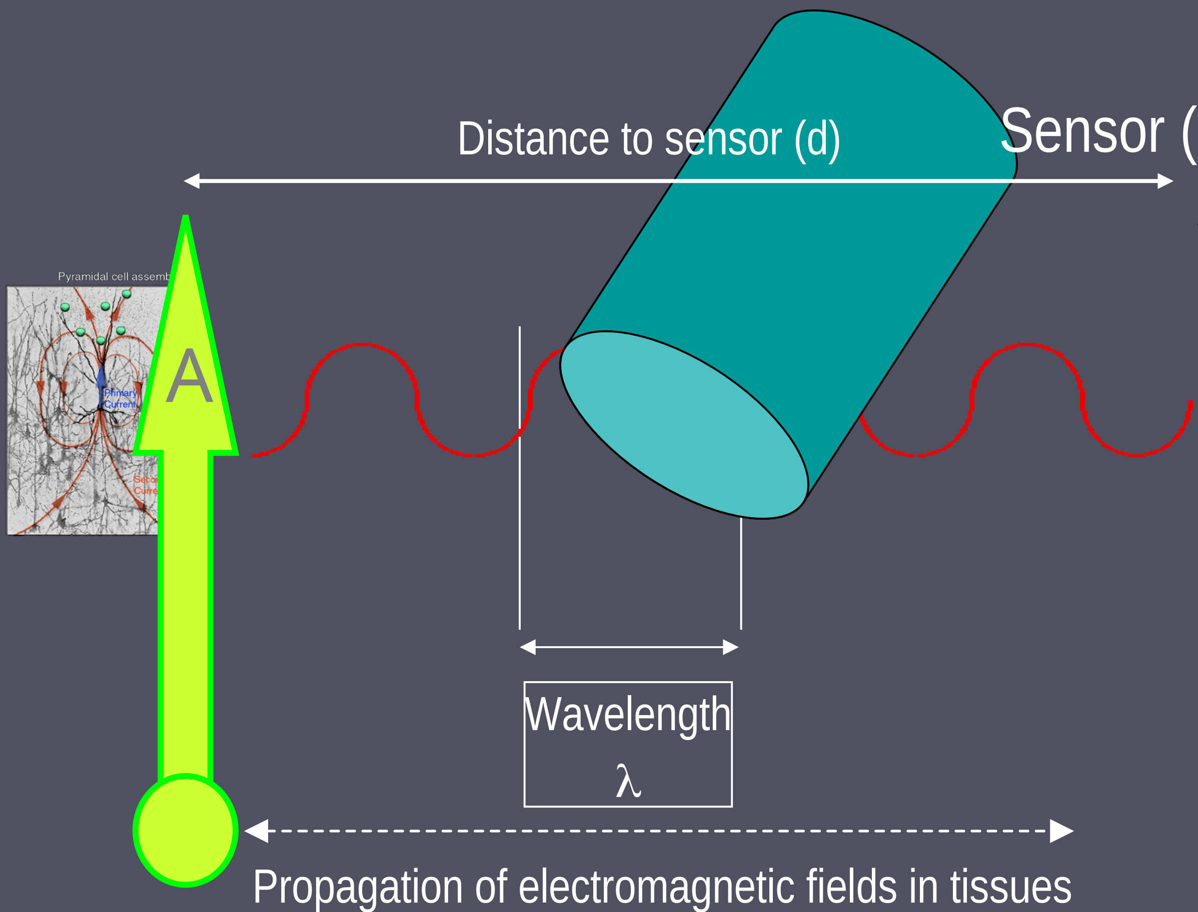
Gradient of magnetic fields of higher order with reference sensors







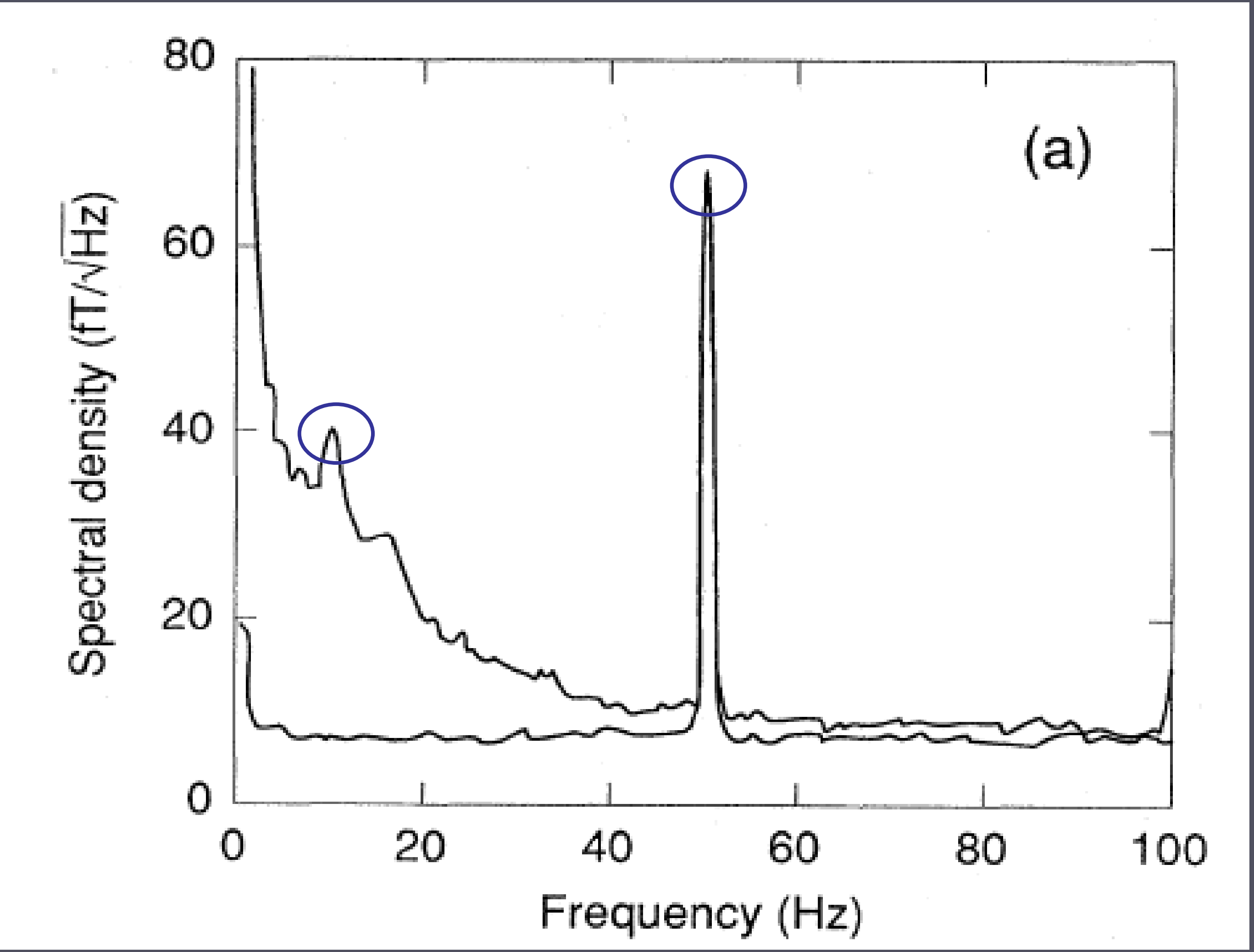
Modelisation of neural electromagnetic fields



Neglect propagation if :

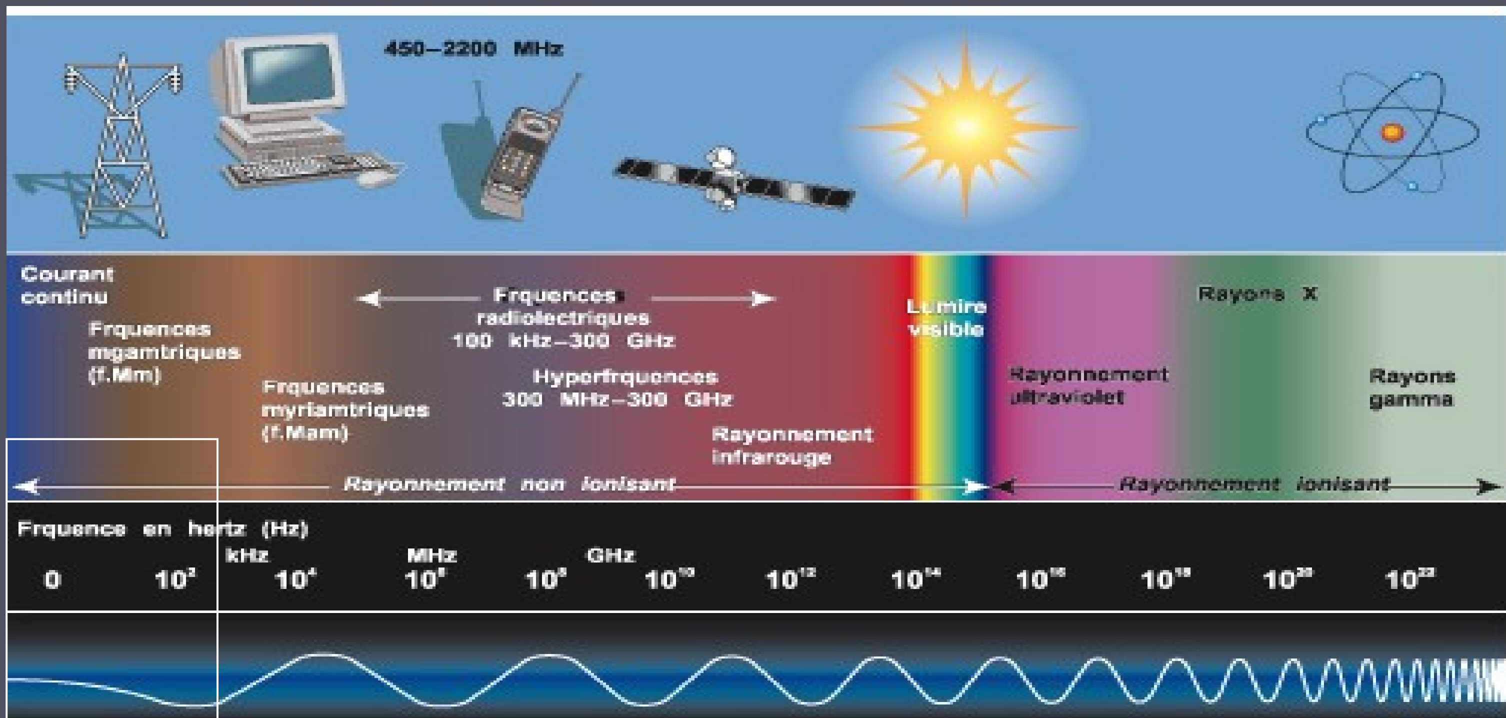
$$\lambda >> d$$

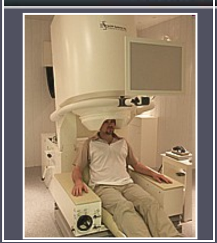
Modelisation of neural electromagnetic fields



Hamalainen et al., Rev Mod. Phys., 1993

Modelisation of neural electromagnetic fields





λ=65m at f = 100Hz

in head tissues

Sensors: average distance to neural generators = 0.15m

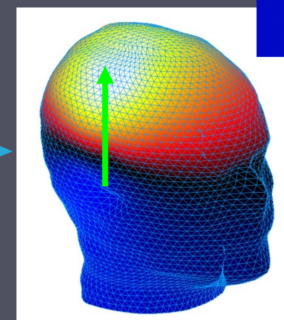
$\Rightarrow$ *Quasistatic assumption*

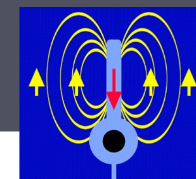
Field propagation effects are neglected.

Fields and potentials produced by a current dipole

Magneto & Electroencephalography

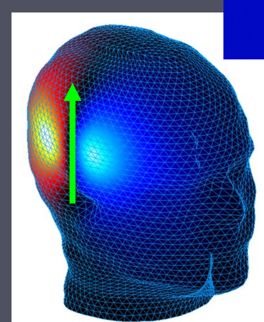
Differences of scalp electric potentials

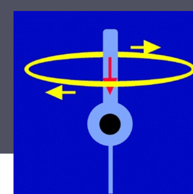




$$\nabla\cdot\left(\sigma\nabla\cdot V\right)=\nabla\cdot J^{p}$$

Magnetic Induction





$$B\left(r\right)=\frac{\mu_0}{4\,\Pi}\int\frac{J\left(r'\right)\times R}{R^3}dv'$$

$$J\left(r\right)=J^{p}\left(r\right)-\sigma\left(r\right)\,\nabla\cdot V\left(r\right)$$

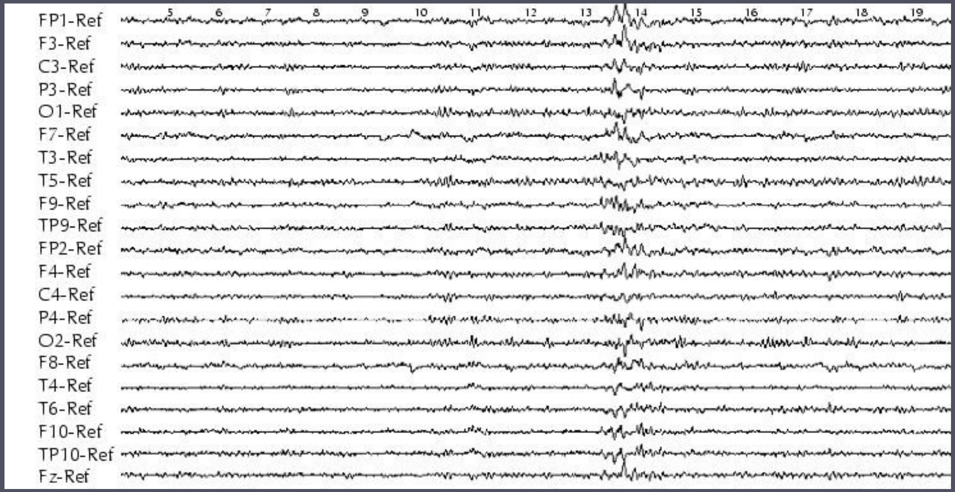
Coupling

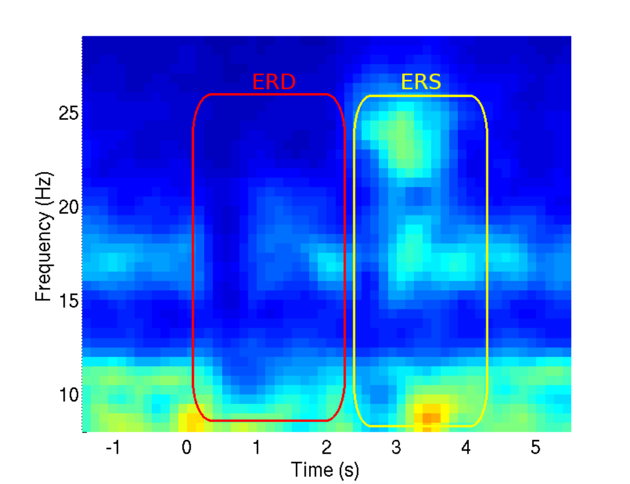
MEG & EEG are complementary and can be combined

MEG/EEG Data

Multivariate temporal series

- Number of sensors depends on the device
  - Up to 256 EEG sensors
    - Setup costs, price of the device.
  - Up to 400 MEG sensors.
- Very noisy data.
- Not easily interpreted (importance of frequency).



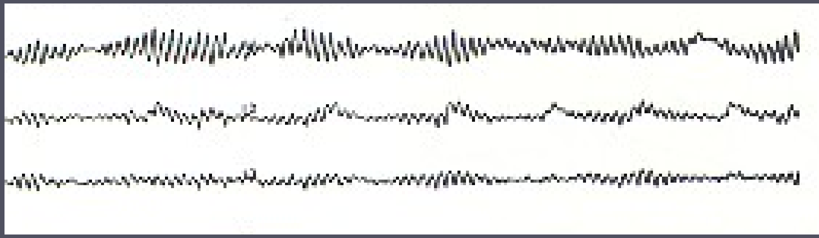


Spontaneous Activity

Artifacts (ocular, cardiac, ...)

Different rythms (thalamo-cortical loops)

- alpha : 8 - 13 Hz (occipital)
- mu : 7 - 11 Hz (motion)
- beta : 18 - 30 Hz (motor)
- gamma : 30 - 50 Hz
- delta : 0.5 - 4 Hz (sleep)

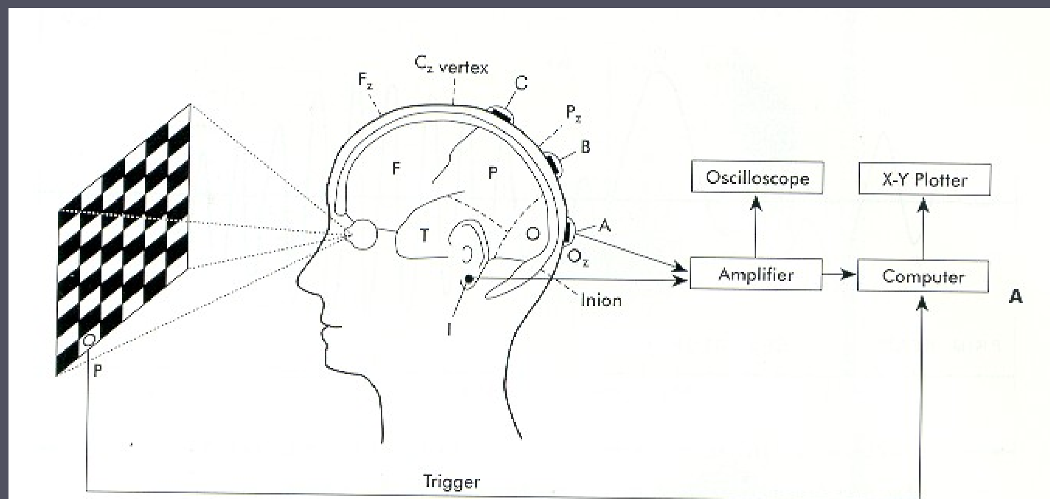


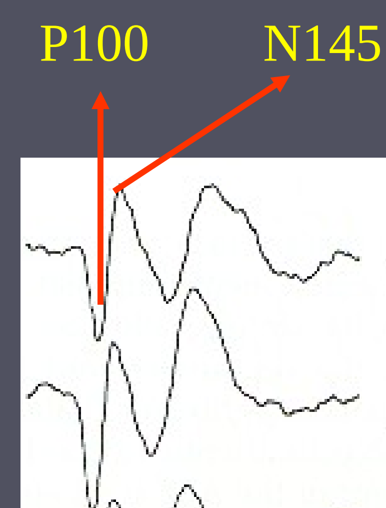
Epileptic signals

- intercritic spikes
- EEG ictal (crisis)

Evoked Potentials

Stimulus synchronized averaging (Dawson 1937)



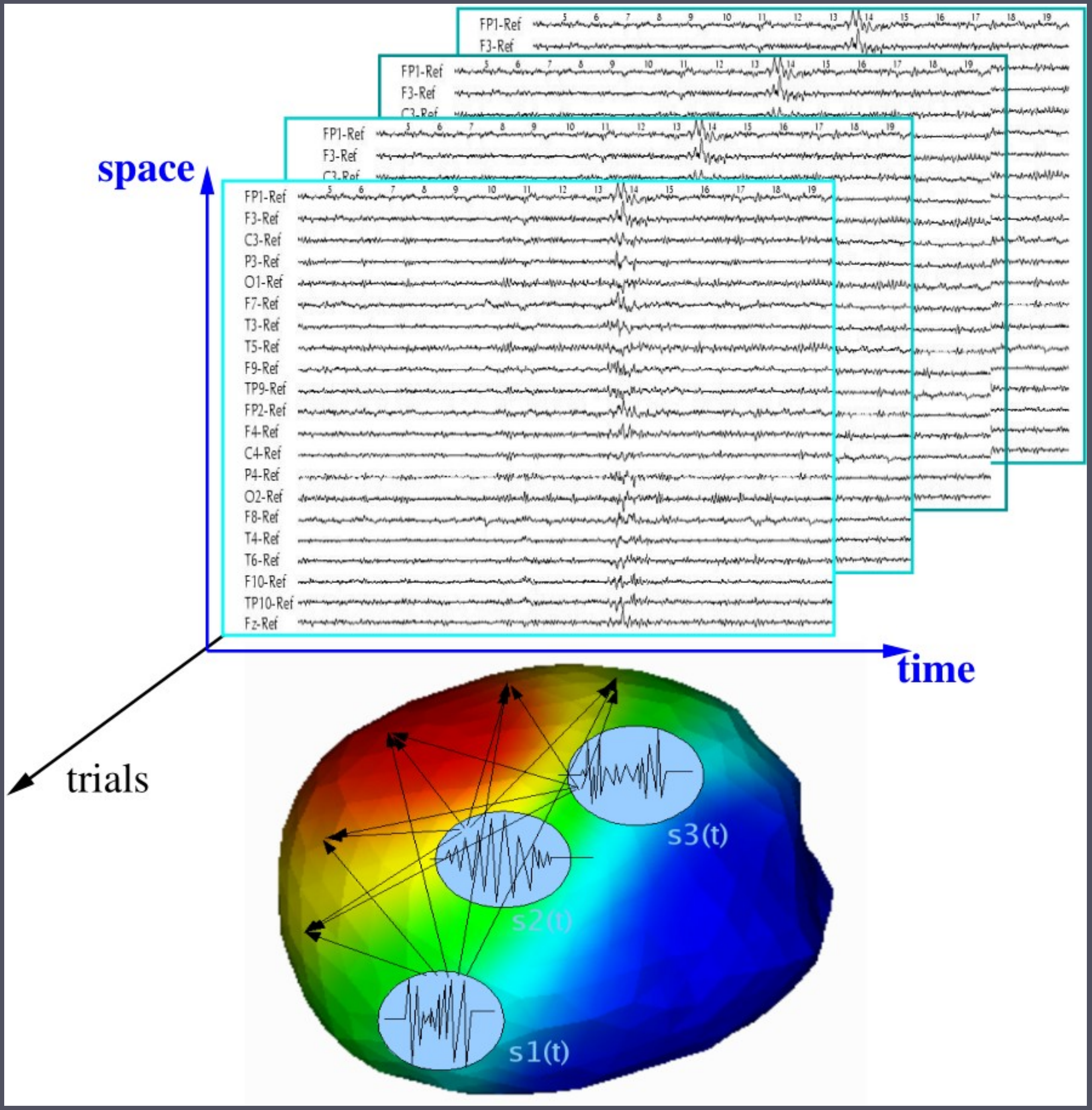


Differents responses (latency and amplitude)

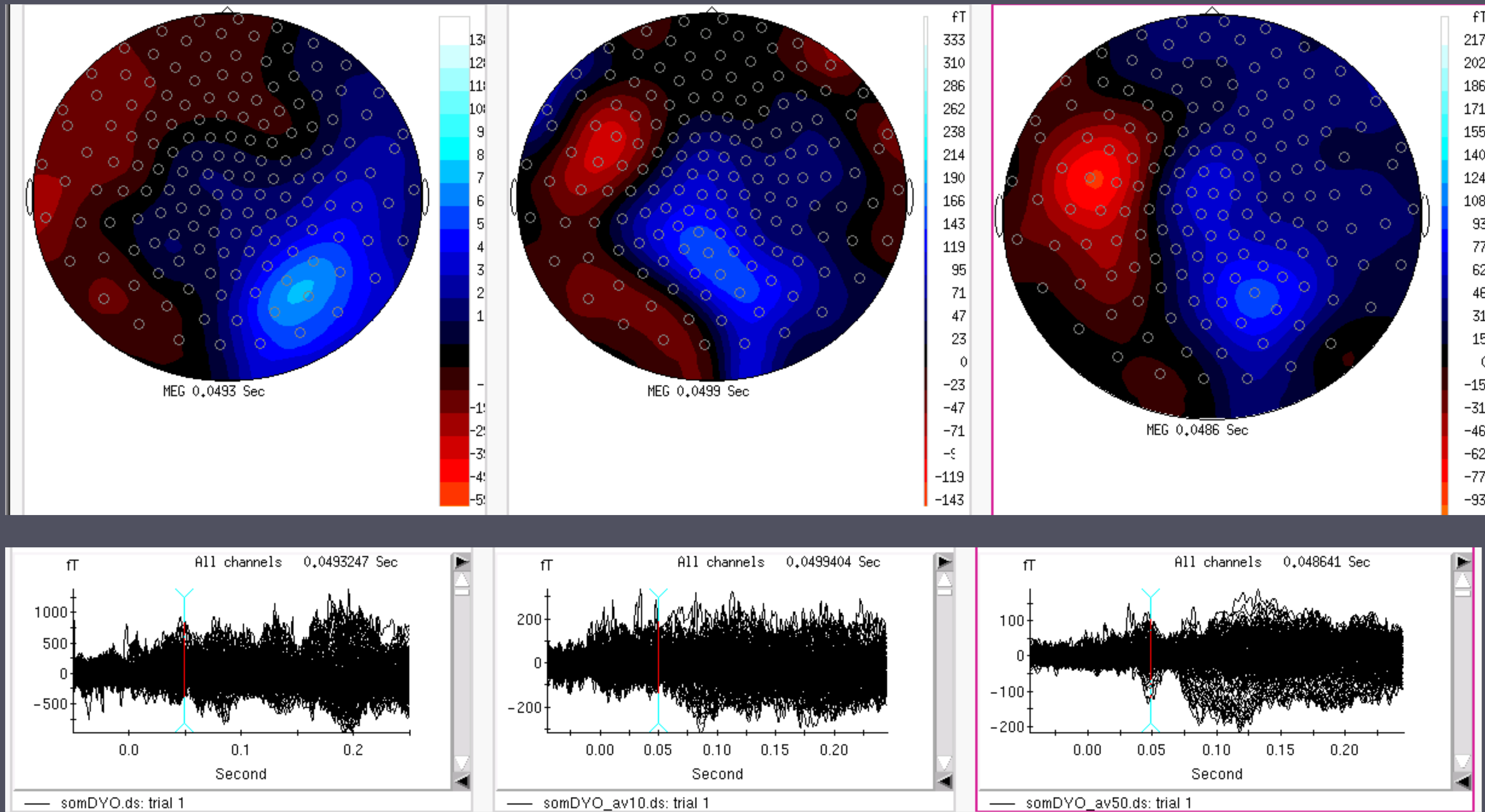
Nomenclature :

- Nxxx : EEG negative wave at xxx ms
- Pxxx : EEG positive wave
- Mxxx : MEG wave …….. at xxx ms

MEG/EEG Data (Evoked potentials).



Influence of the number of repetitions

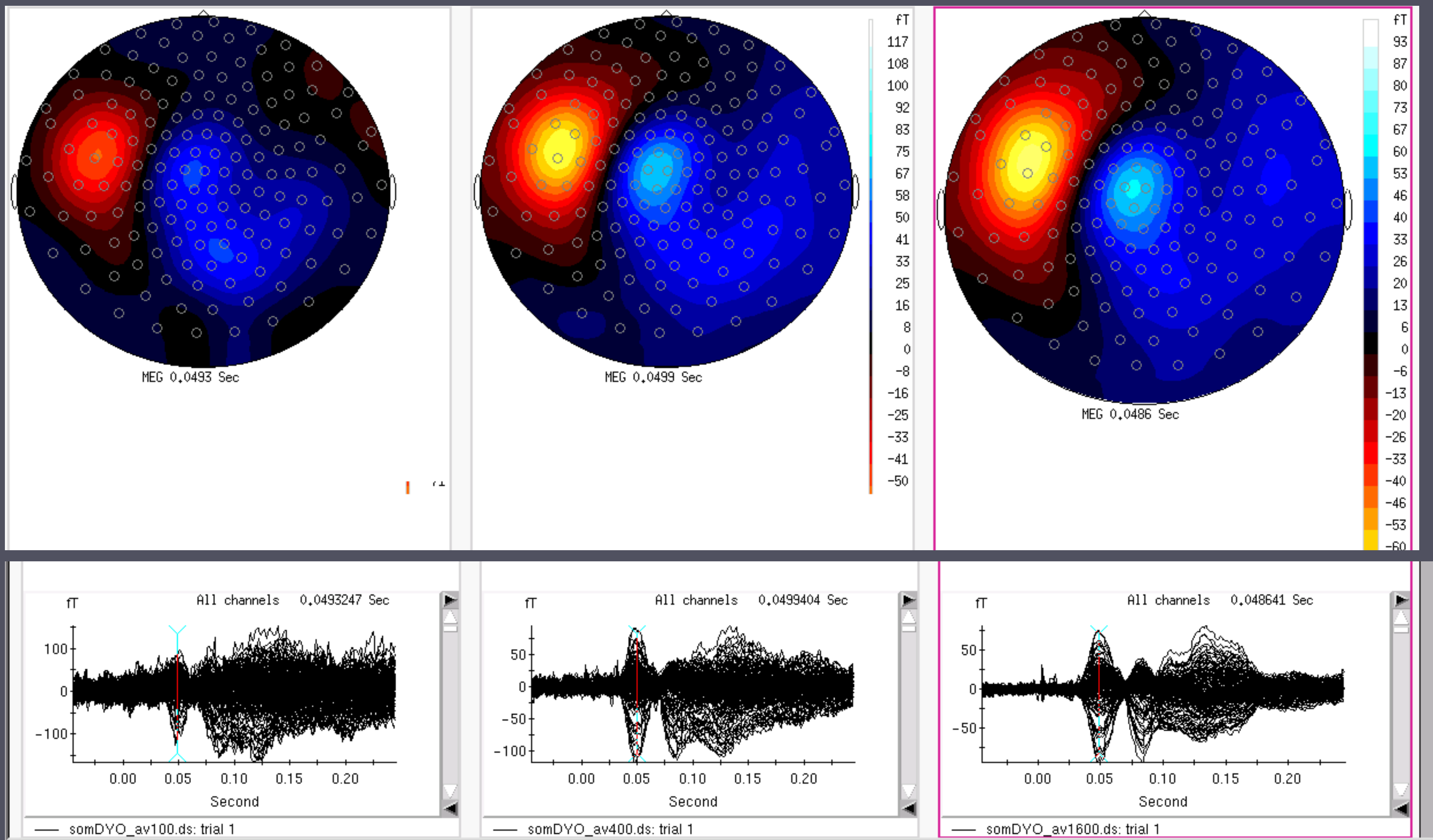


1 trial

10 trials

50 trials

Influence of the number of repetitions



100 trials

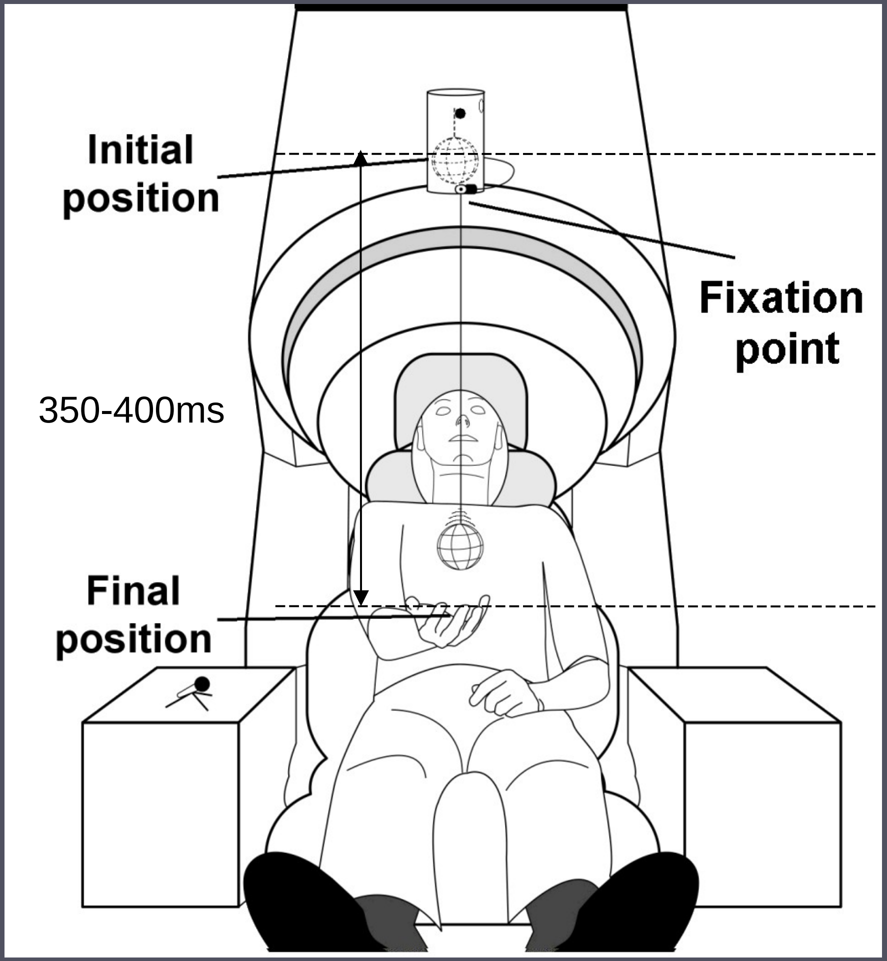
400 trials

1600 trials

Example of MEG measures

Tennis ball catching

- 100 trials
    - 70 cm – fall
    - Paris CTF 151-channel system



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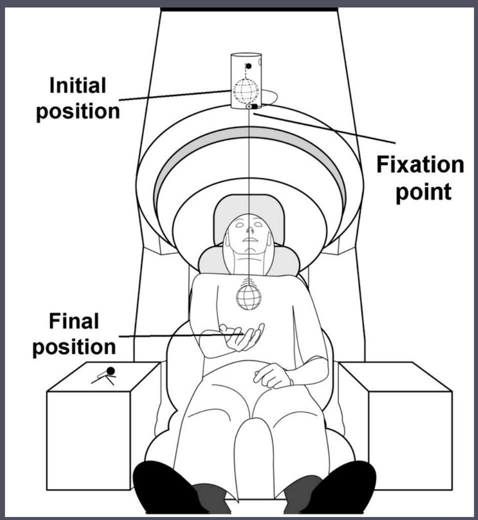
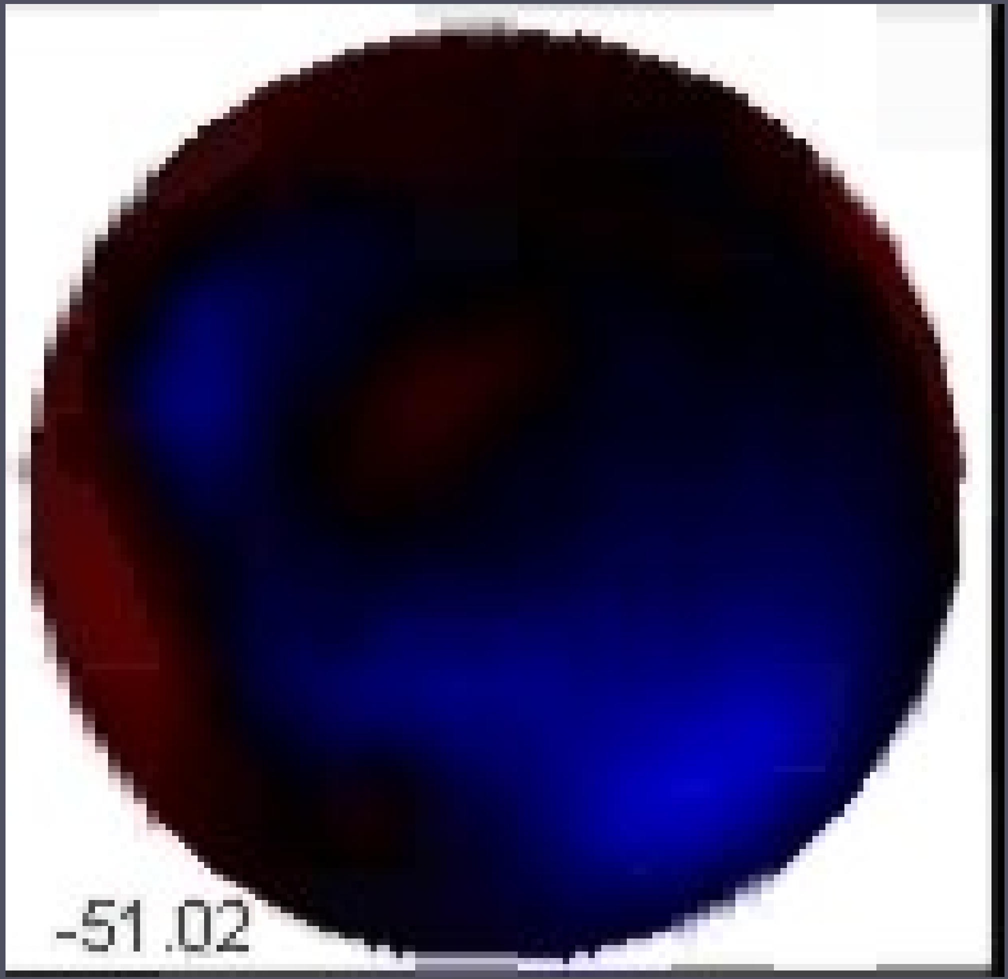
P. Senot et al., J. Cog. Neurosc., (rev)

Example of MEG measures

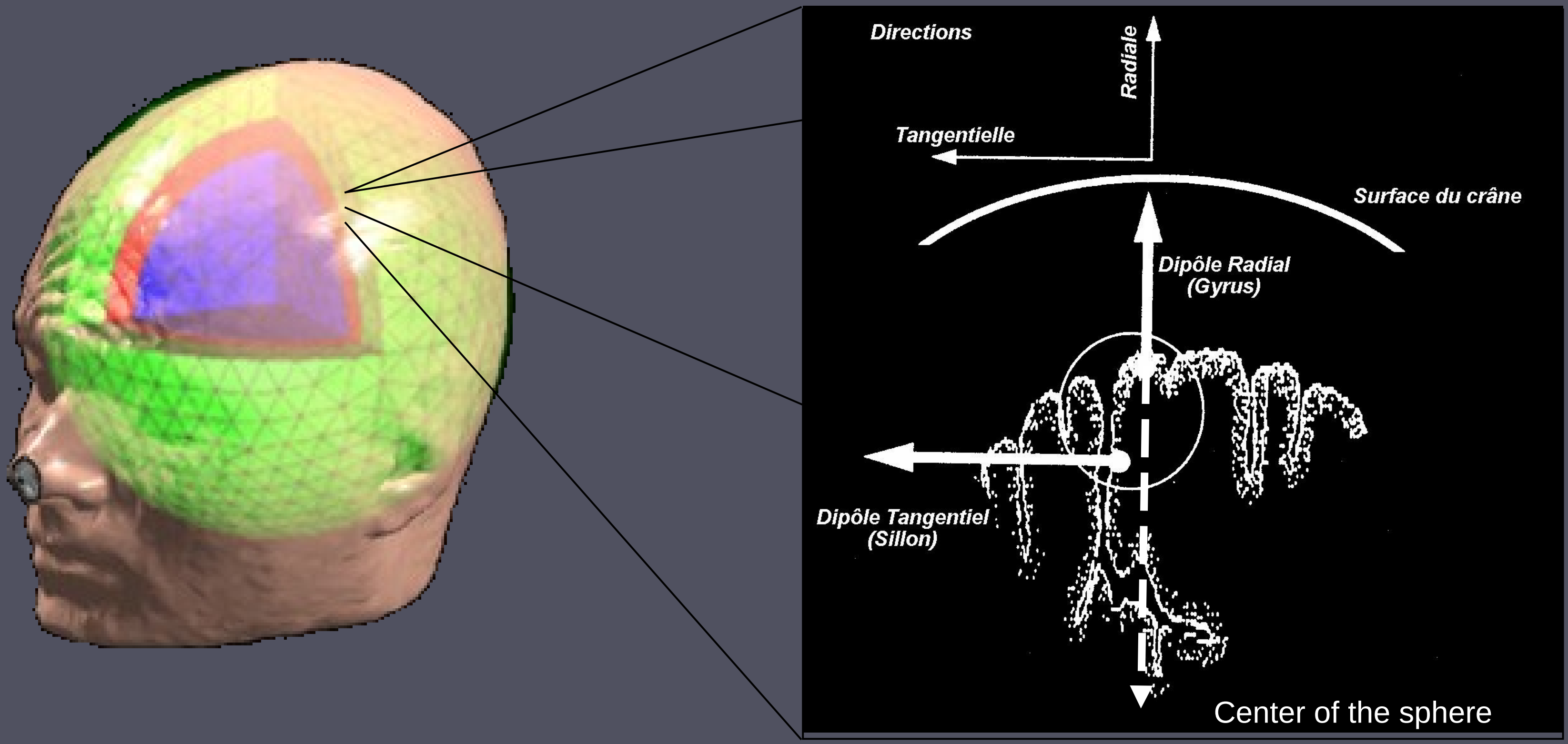




Data courtesy of Patrice Senot, LPPA, Collège de France

Radial and tangential dipoles

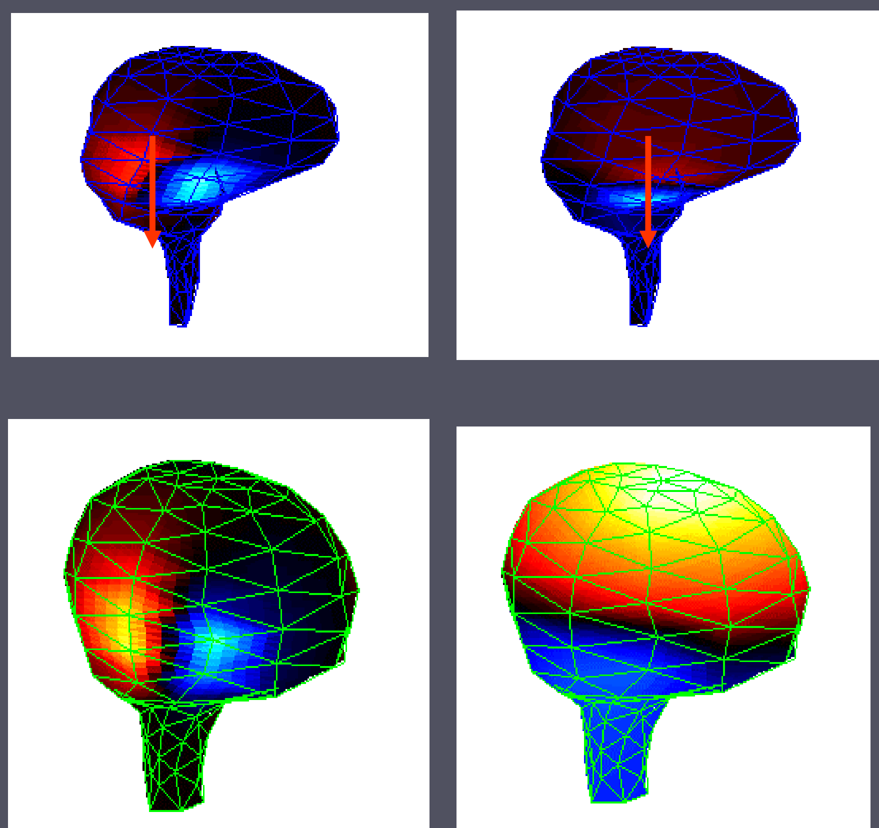
- Defined for spherical geometries



MEG/EEG differences: influence of tissues

MEG

EEG



Cortex

External skull

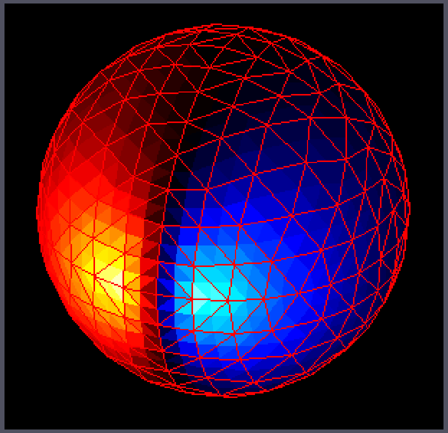
Influence of source orientation

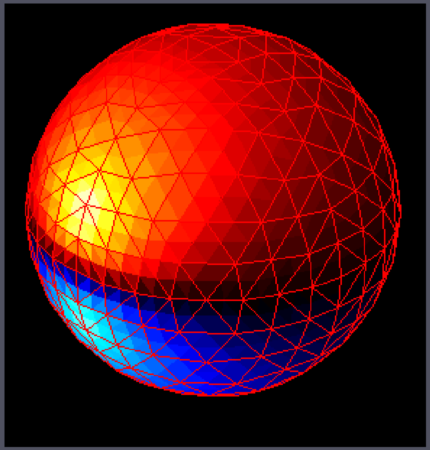
- Spherical geometry

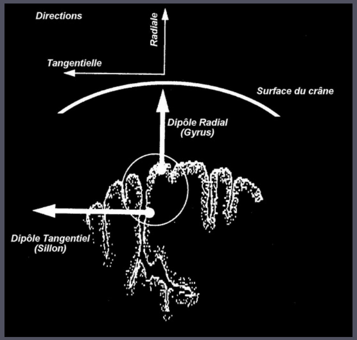
MEG

EEG

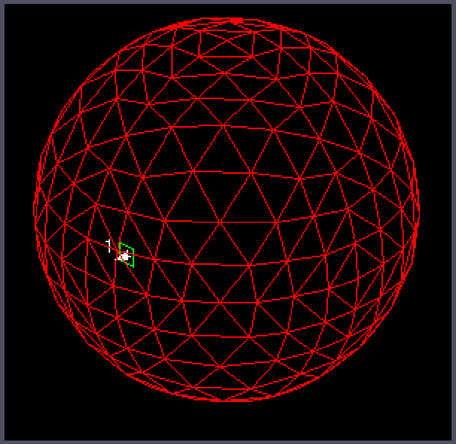
Tangential dipole

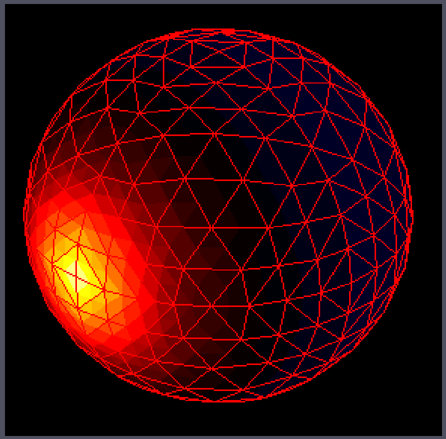






Radial dipole





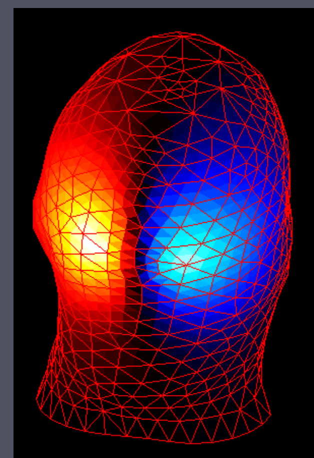
Influence of source orientation

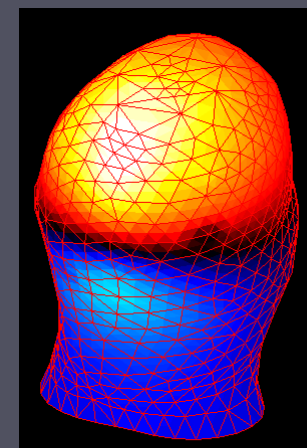
- Realistic geometry

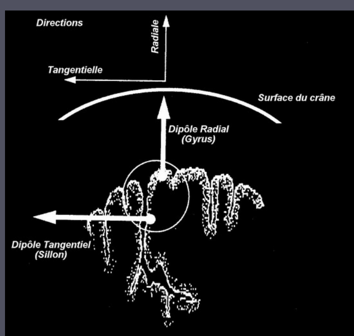
MEG

EEG

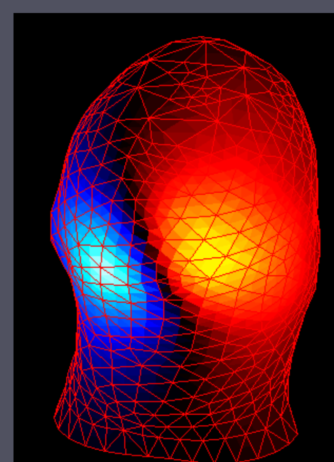
Tangential dipole



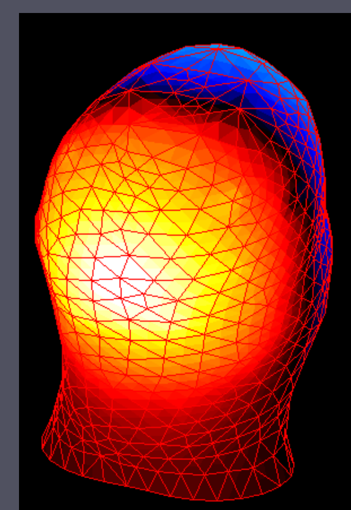




Radial dipole



1/10



2

Influence of the source depth

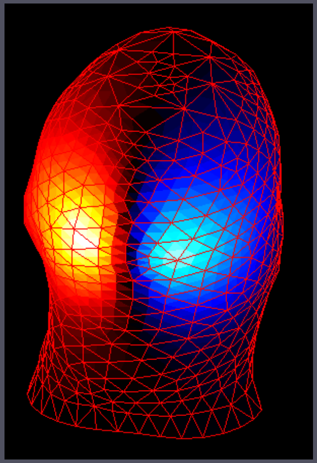
- Realistic geometry

MEG

EEG

Superficial source

External cortex



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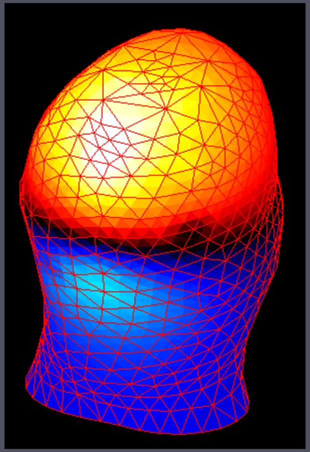
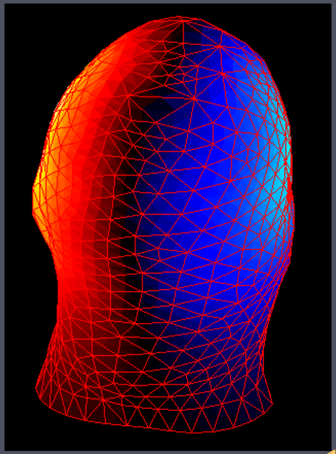


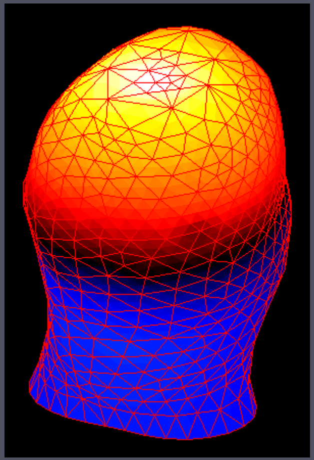
1

Deep source

Internal cortex



1/100

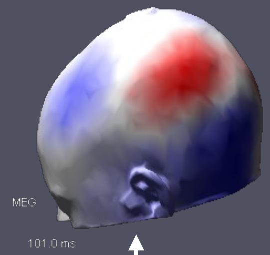


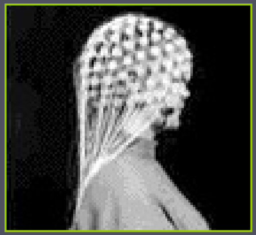
1/3

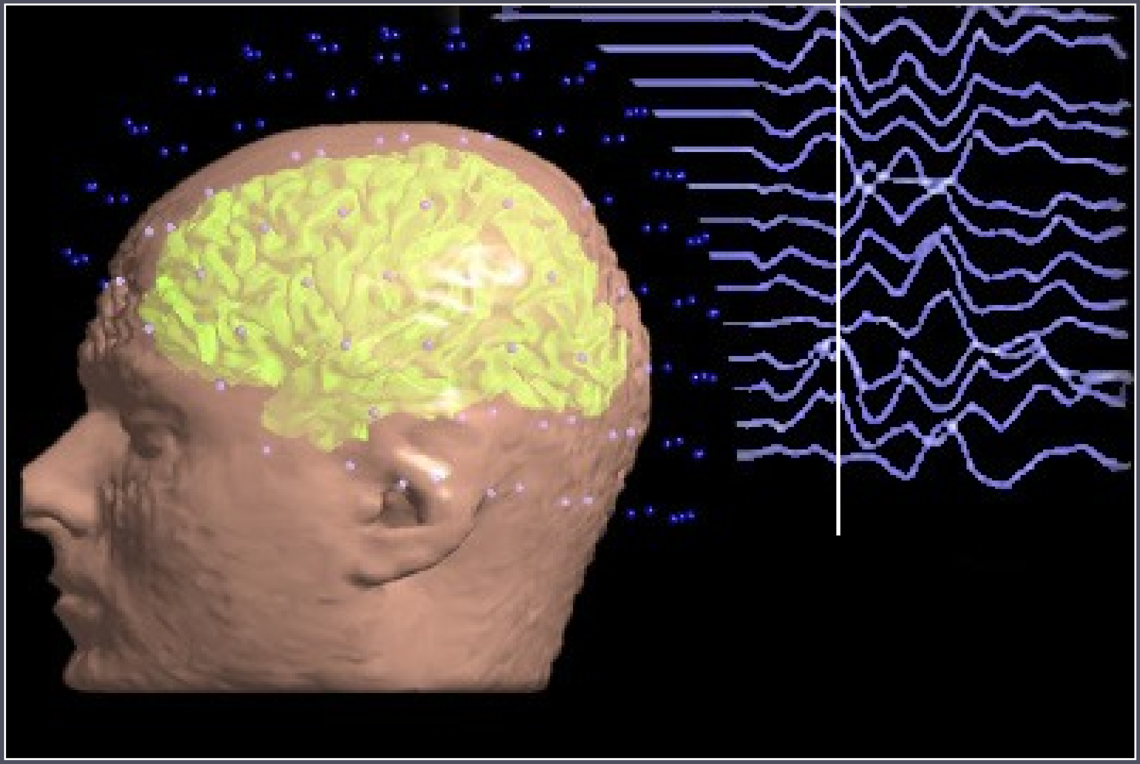
DIFFERENCES BETWEEN MEG and EEG: SUMMARY

MEG	EEG
Measures magnetic field.	Measures electrical potential.
Dipolar response perpendicular to dipole direction.	Dipolar response parallel to that of the dipole.
Focal response.	Diffuse response.
Only slightly affected by head tissues.	Strongly affected by head tissues.
Selective to tangential sources.	Sensitive to all dipole orientations.
Low sensitivity to deep sources.	Sensitive to deep sources.
Expensive instrument.	Less expensive instrument.

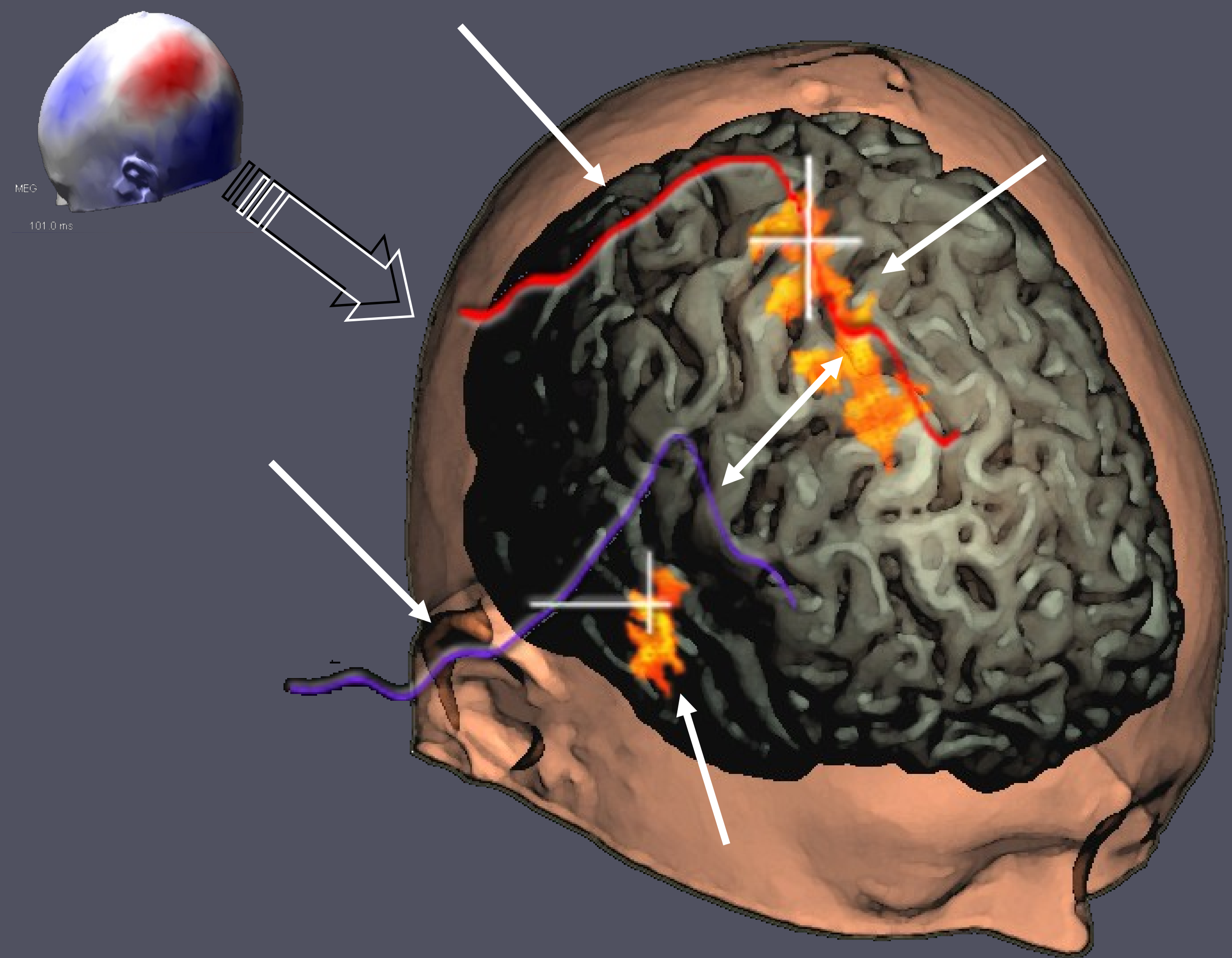
From empirical localization…







…to Dynamic Brain Mapping



EEG/MEG Applications

- Clinical (epilepsy, SEP, ...).
  - Localization
  - Pre-surgical planning
- Cognitive (audition, motor, visual, sensory tasks).
  - Localization.
  - Timing of events.
- Brain Computer Interfaces
  - Primarily EEG.
  - Mostly at signal level.