

High Temporal Resolution Brain Electromagnetic Imagery

Physiological & instrumental bases

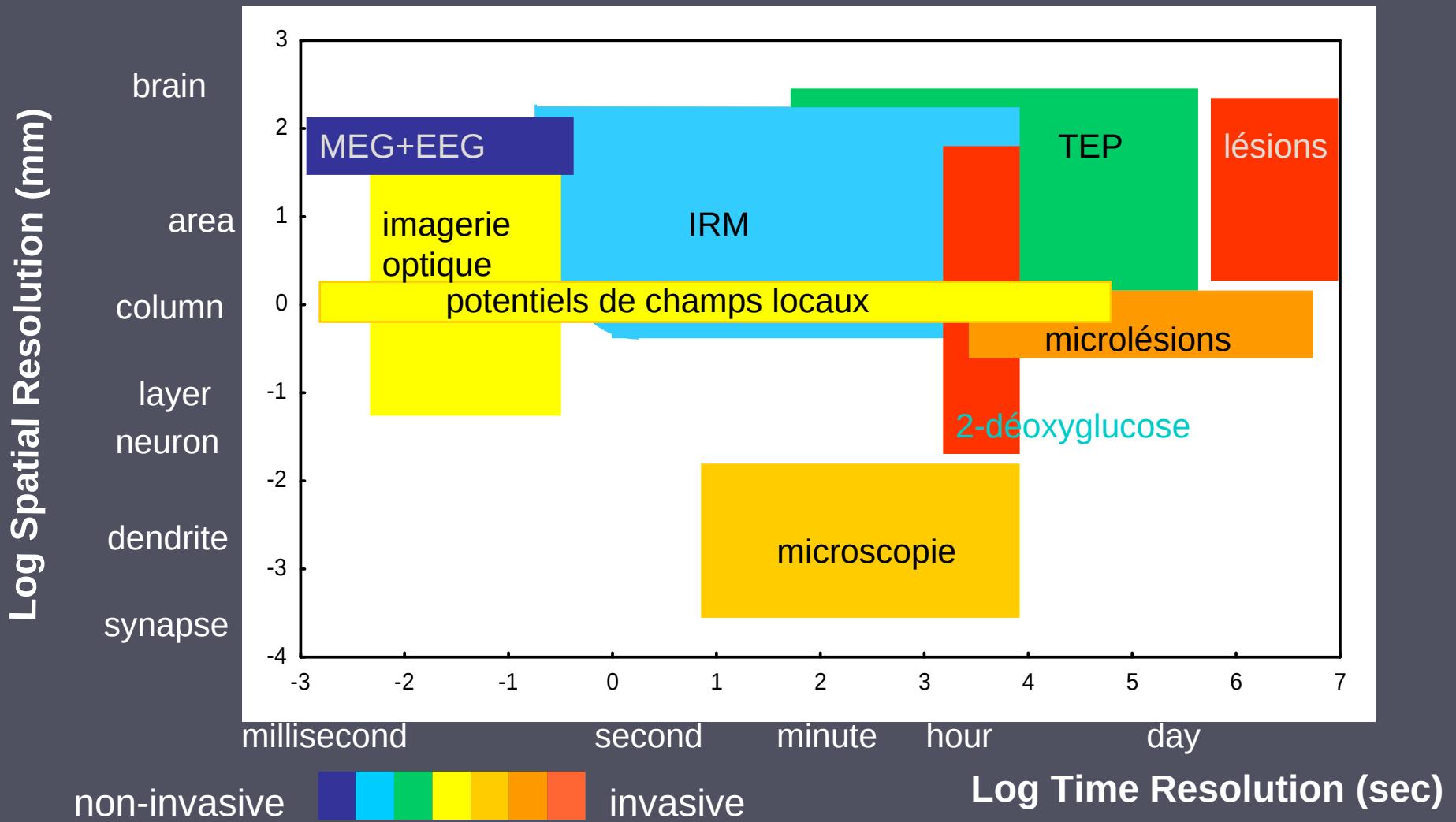
Théo Papadopulo

INRIA



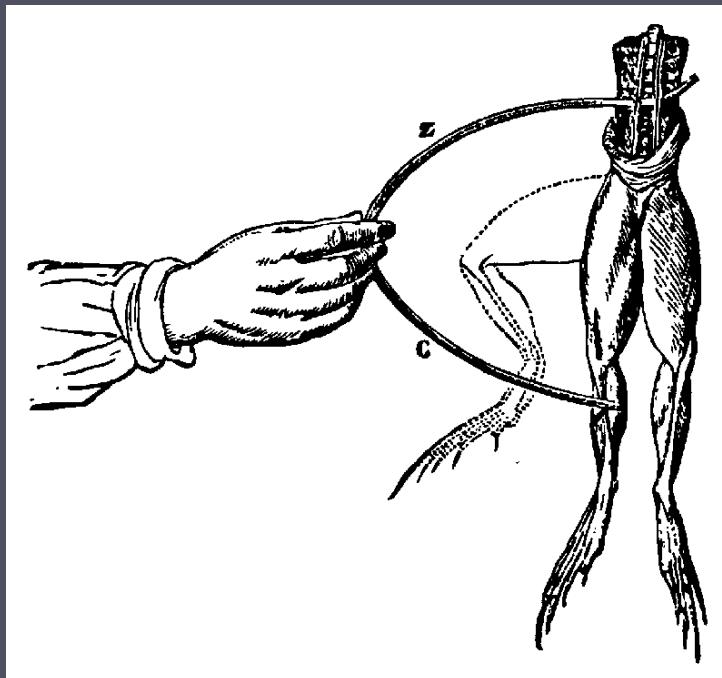
Cours Master MVA, January 2022

Spatio-temporal properties of various brain functional imagery modalities





1791: Galvani discovers bio-electricity.

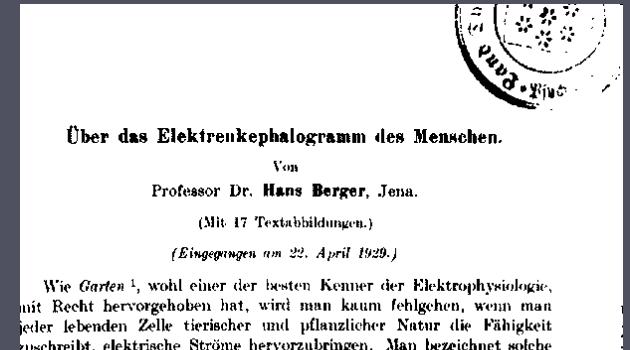
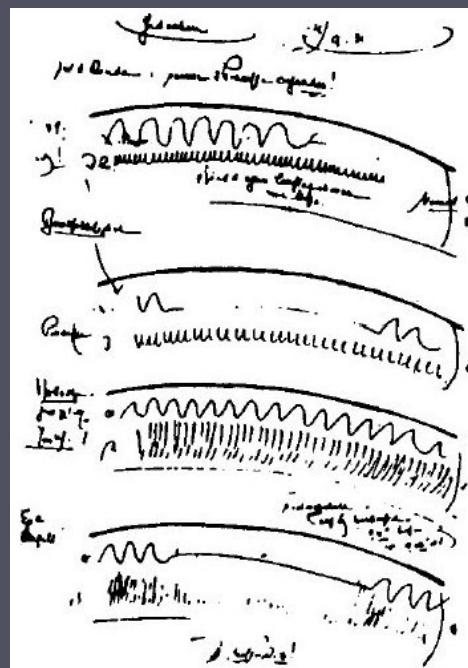
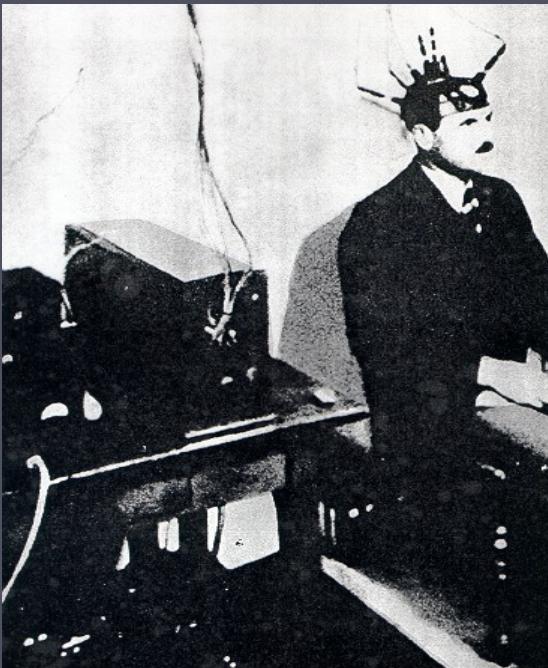


- Experiment of “galvanic paw”.
- Two metallic stalks of different metals (copper & zinc) cause an ionic current flow.



1924: Hans Berger invents electroencéphalography

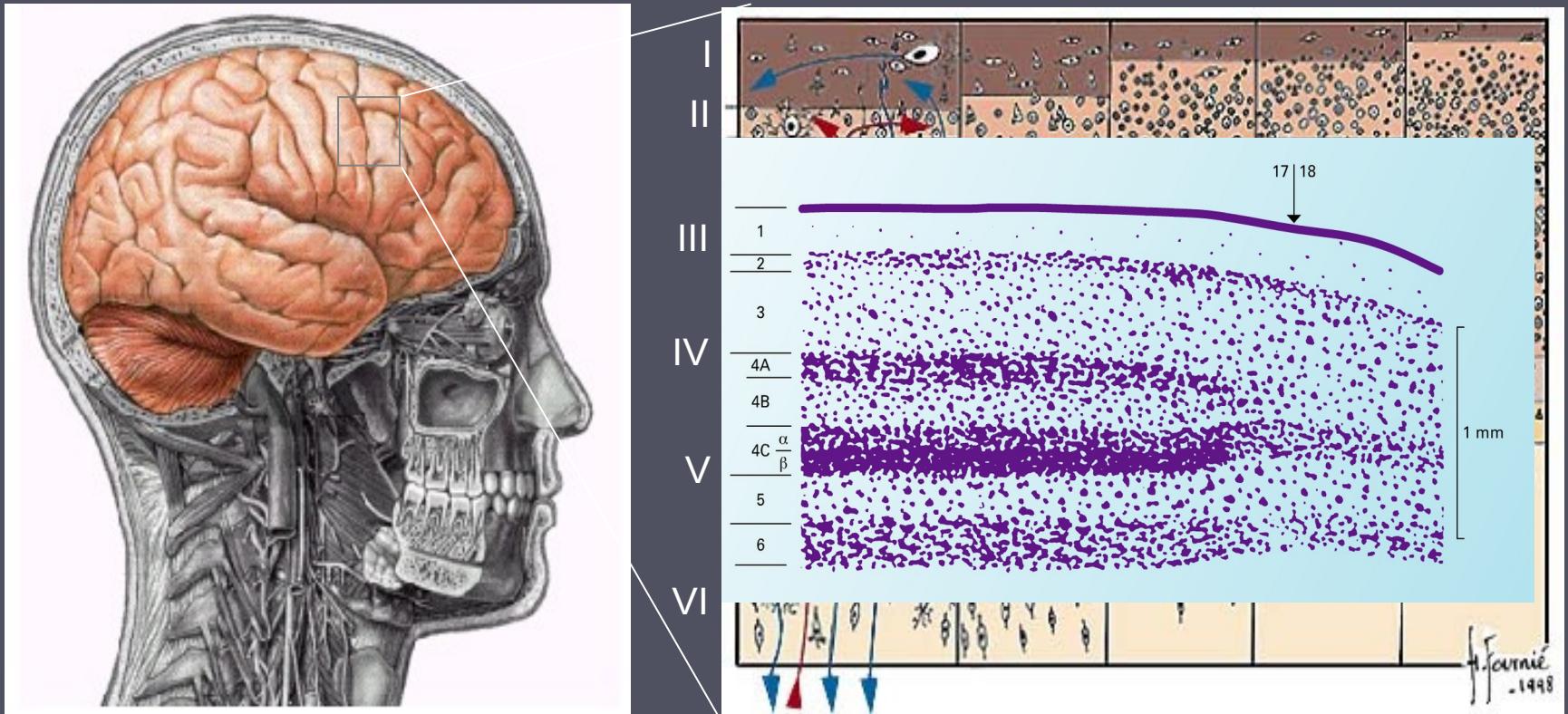
- Demonstration of electrical activity of the brain at the surface of the scalp.
- This raises the question of the precise origin of this signal.



- First publication: 1929
- Discovery of two types of rhythms/oscillations
 - alpha: 10Hz
 - beta: 15Hz
 - Up to 200 μ V

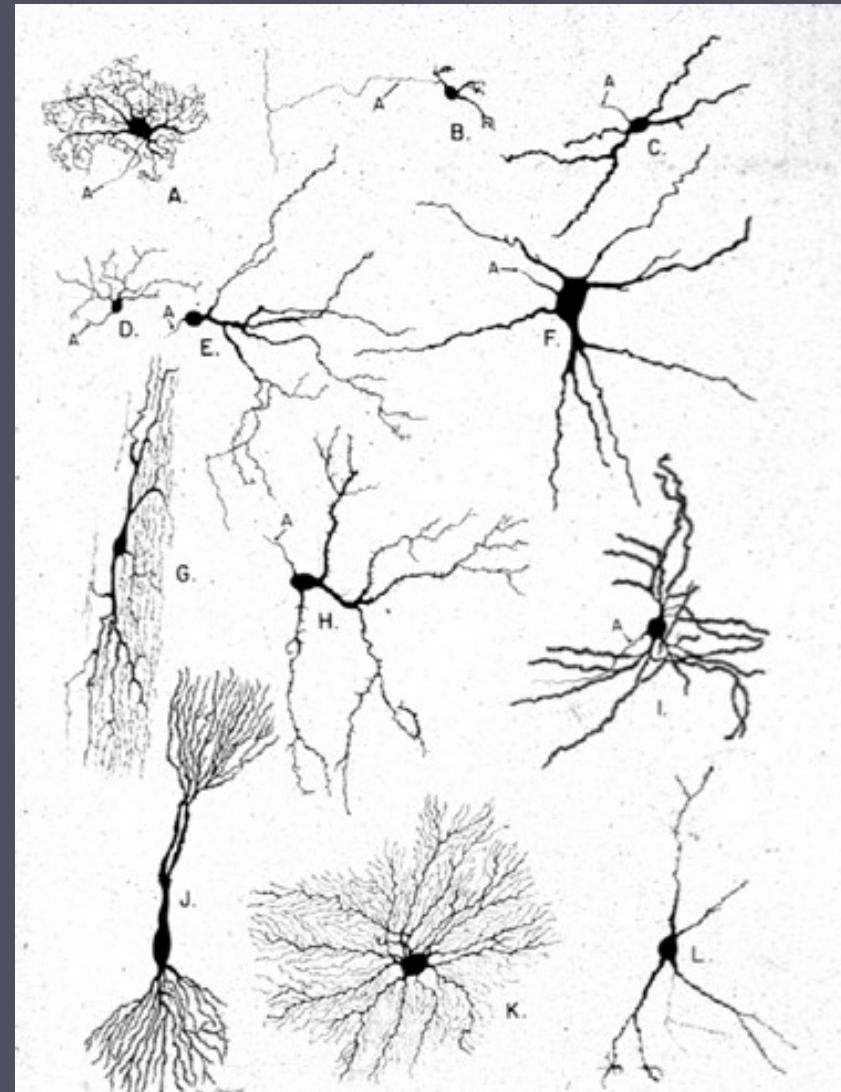
Bases of Neuroanatomy

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



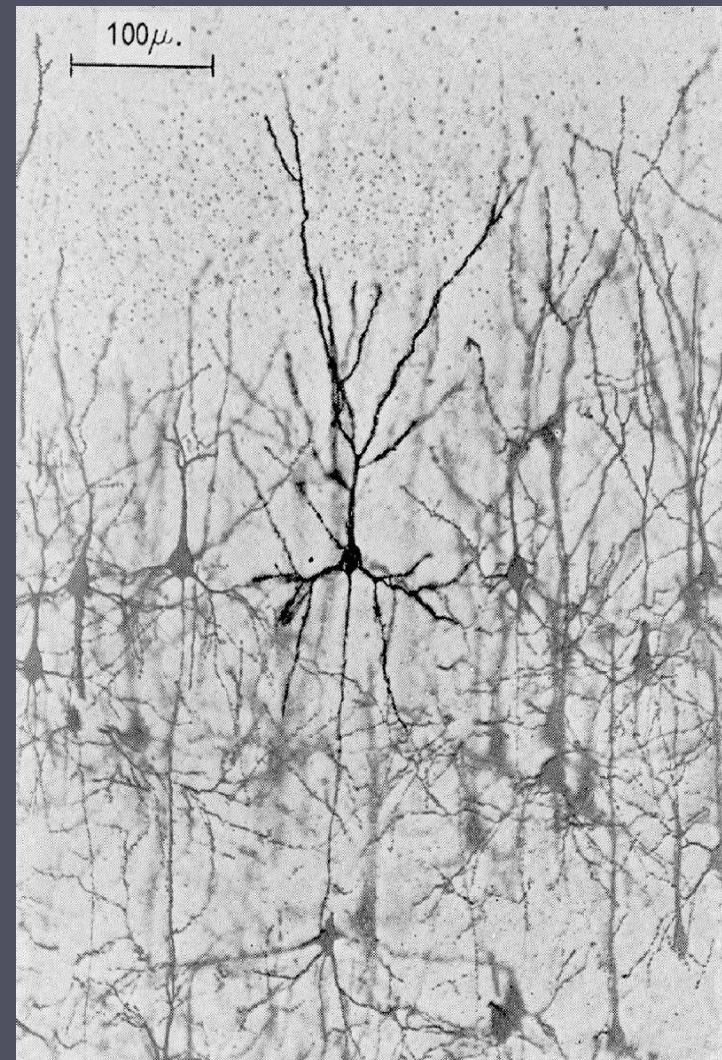
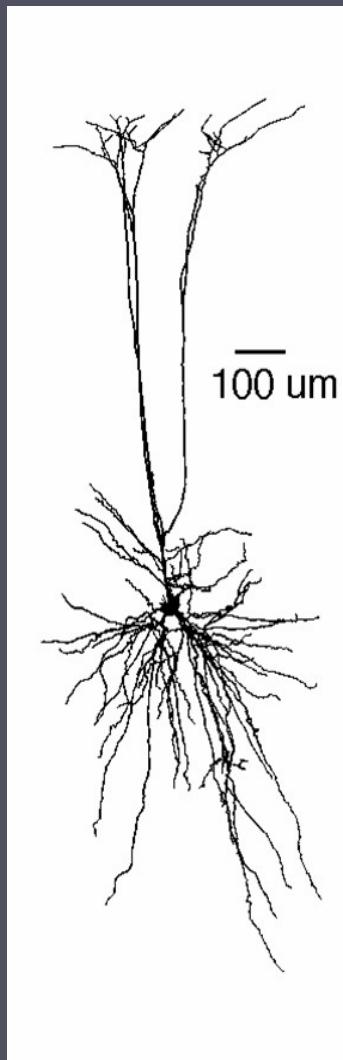
Neuroanatomy bases

- 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).

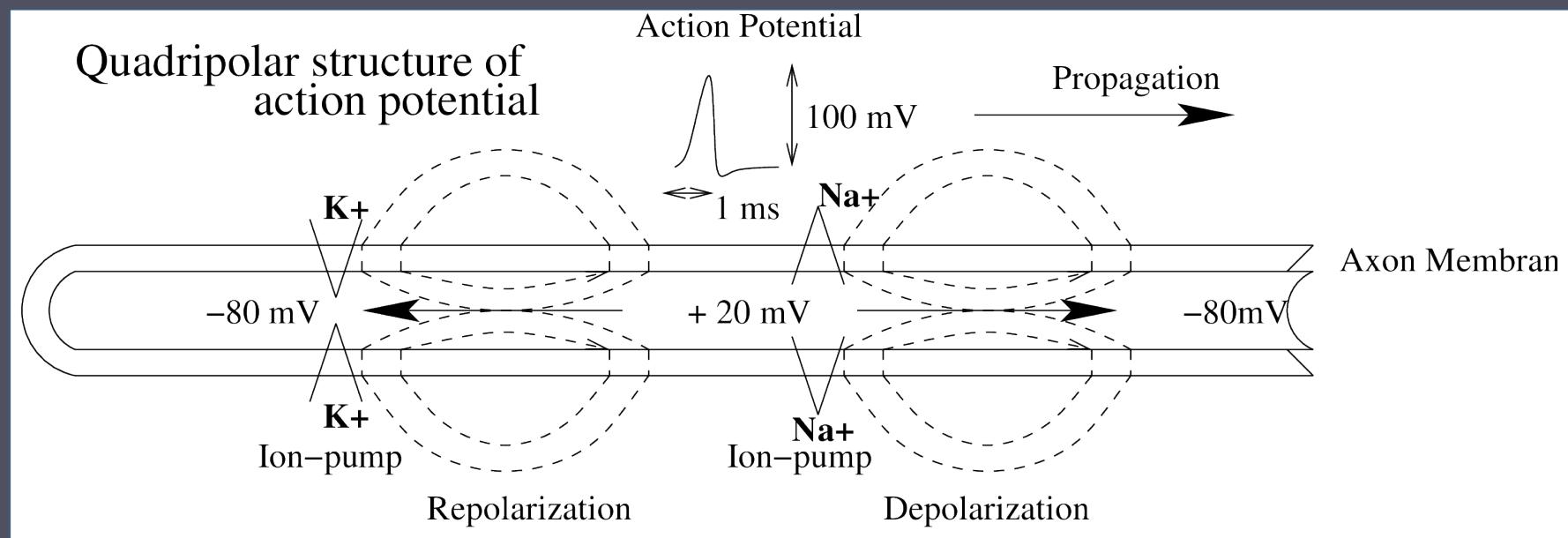


Elements of neural electrophysiology

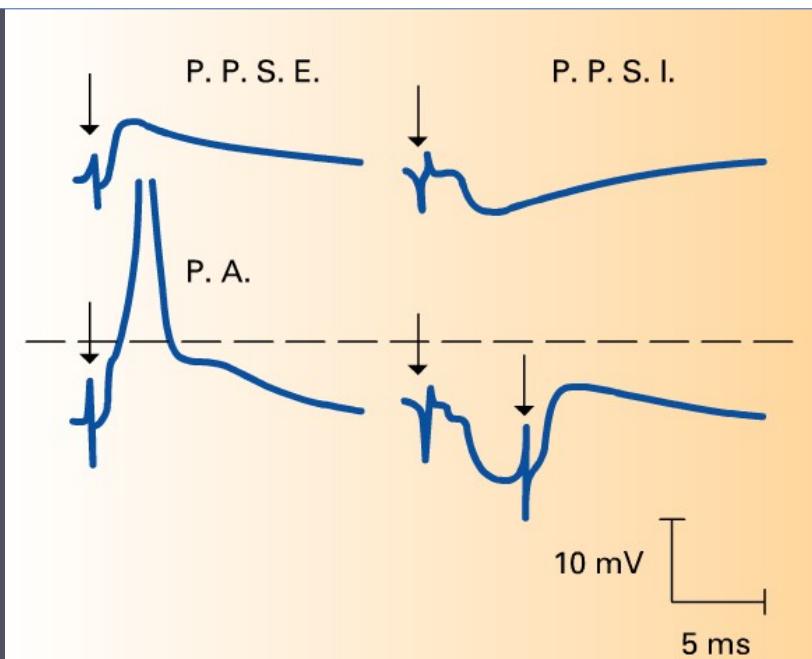
- The pyramidal neuron case
 - Big cell
 - Organized into macro-assemblies
 - Superposition of elementary currents
 - « traces » visible at distance, at the scalp surface



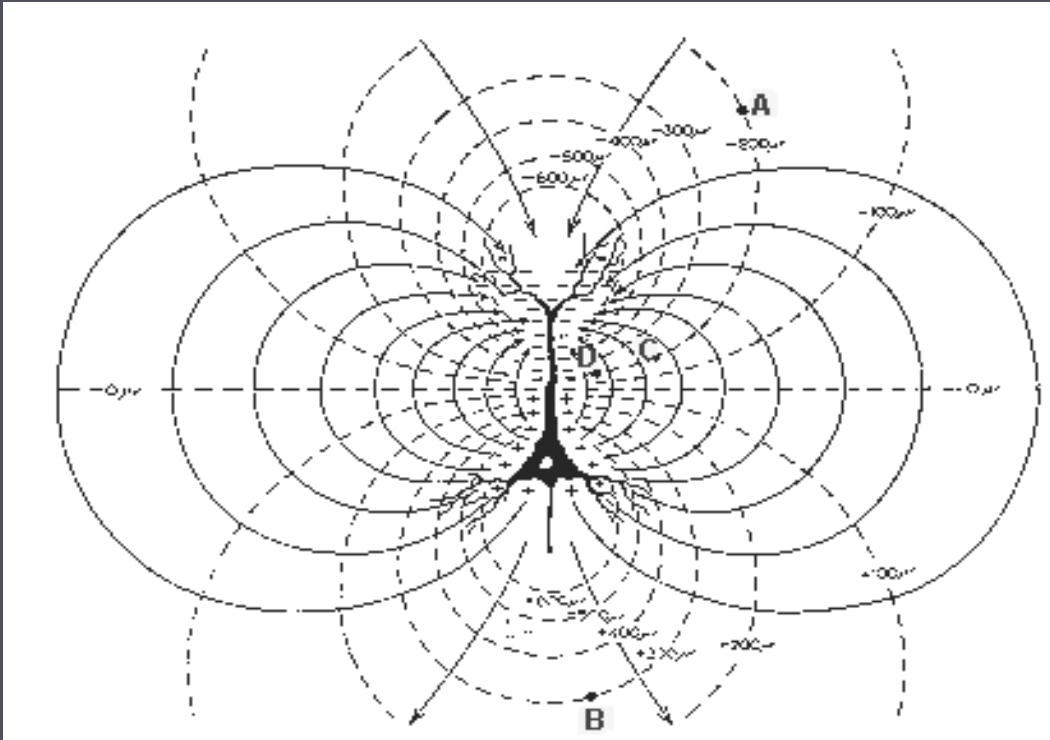
Elements of neural electrophysiology



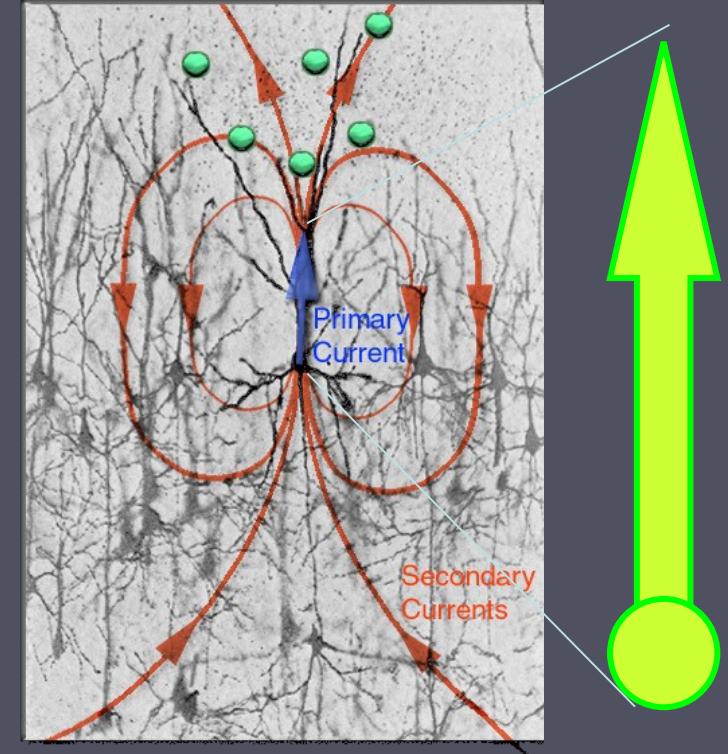
- Post-Synaptic Potentials
 - Evoked by action potentials (AP) of afferent cells.
 - Excitatory (EPSP) or inhibitory (IPSP)
 - Summation effect with eventual emission of an efferent AP.
 - Wider and slower than AP.
 - This reinforces superposition of PSPs of the same neural assemblies.



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



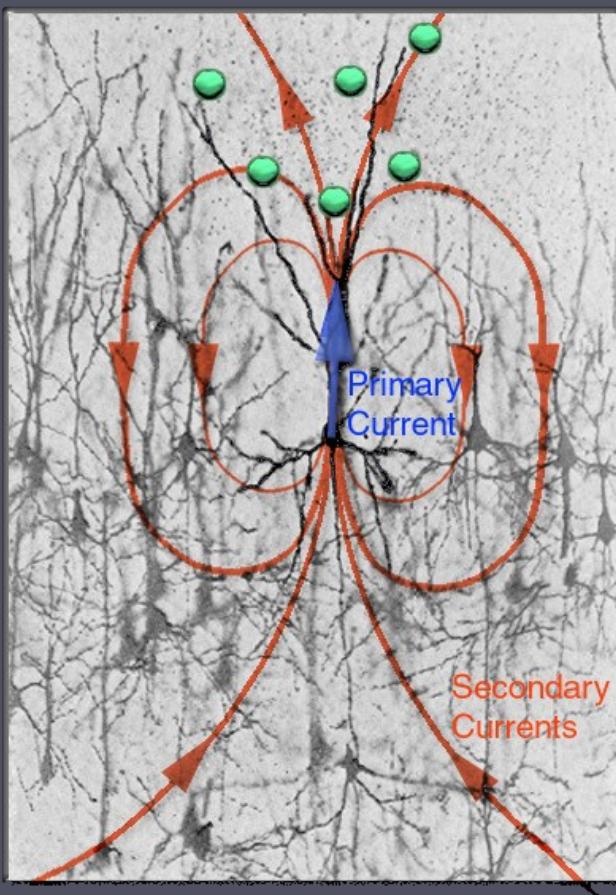
Current flow lines (-) and isopotential lines (--)



Excitatory post-synaptic potentials

Current dipole

Pyramidal cell assembly

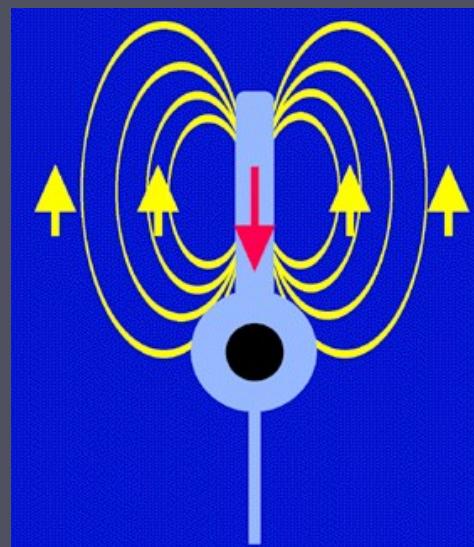


- $Q = I \times d = 10 \text{ fAm} (20 \text{ fAm})$
- Cortical macrocolumn
 - 10^6 neurons
 - $Q = \sim 10 \text{nAm}$
 - Homogeneous infinite domain:

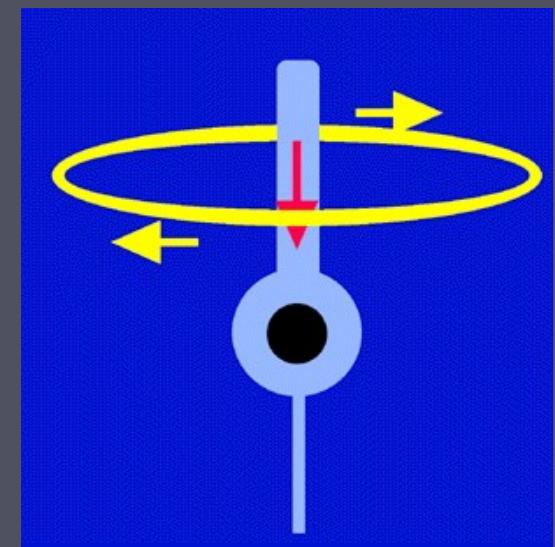
$$V = \frac{1}{4\pi\sigma} \frac{Q \cdot R}{\|R\|^3} \approx 2 \text{ mV}$$

From bio-electricity to bio-magnetism

- Magnetic field: dual of the neural electric potential.



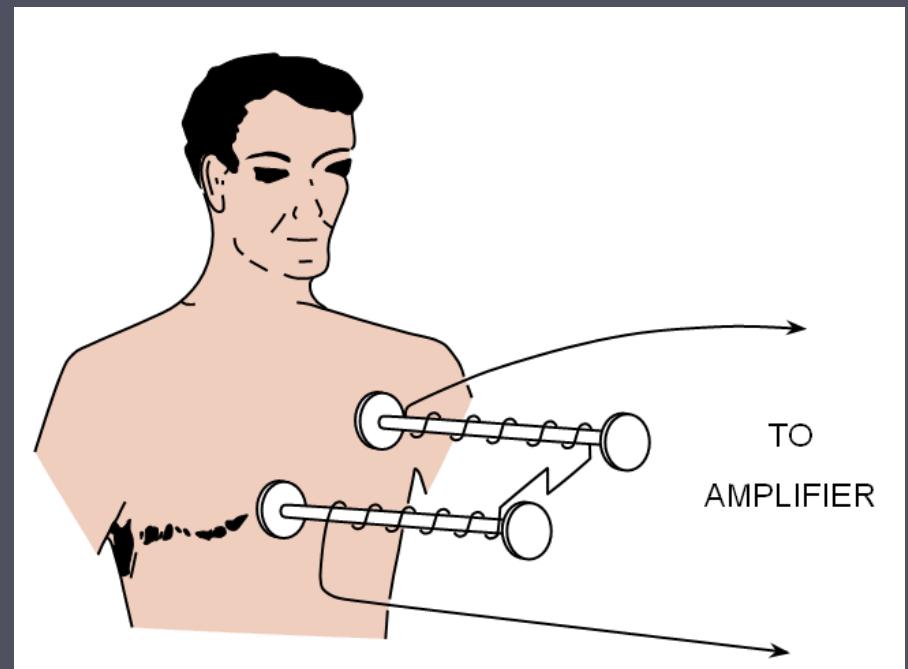
Electrical current flow lines



Magnetic field flow lines

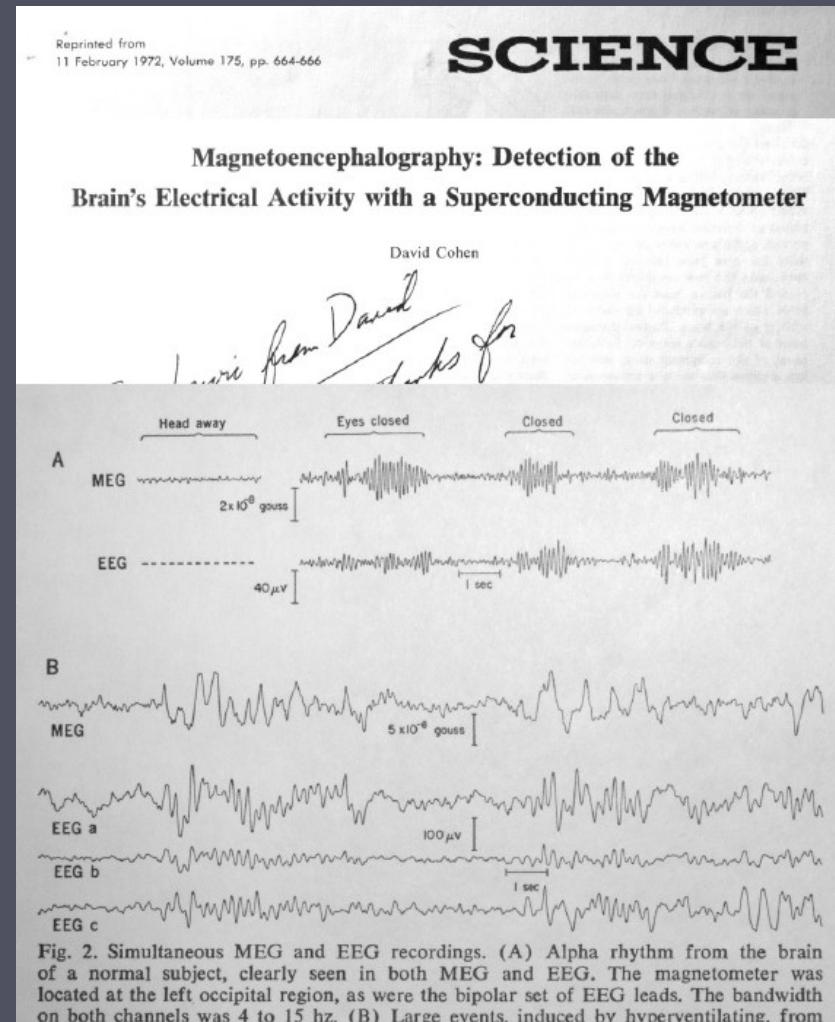
1963: First magnetocardiogram (MCG)

- Baul & McFee,
1963

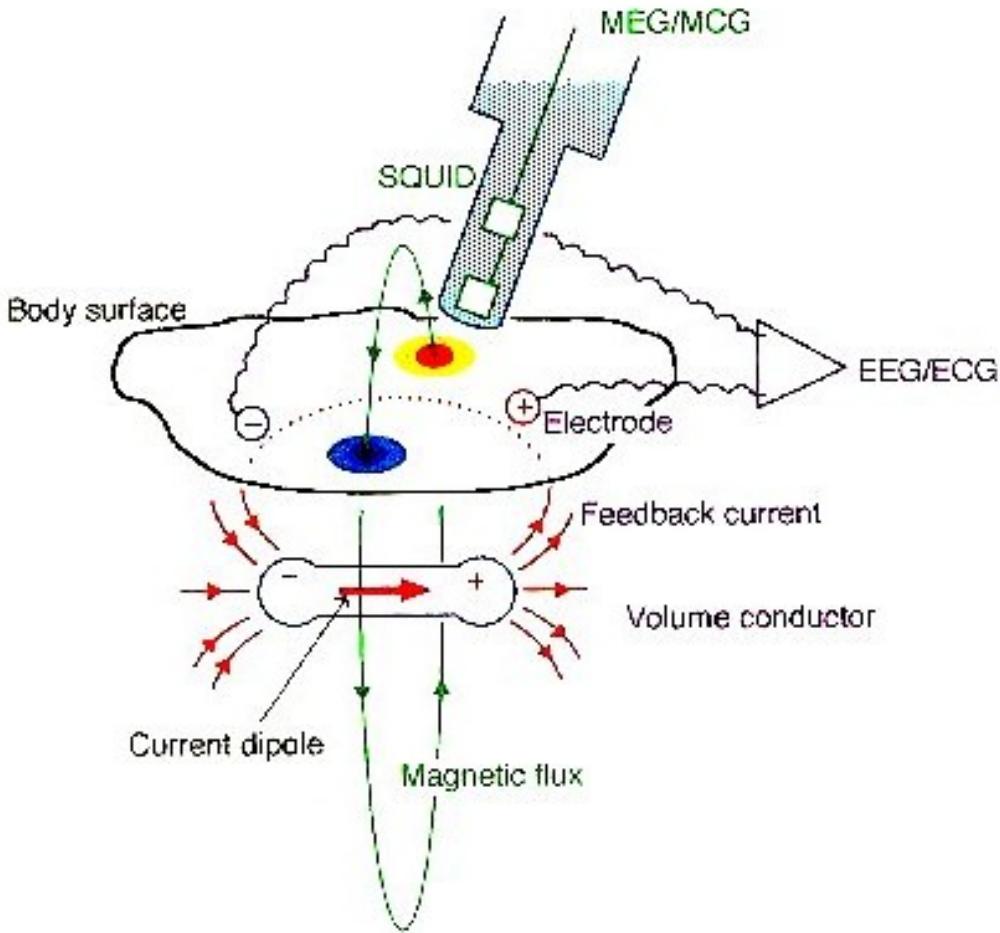


1972: First magnetoencephalogram (MEG)

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



Summary :



EEG:

- From 1 to 100 μ V

MEG:

- About 100 fT
- Earth static magnetic field (50μ T)
- ~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



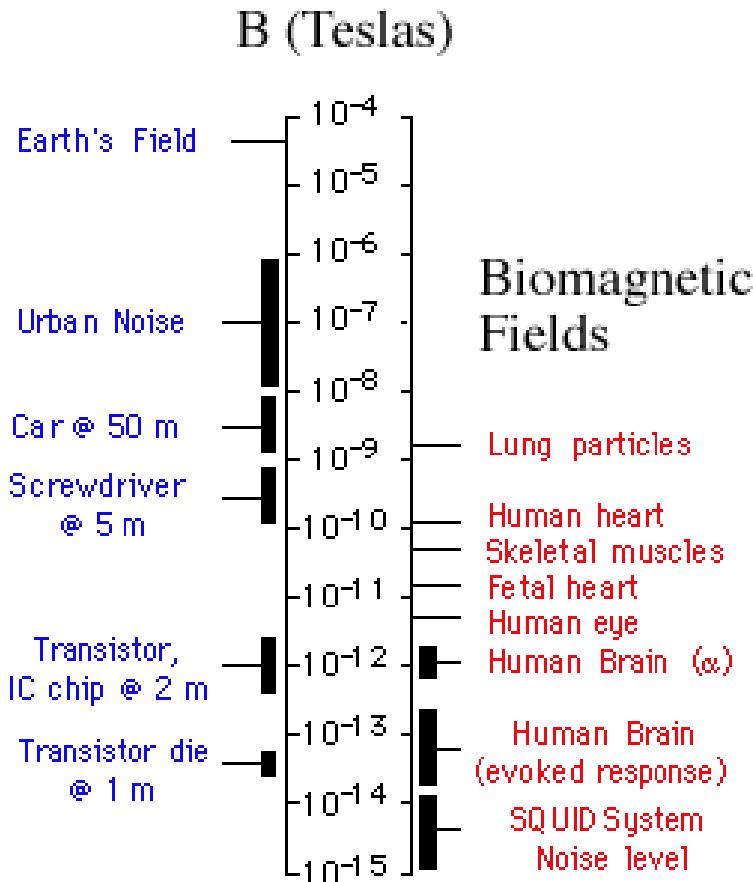
NeuroScan



MicroMed

Magnitude of cerebral magnetic fields

Magnetic Fields

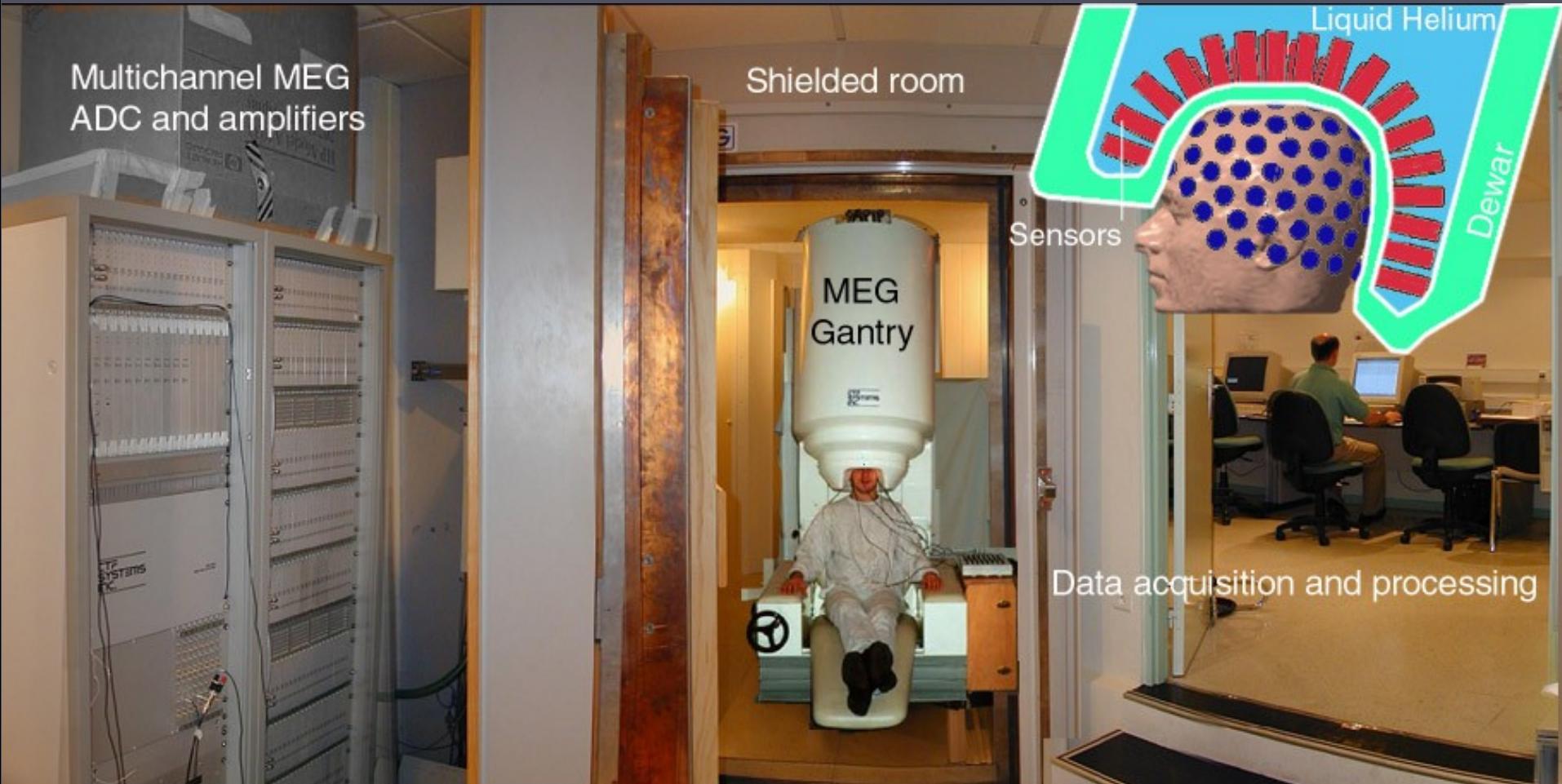


Instrumentation: MEG

(a)

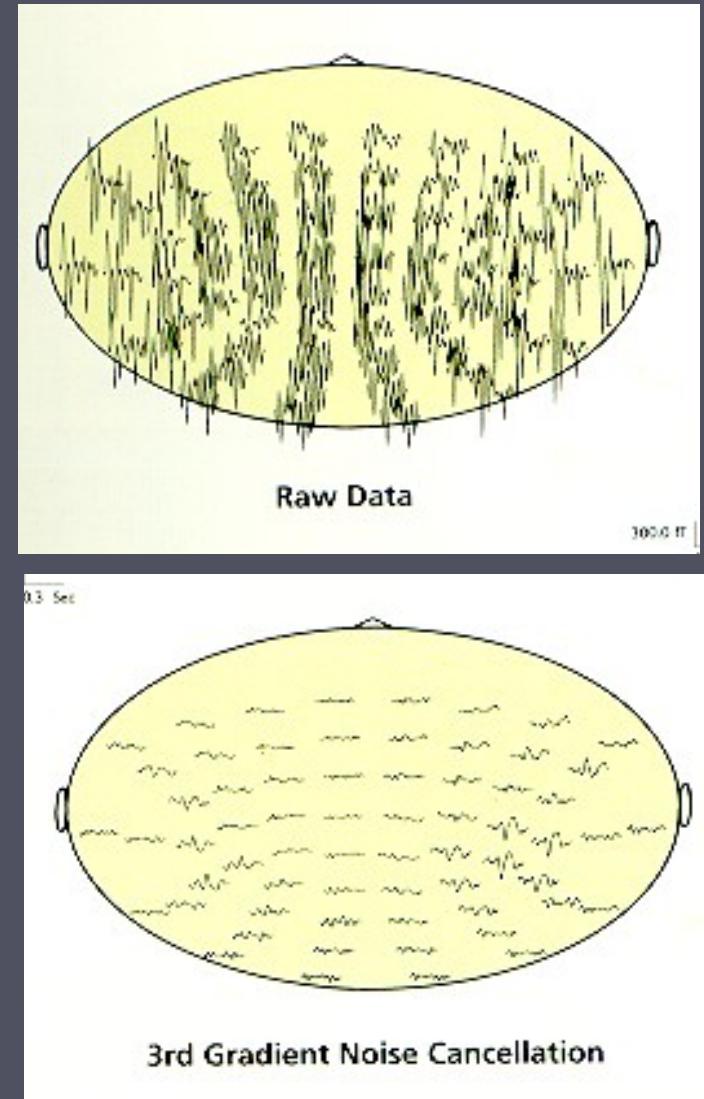
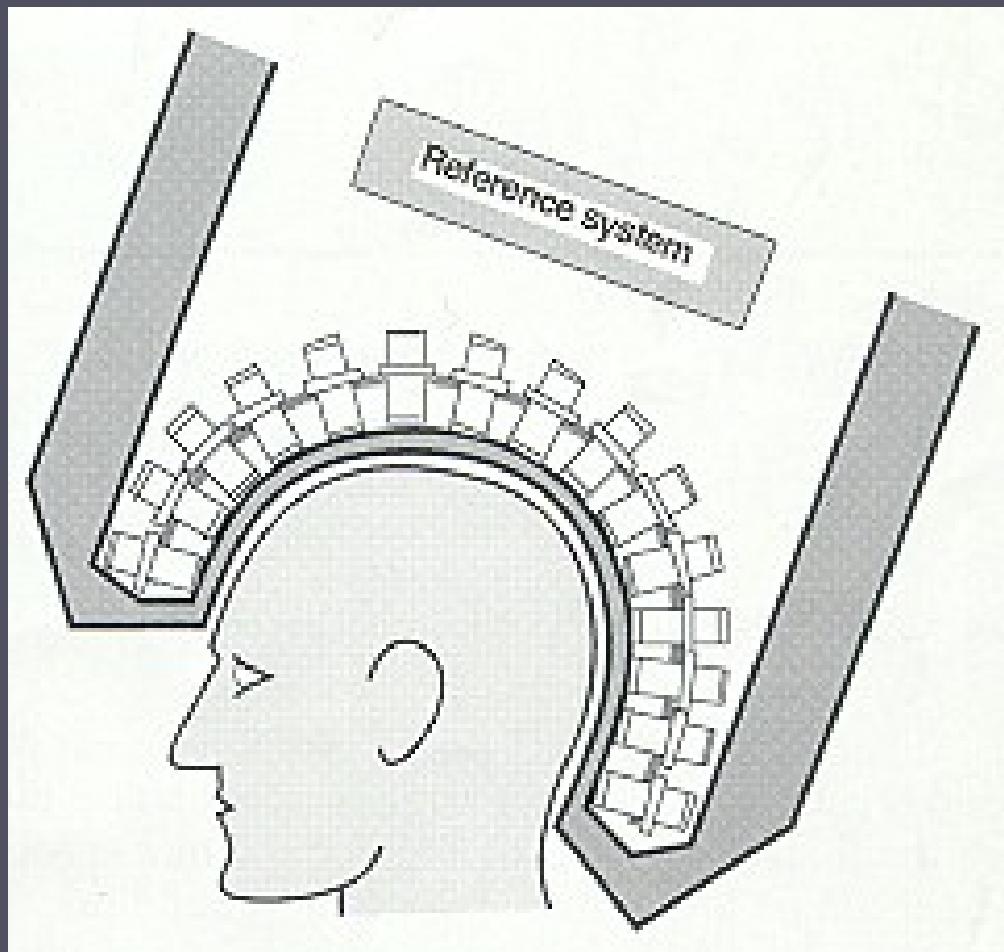


Instrumentation: MEG

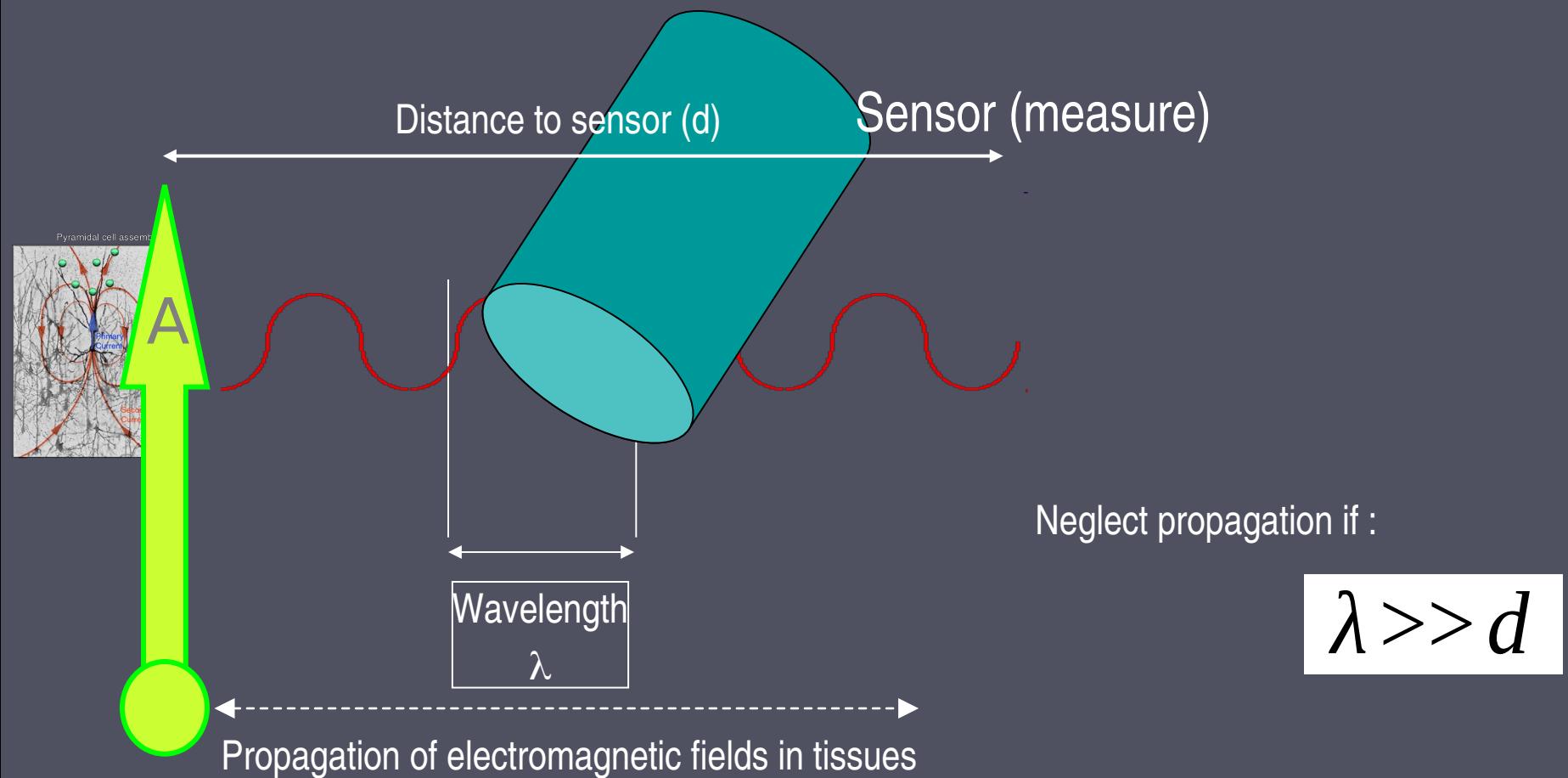


MEG: improving the SNR

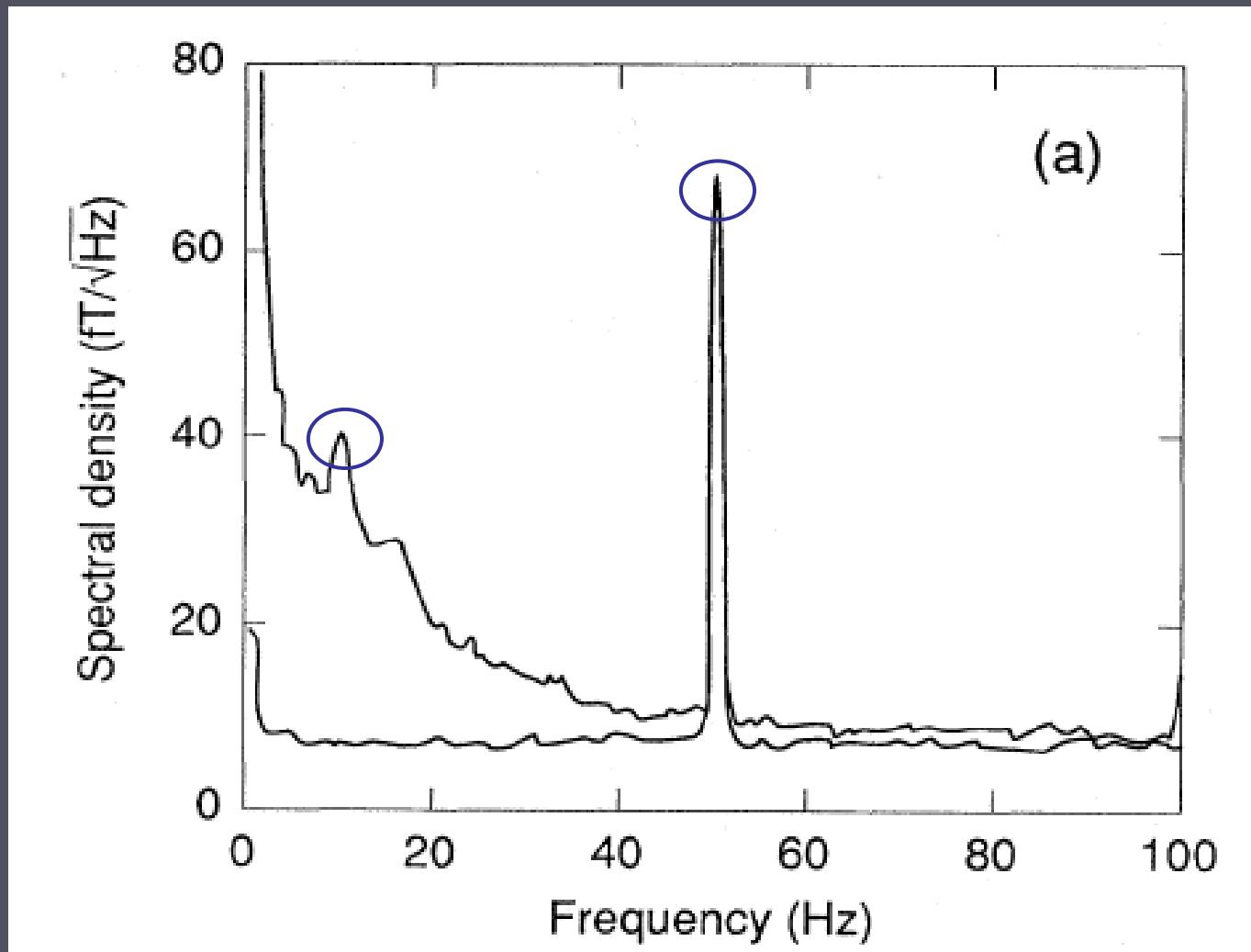
Gradient of magnetic fields of higher order with reference sensors



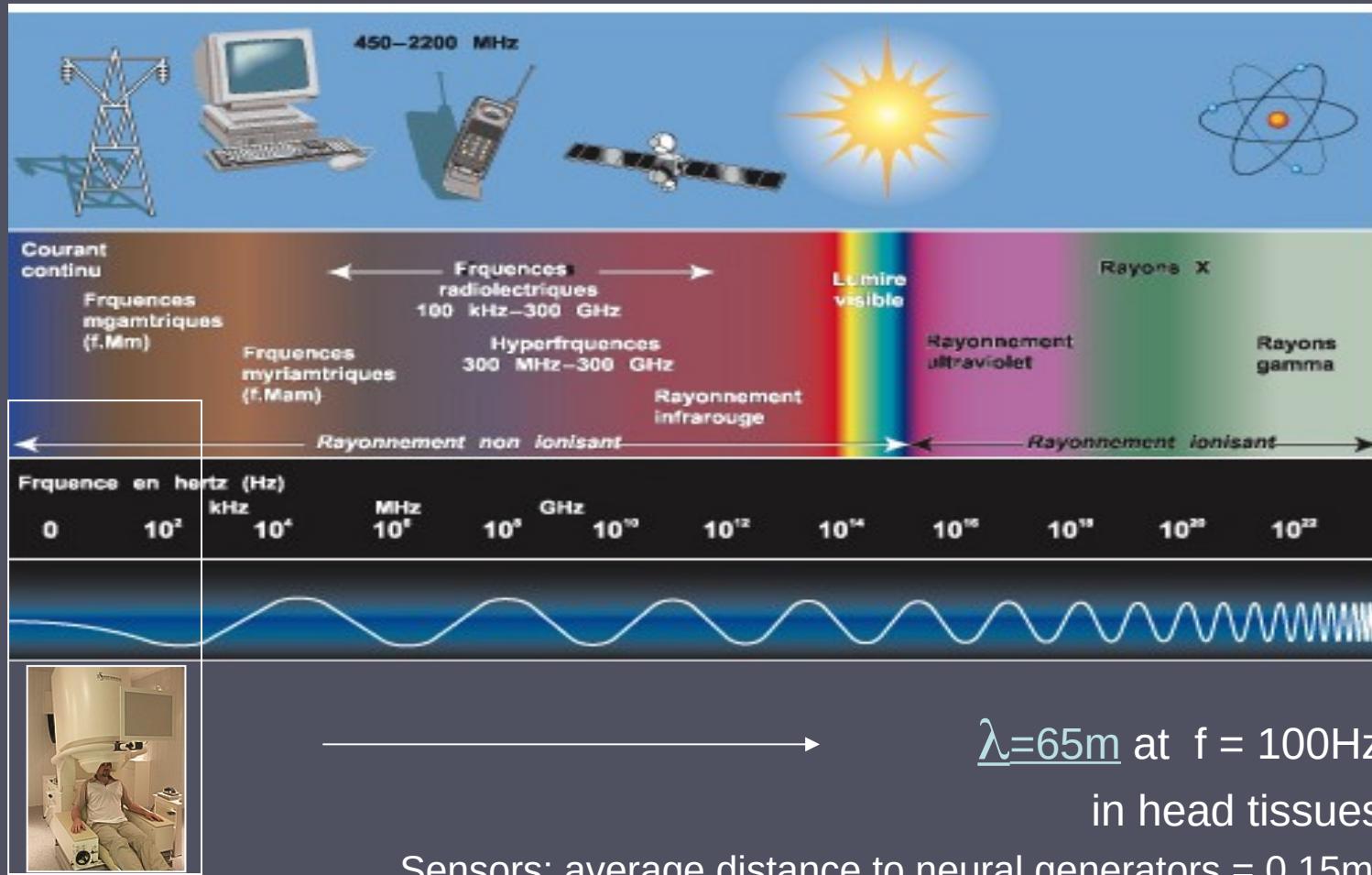
Modelisation of neural electromagnetic fields



Modelisation of neural electromagnetic fields



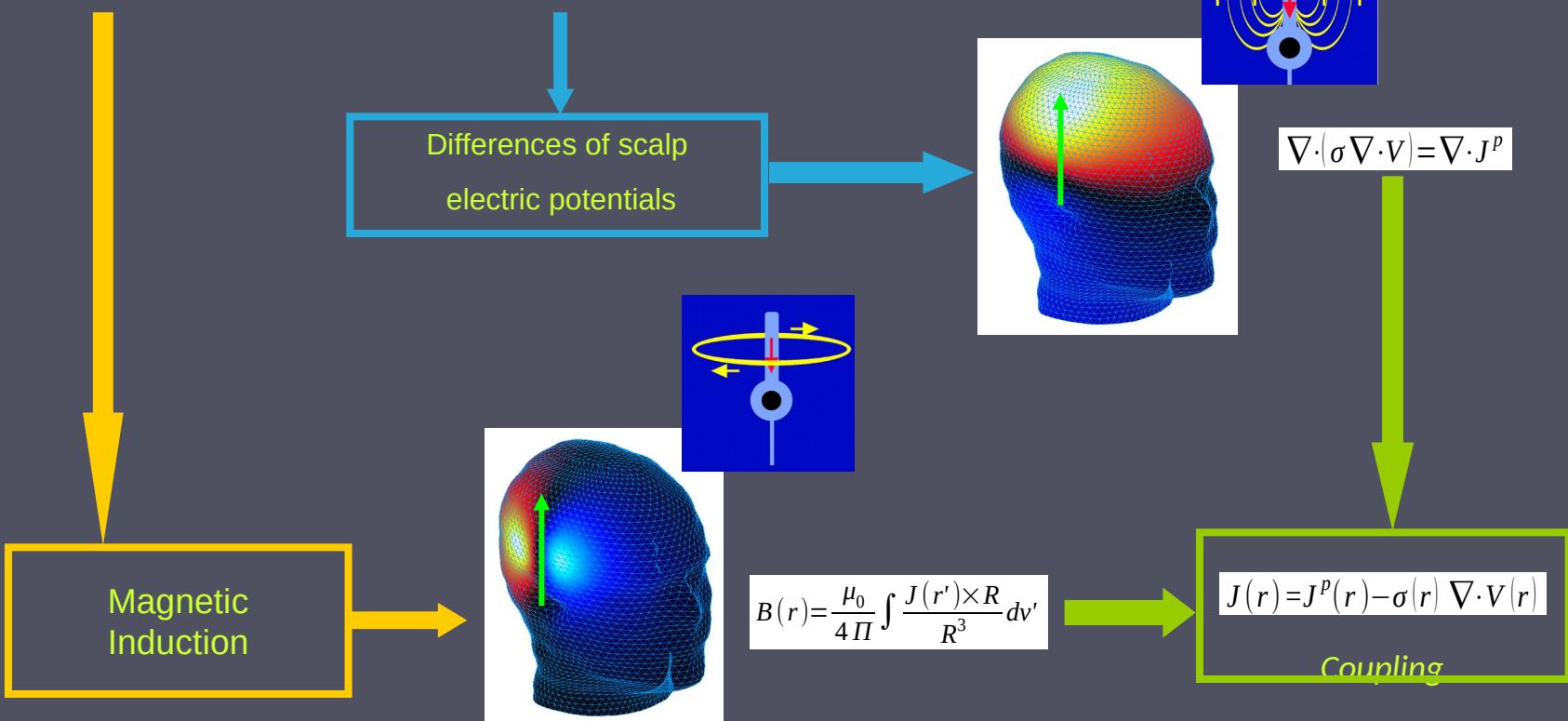
Modelisation of neural electromagnetic fields



Field propagation effects are neglected.

Fields and potentials produced by a current dipole

Magneto & Electroencephalography



MEG & EEG are complementary and can be combined

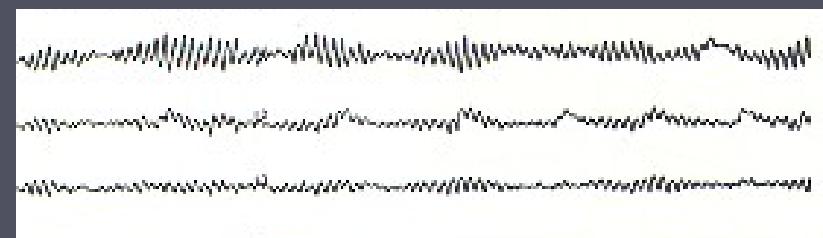


Spontaneous Activity

Artifacts (ocular, cardiac, ...)

Different rhythms (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)



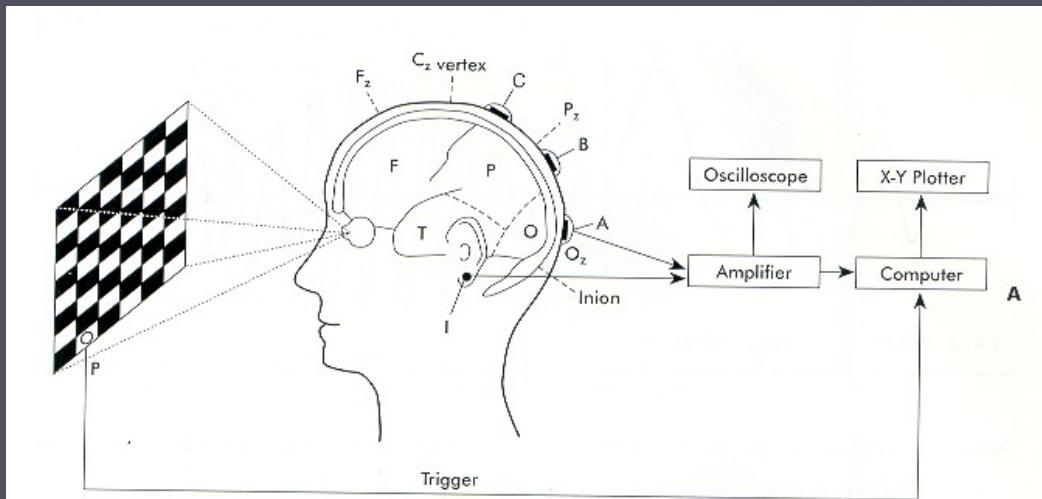
Epileptic signals

- interictic spikes
- EEG ictal (crisis)



Evoked Potentials

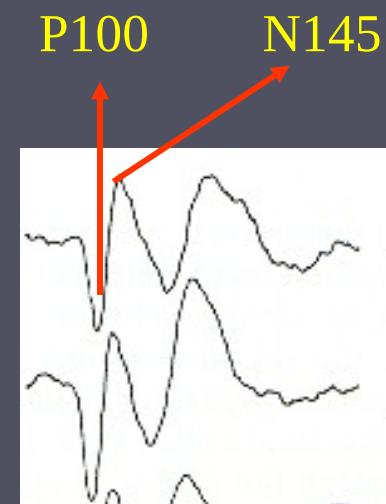
Stimulus synchronized averaging (Dawson 1937)



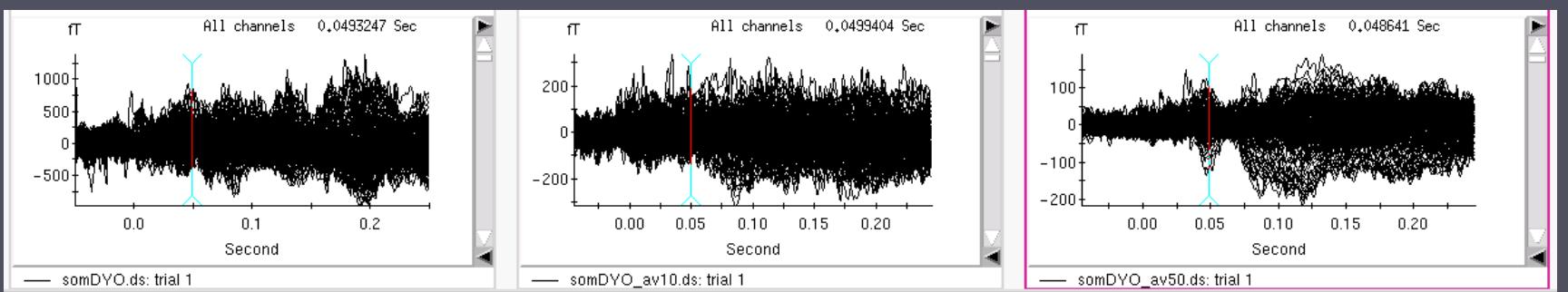
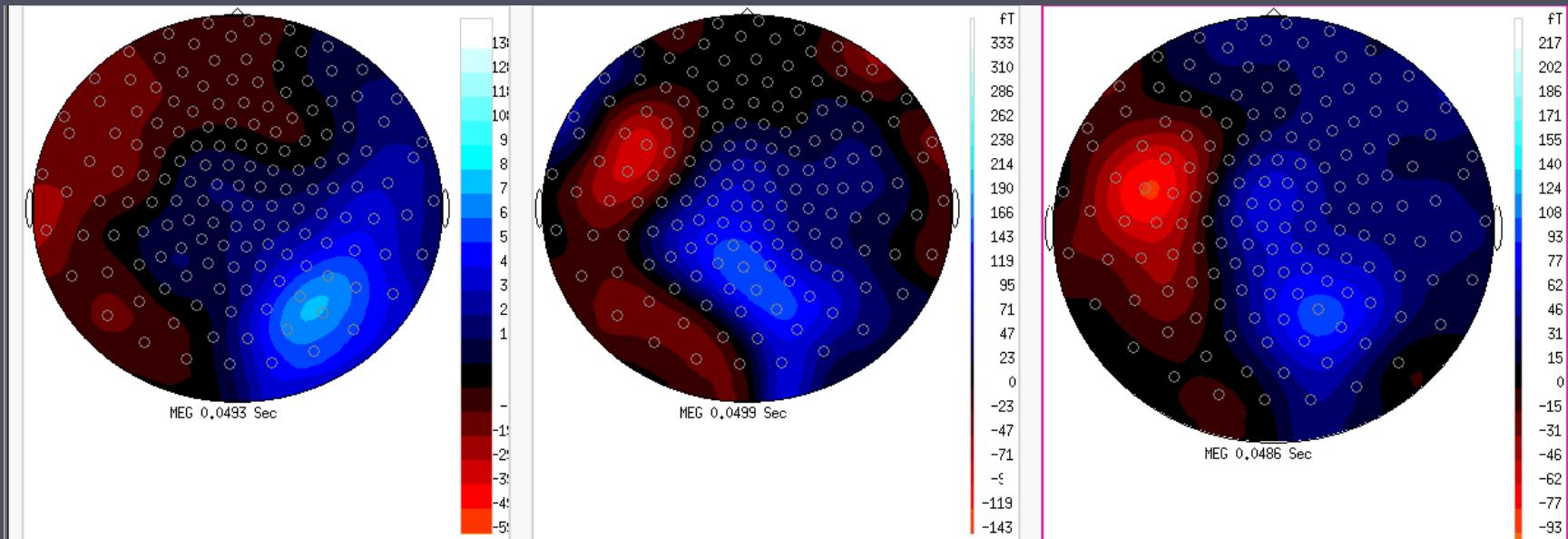
Different responses (latency and amplitude)

Nomenclature :

- N_{xxx} : EEG negative wave at xxx ms
- P_{xxx} : EEG positive wave
- M_{xxx} : MEG wave at xxx ms



Influence of the number of repetitions

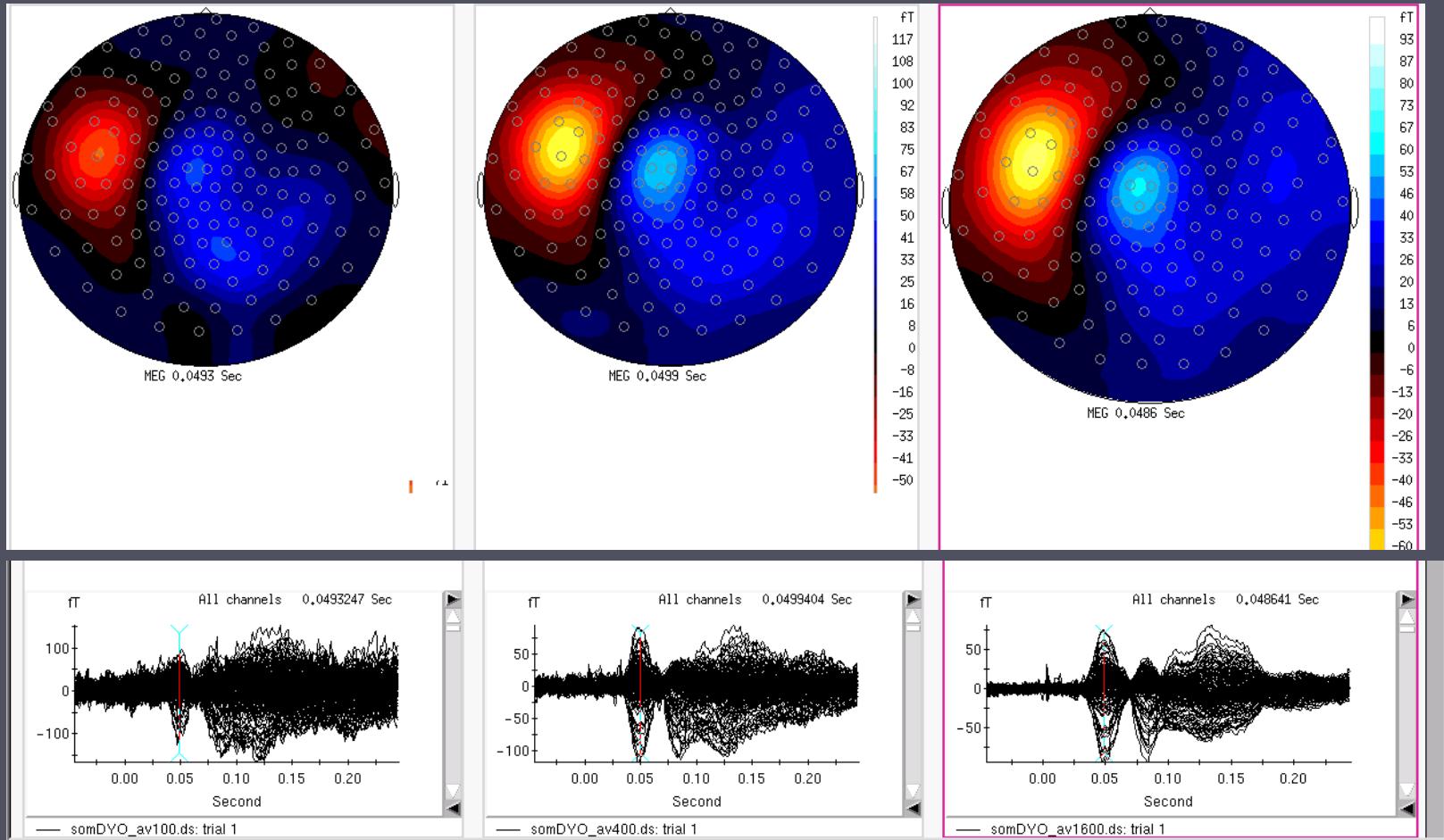


1 trial

10 trials

50 trials

Influence of the number of repetitions



100 trials

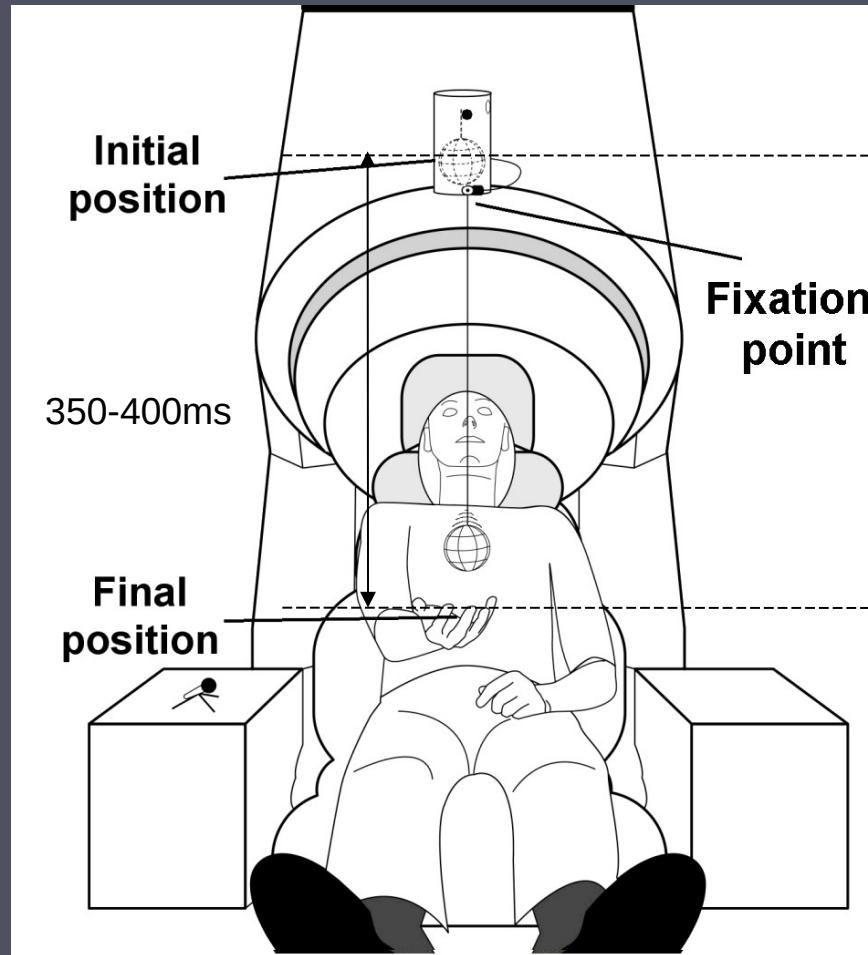
400 trials

1600 trials

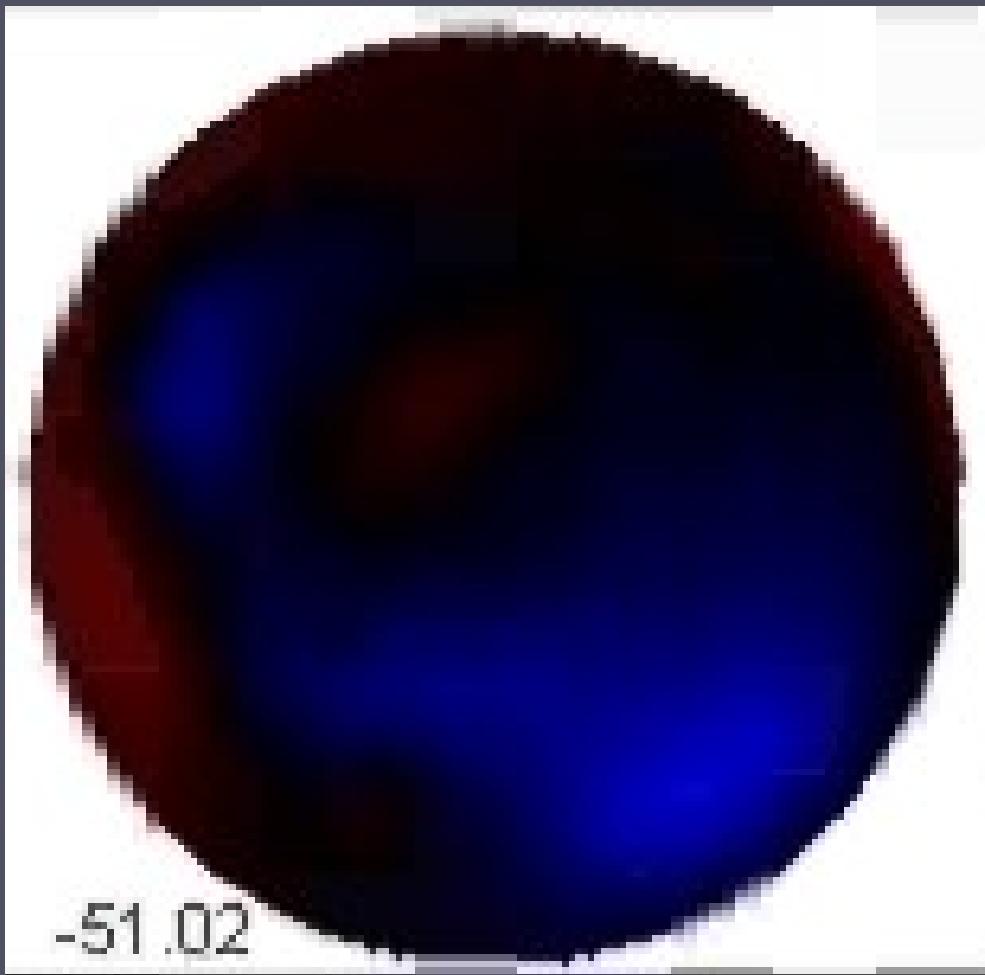
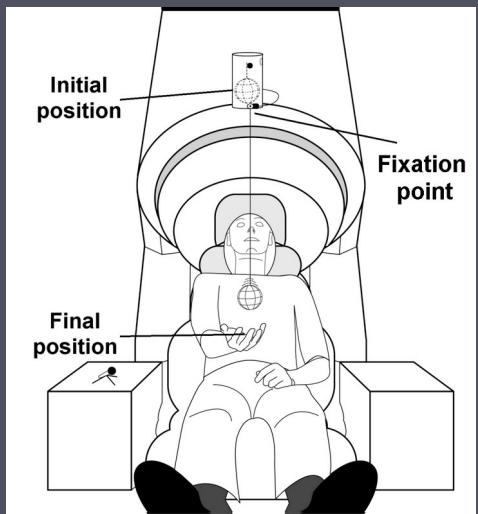
Example of MEG measures

Tennis ball catching

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



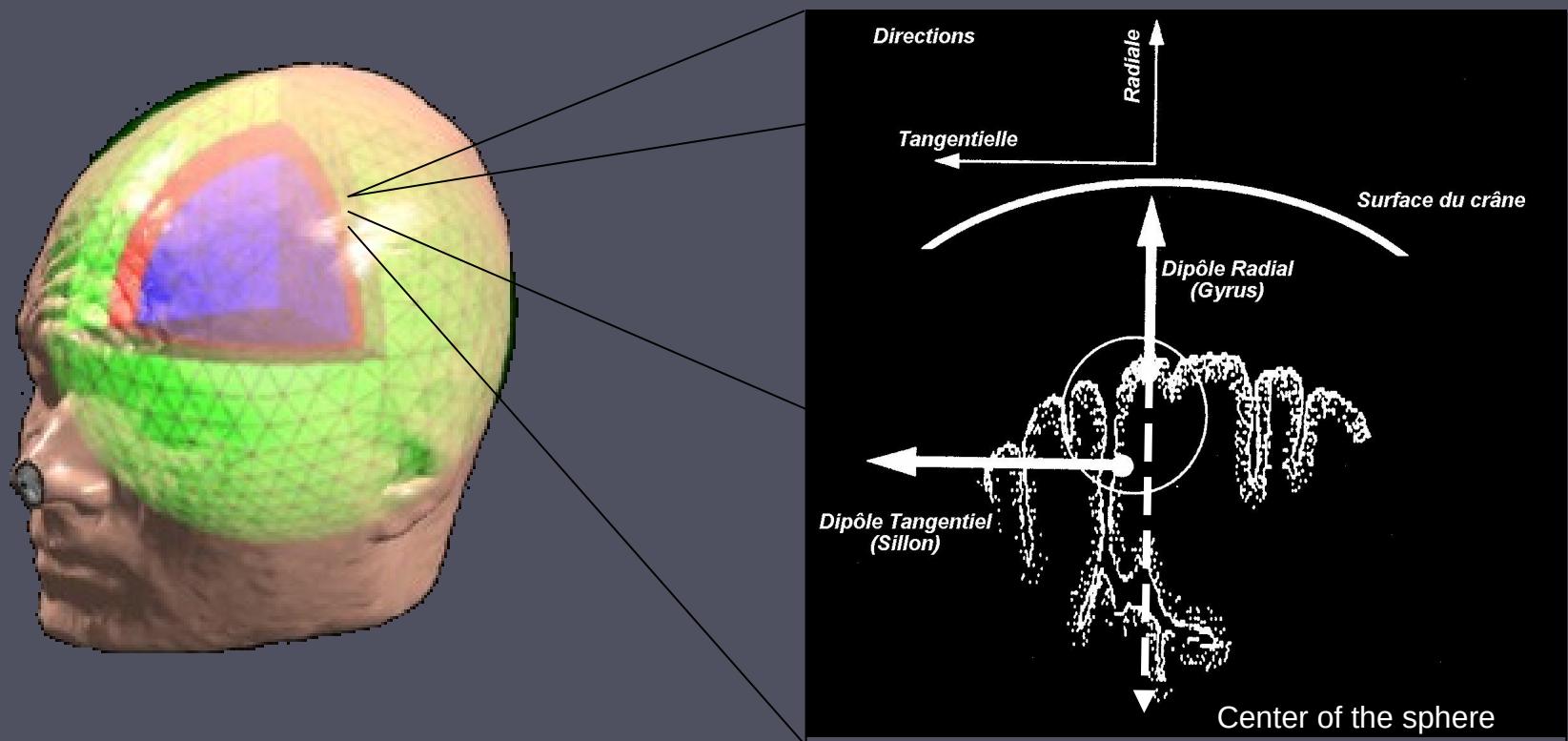
Example of MEG measures



Data courtesy of Patrice Senot, LPPA, Collège de France

Radial and tangential dipoles

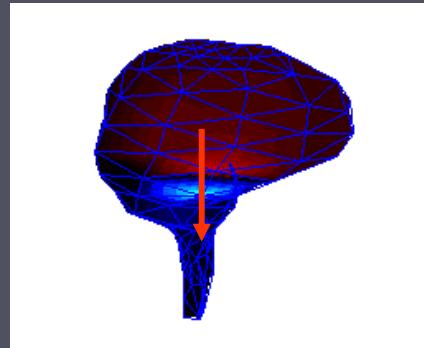
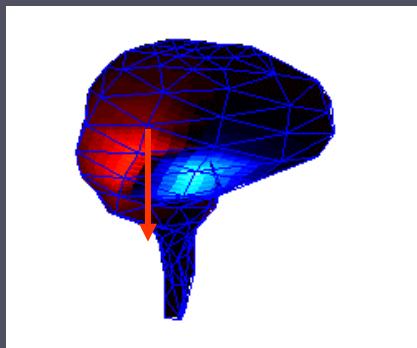
- Defined for spherical geometries



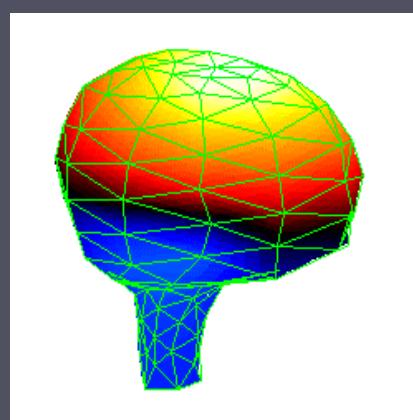
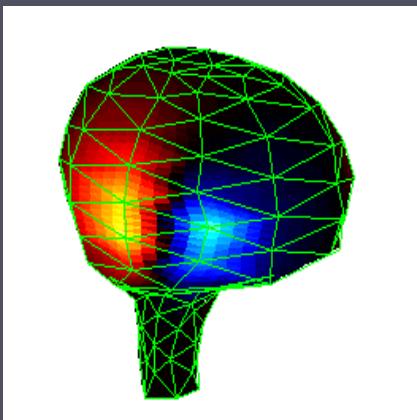
MEG/EEG differences: influence of tissues

MEG

EEG



Cortex

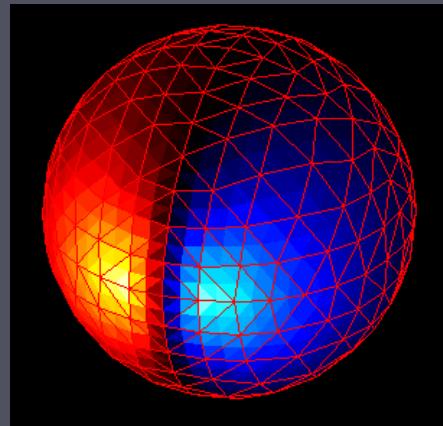


External skull

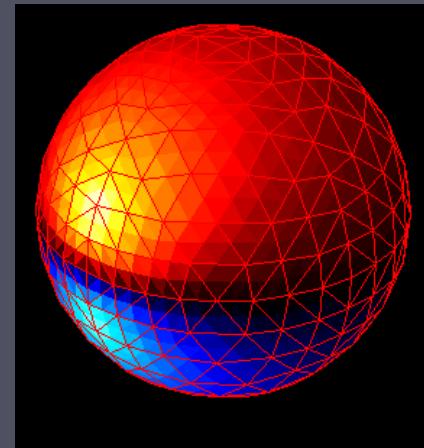
Influence of source orientation

- Spherical geometry

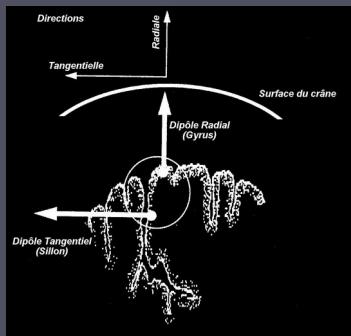
MEG



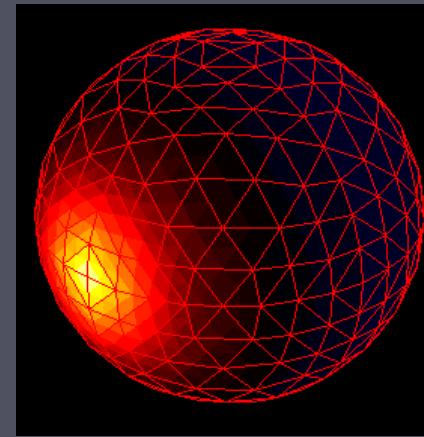
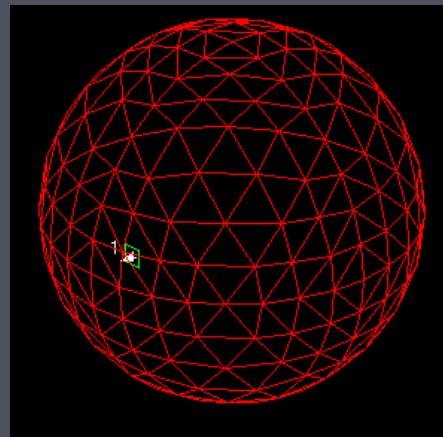
EEG



Tangential dipole



MEG

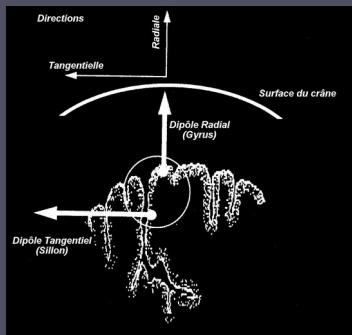


Radial dipole

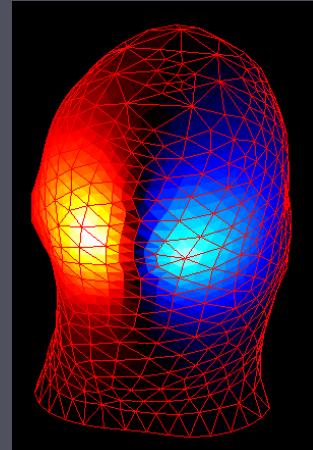
Influence of source orientation

- Realistic geometry

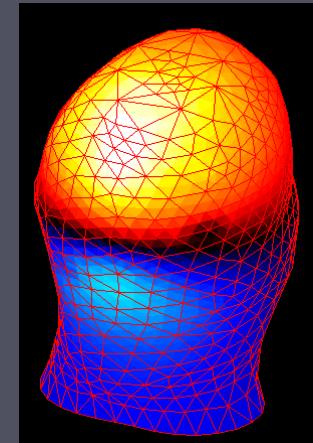
Tangential dipole



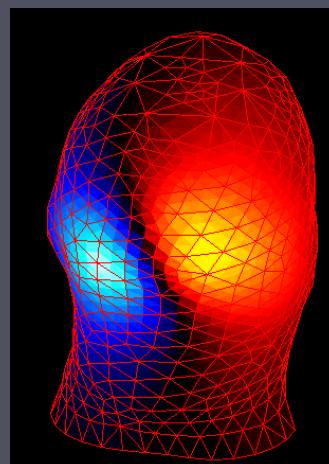
MEG



EEG



Radial dipole



Influence of the source depth

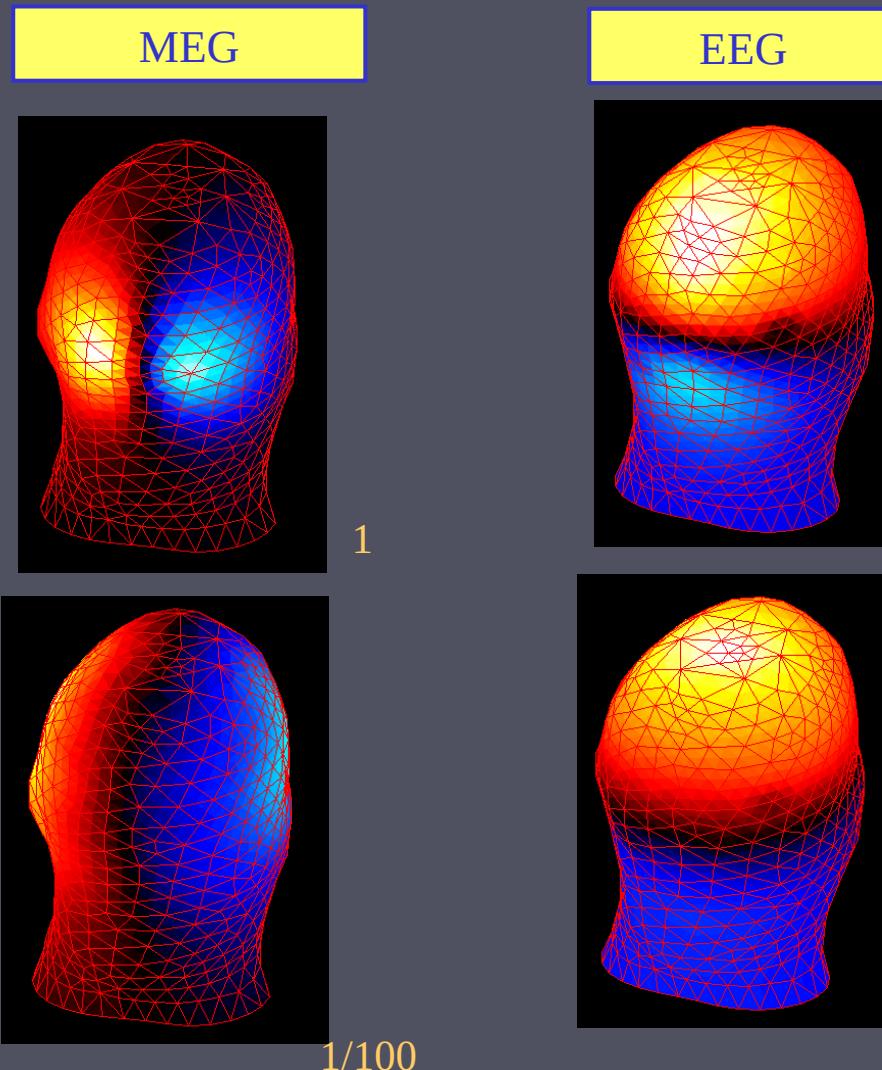
- Realistic geometry

Superficial source

External cortex

Deep source

Internal cortex



DIFFERENCES BETWEEN MEG and EEG: SUMMARY

MEG

- Measures magnetic field.
- Dipolar response perpendicular to dipole direction.
- Focal response.
- Only slightly affected by head tissues.
- Selective to tangential sources.
- Low sensitivity to deep sources.
- Expensive instrument.

EEG

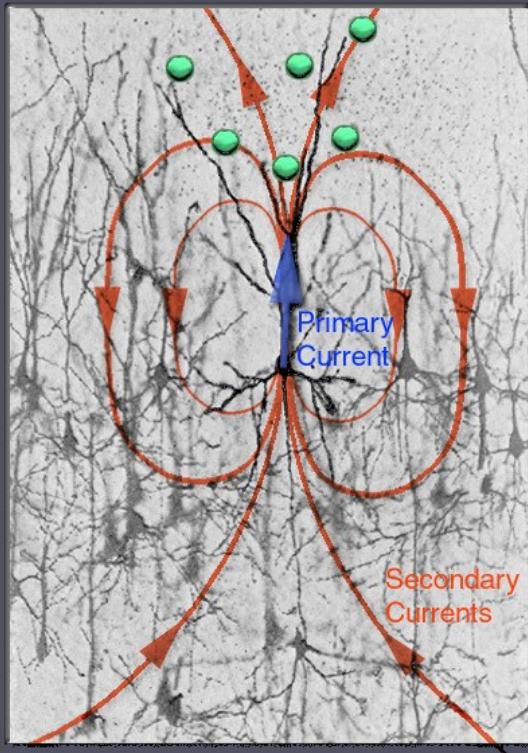
- Measures electrical potential.
- Dipolar response parallel to that of the dipole.
- Diffuse response.
- Strongly affected by head tissues.
- Sensitive to all dipole orientations.
- Sensitive to deep sources.
- Less expensive instrument.

A question of scale

Excitatory post-synaptic potentials ●

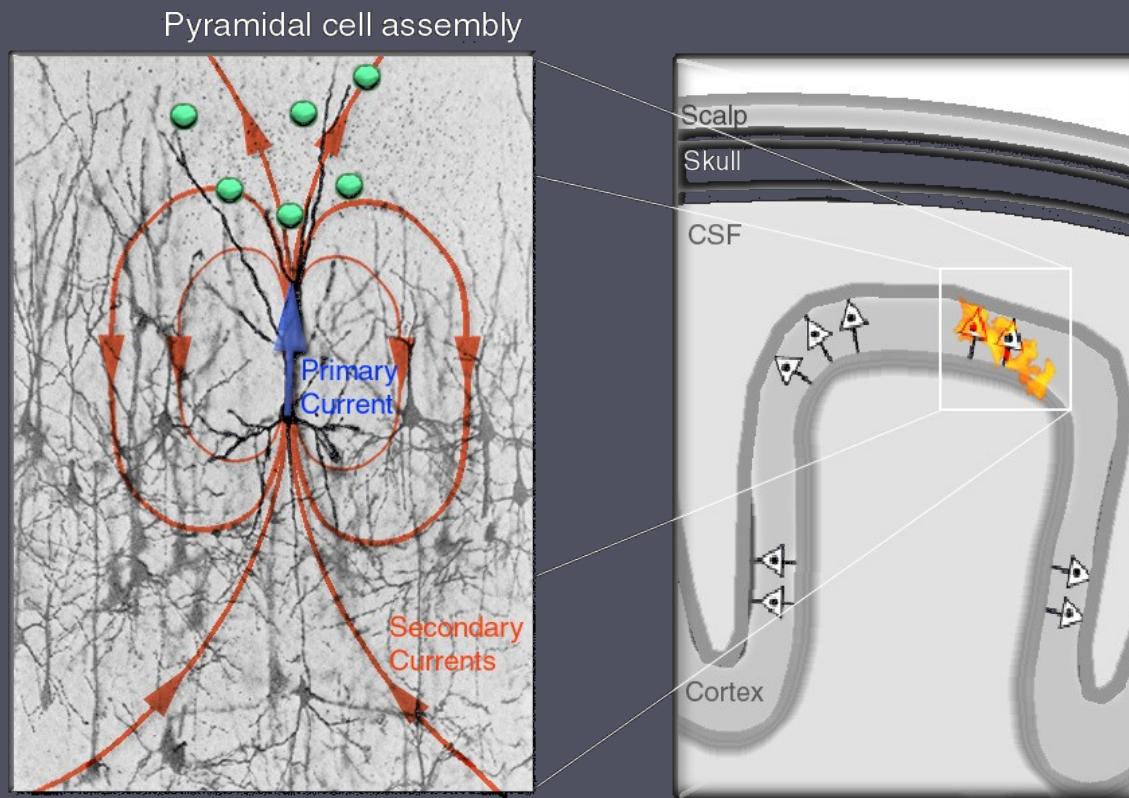
Scale: micro

Pyramidal cell assembly



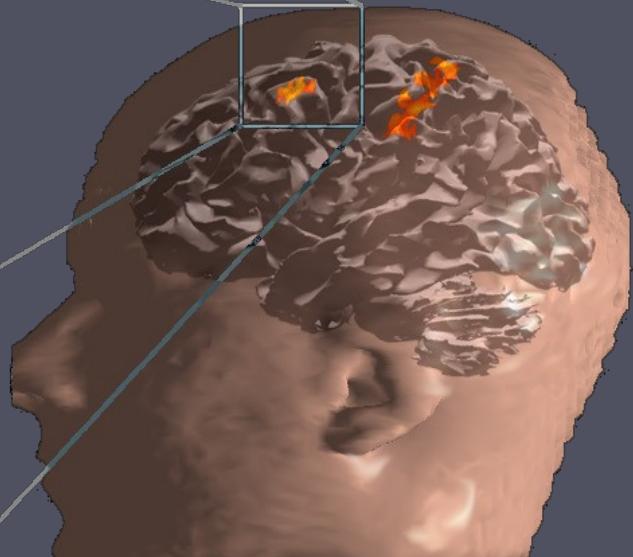
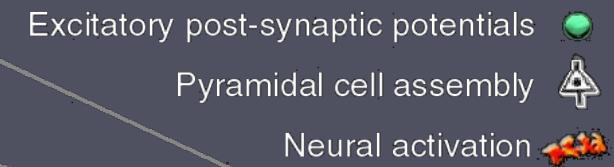
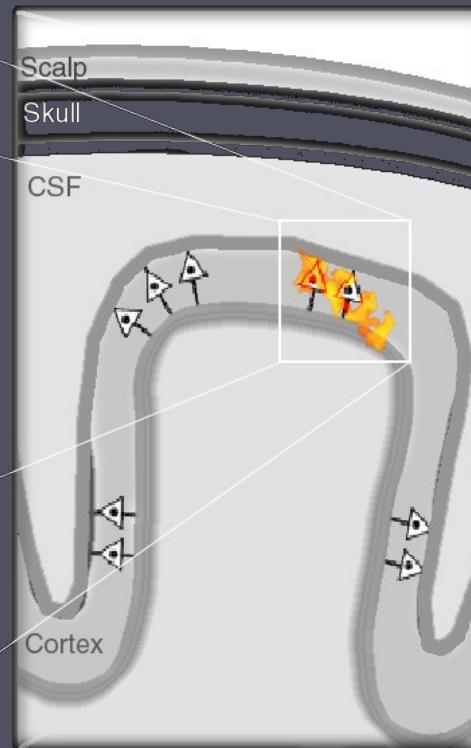
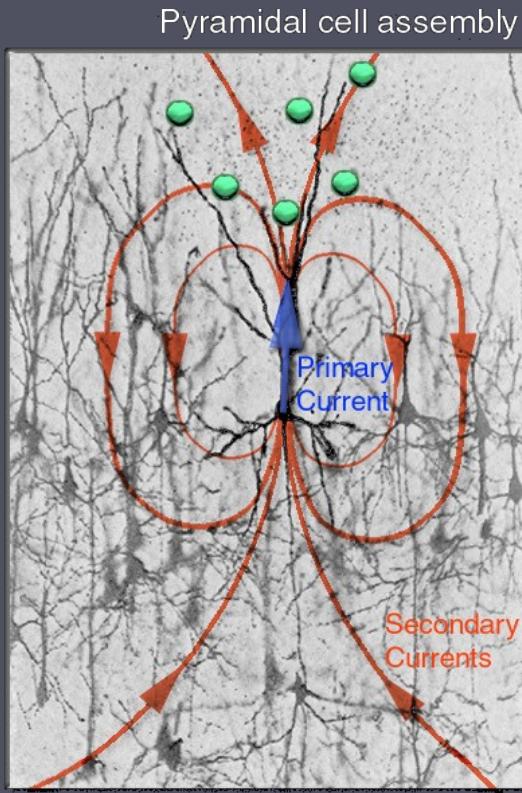
A question of scale

Scale: micro → meso



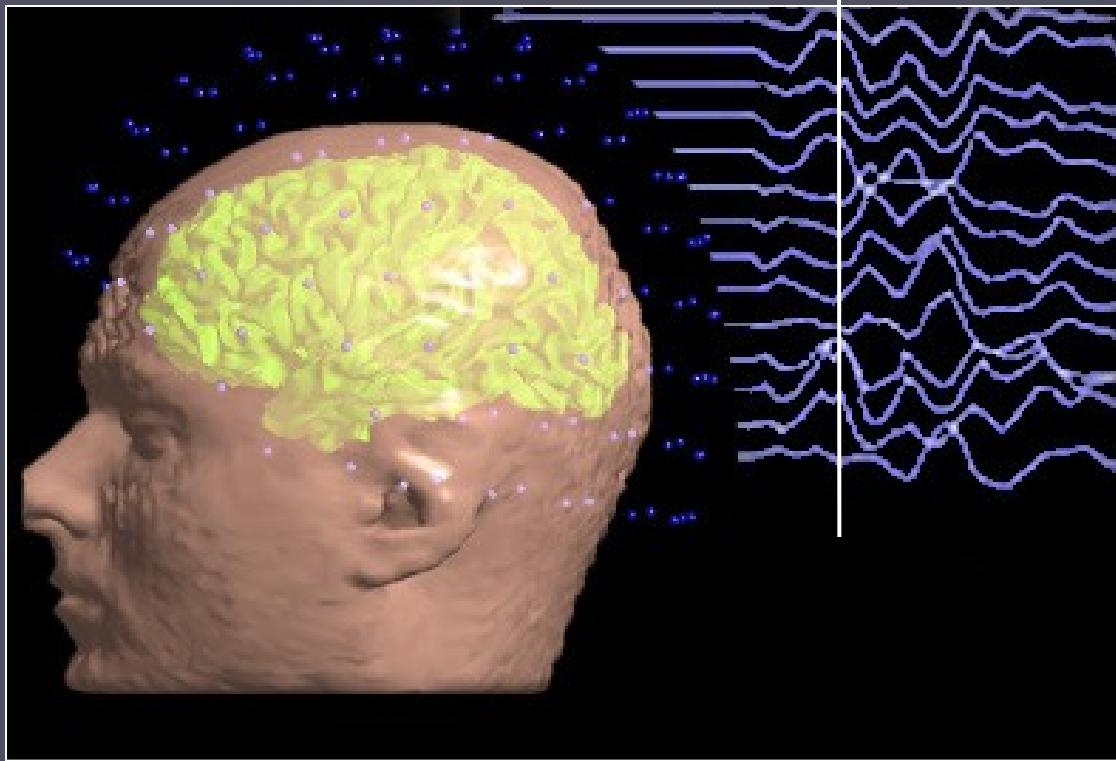
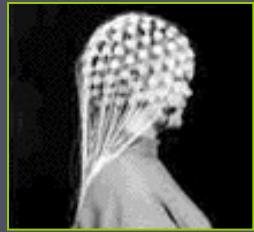
A question of scale

Scale: micro → meso → macro

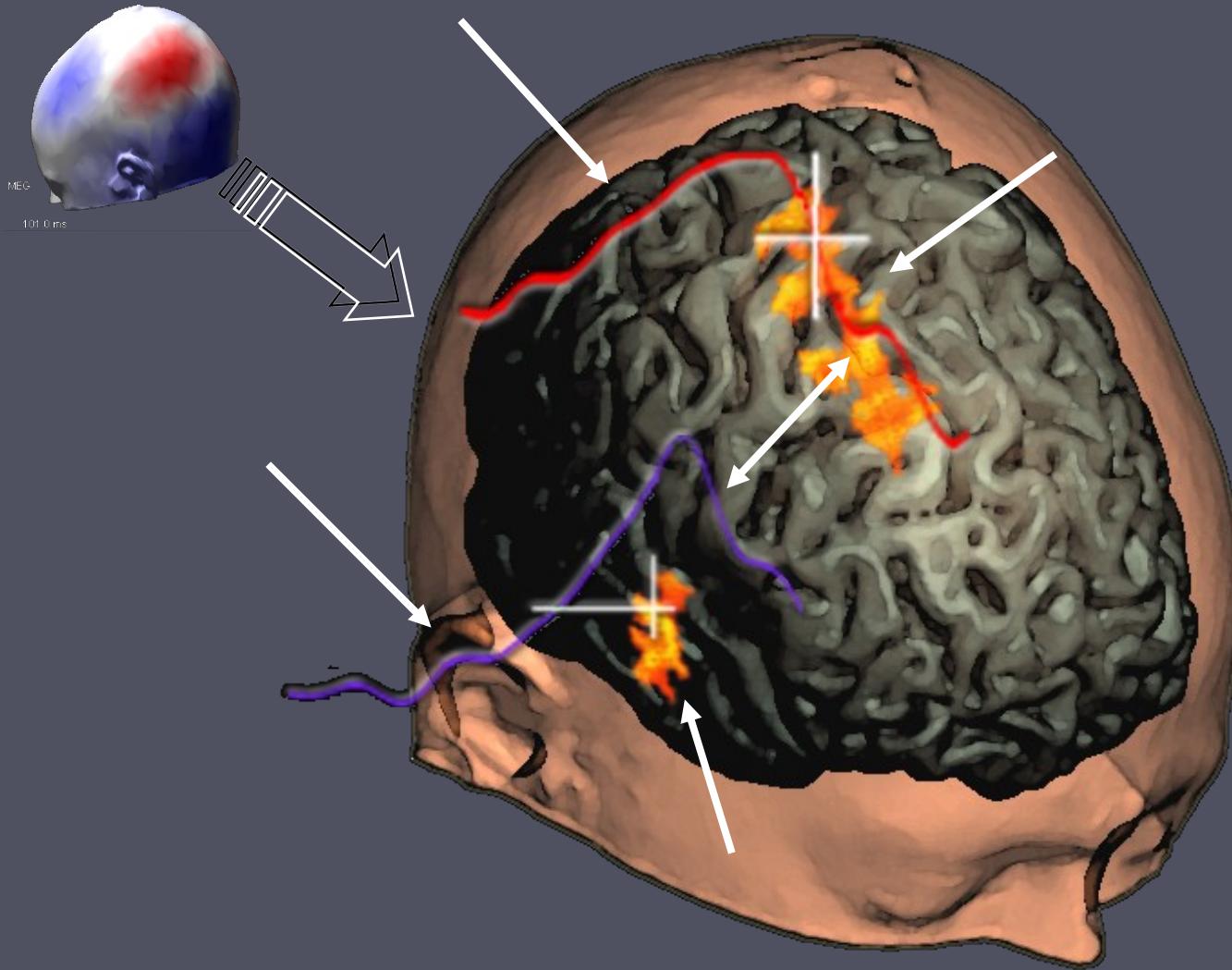


CNRS UPR640 - USC - LANL

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.