



MRC Cognition  
and Brain  
Sciences Unit



UNIVERSITY OF  
CAMBRIDGE

# EEG/MEG 1:

History, Measurement, Signal Generation

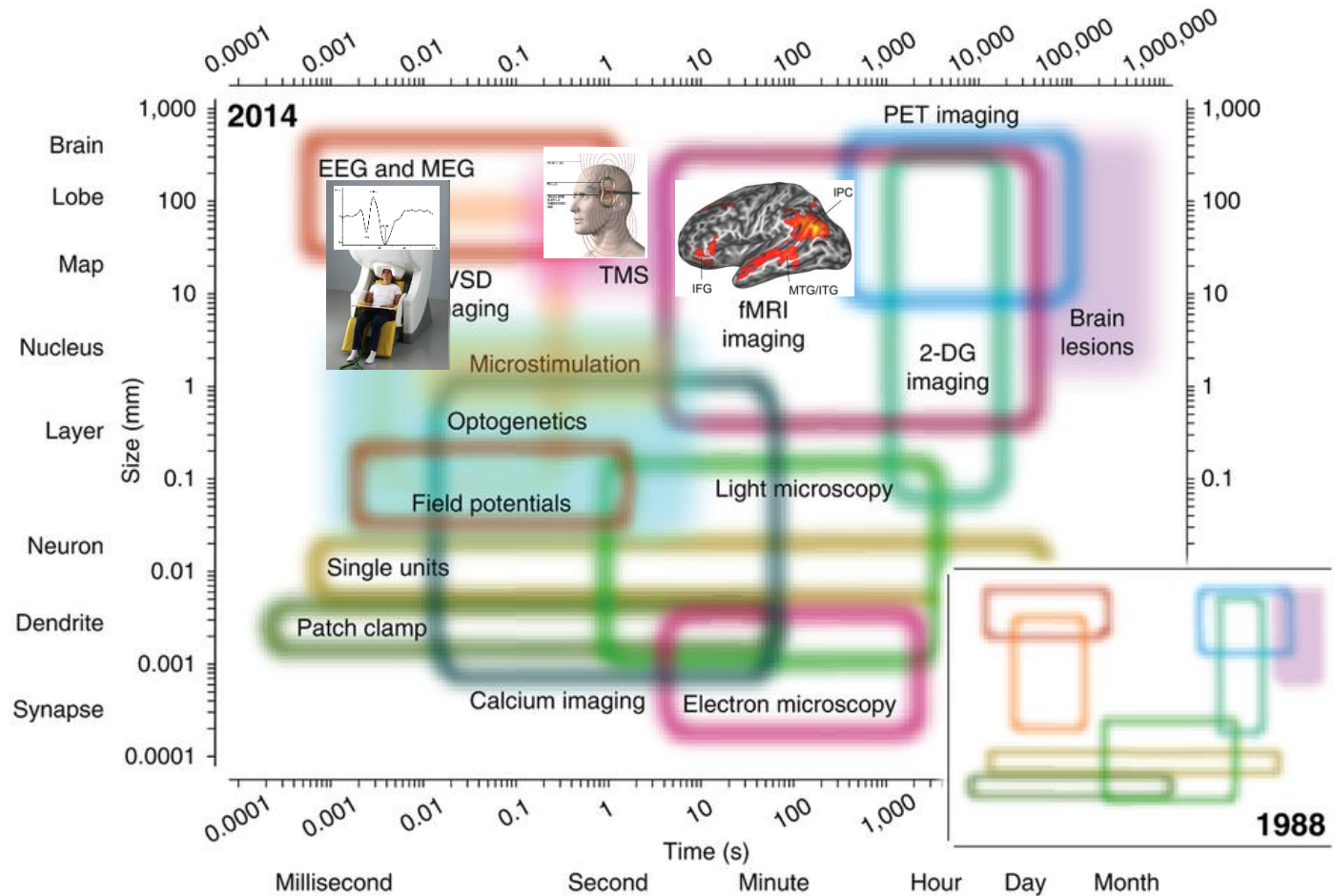
Olaf Hauk

[olaf.hauk@mrc-cbu.cam.ac.uk](mailto:olaf.hauk@mrc-cbu.cam.ac.uk)

COGNESTIC 2023

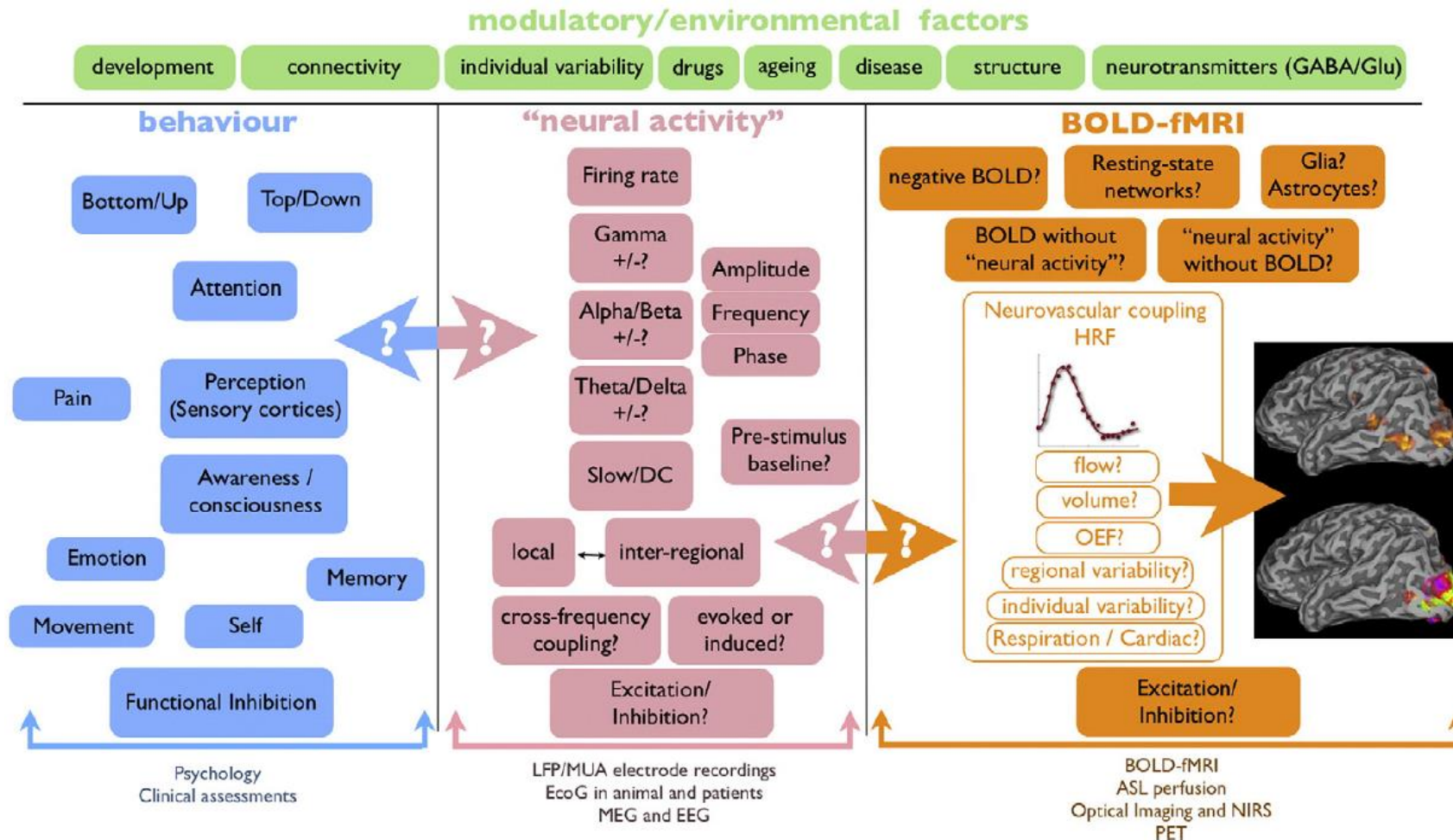
# Neuroimaging Methods Vary With Respect To Spatial and Temporal Resolution

(and their invasiveness, physiology, etc.)

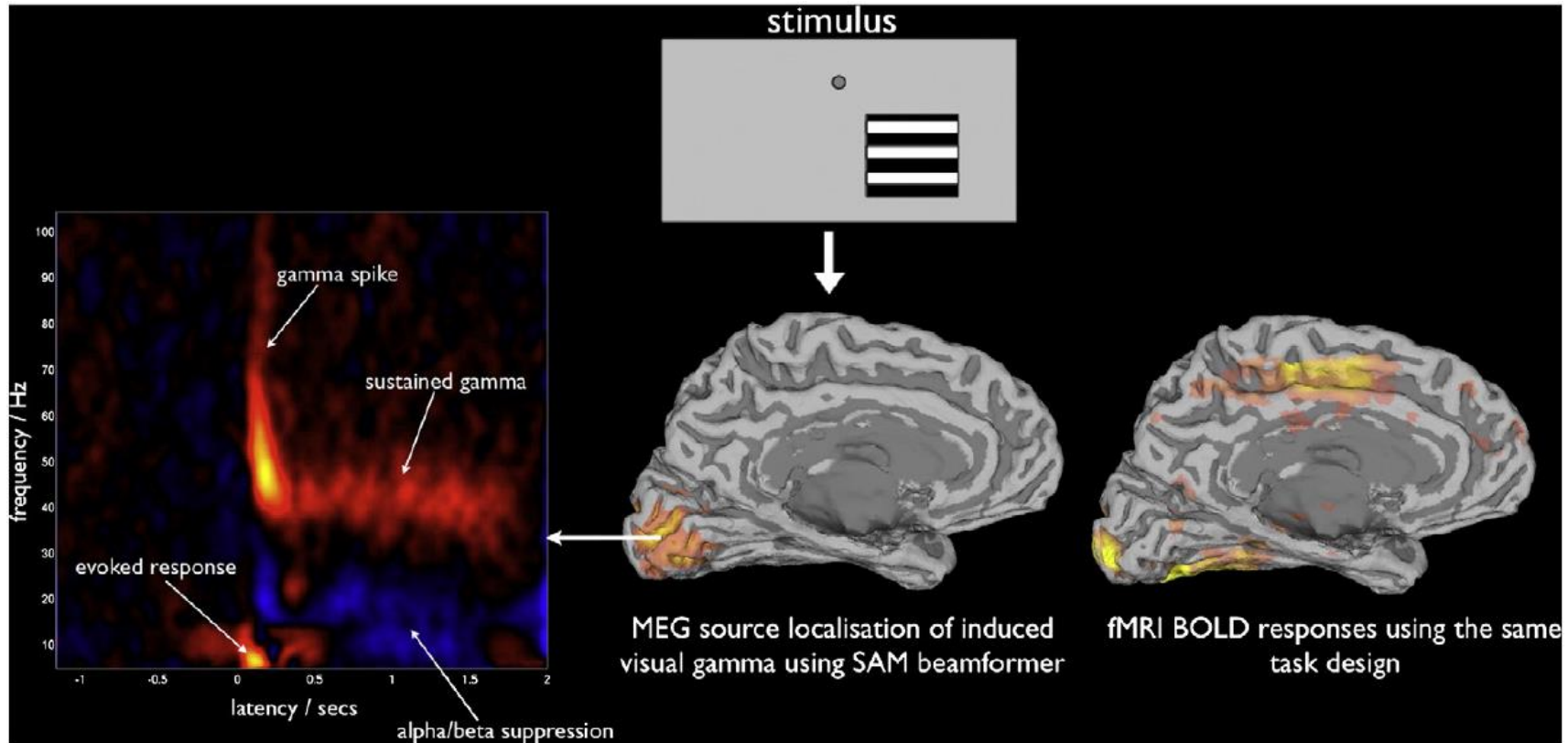


Sejnowski, Churchland, Movshon, Nat Nsc 2014

# Which “Neural Activity” Do You Mean?

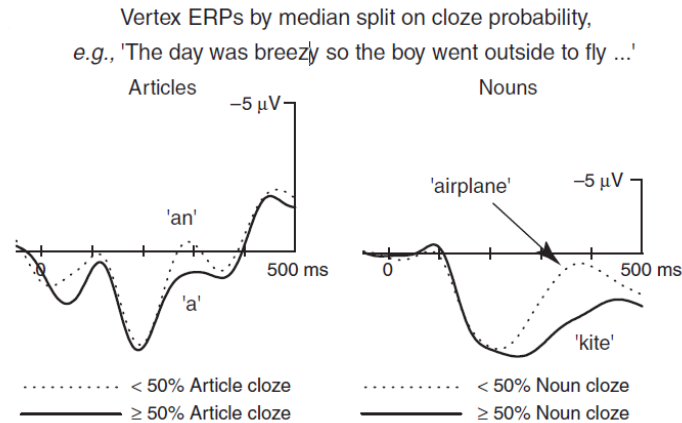


# Which “Neural Activity” Do You Mean?

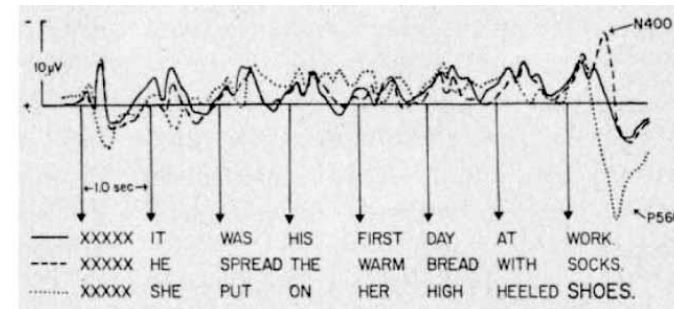


# EEG/MEG “Activity” Can Be Analysed In A Number Of Ways, e.g.

## Event-Related Potentials

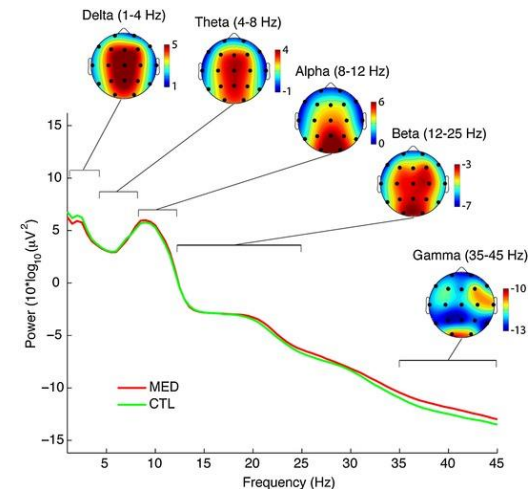
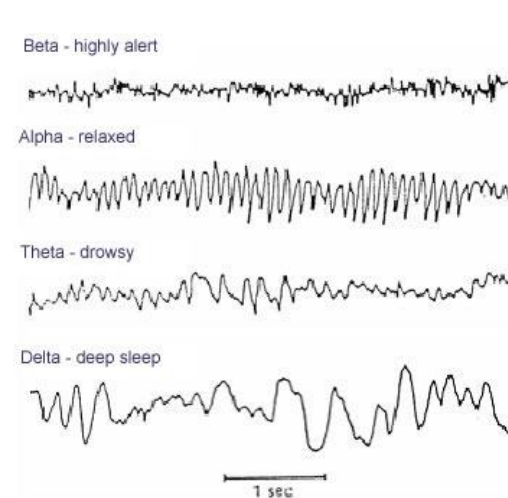


deLong, Urbach, Kutas, Nat Nsc 2005



Kutas&Hillyard, Science 1980

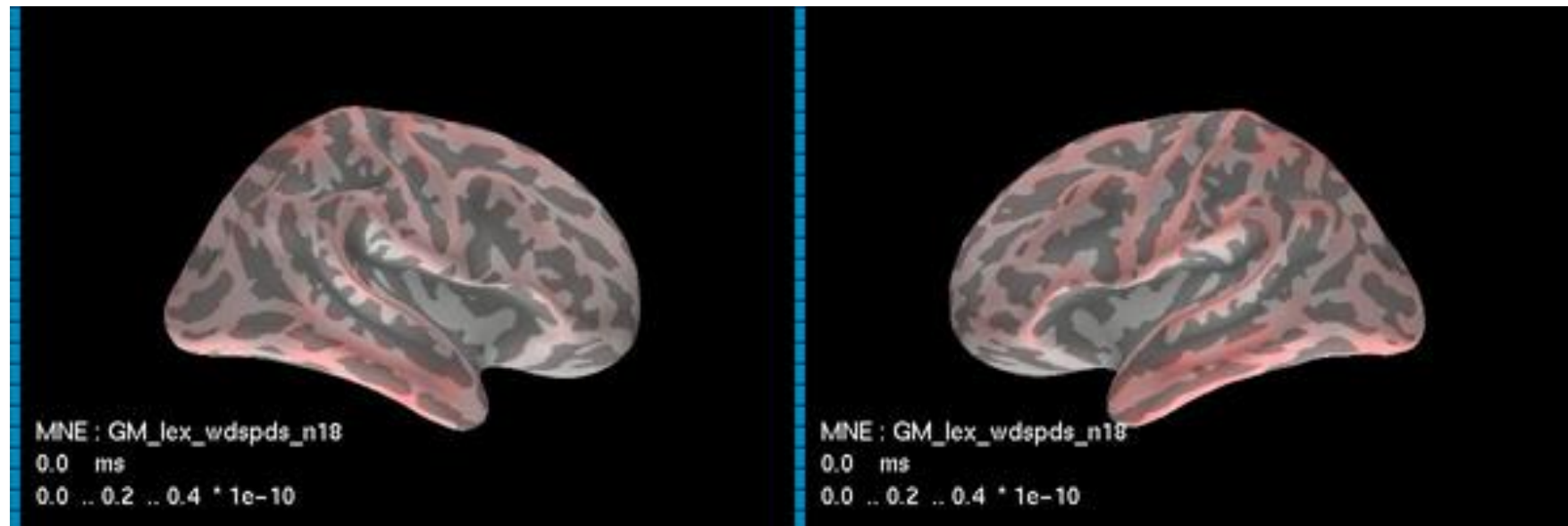
## Brain “Rhythms”/”Oscillations”



<http://link.springer.com/article/10.1007%2Fs10339-009-0352-1/>

# What We Really Want: Spatio-Temporal Brain Activity

(Movies rather than pictures)



# EEG/MEG Literature

## Books:

- Supek & Aine: “Magnetoencephalography (2<sup>nd</sup>)”, Springer 2019
- Ilmoniemi & Sarvas: Brain Signals – Physics and Mathematics of MEG and EEG”, MIT 2019
- Hari R, Puce A. “MEG-EEG Primer”. Oxford University Press 2017.
- Sekihara & Nagarajan: “Electromagnetic Brain Imaging”, Springer 2015.
- Cohen, Mike X; “Analyzing Neural Time Series Data”; MIT Press 2014.
- Hansen, Kringelbach, Salmelin: “MEG: An Introduction to Methods”, OUP 2010.
- Sekihara & Nagarajan: “Adaptive Spatial Filters For Electromagnetic Brain Imaging”. Springer 2008.
- SJ Luck: “An Introduction to The Event-Related Potential Technique”, MIT 2005.
- TC Handy: “Event-Related Potentials”, MIT 2004.
- <http://imaging.mrc-cbu.cam.ac.uk/meg/IntroEEGMEG>

## Guidelines for MEG and EEG research:

- Gross et al., “Good practice for conducting and reporting MEG research.“, Neuroimage 2013.
- Picton et al., “Guidelines for using human event-related potentials to study cognition: recording standards and publication criteria.“, Psychophysiology 2000.

## Demos of some open software packages:

<https://www.frontiersin.org/research-topics/5158/from-raw-megeeg-to-publication-how-to-perform-megeeg-group-analysis-with-free-academic-software>

Plus software tutorials, online talks, etc. etc.

Plus specialised papers etc. etc.

# A Brief History Of Bioelectromagnetism

## Ancient Egypt, 2750 BC:

Electric Fish (“Thunderer of the Nile”)  
Some Roman writers mention electric shocks as an ailment for headaches (~ 0 AC)...



## Ancient Greece, 600 BC:

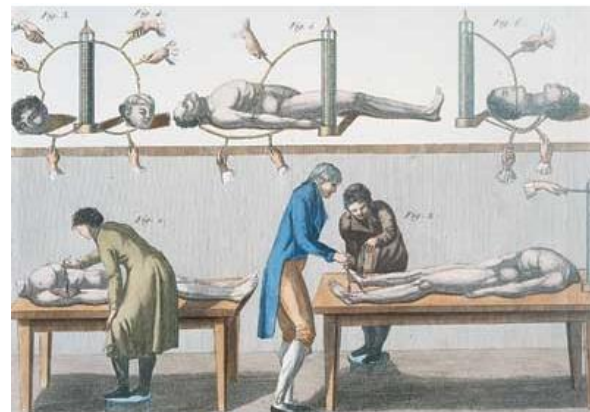
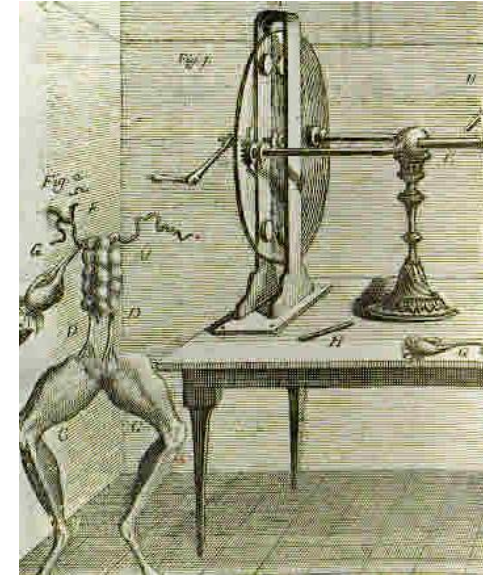
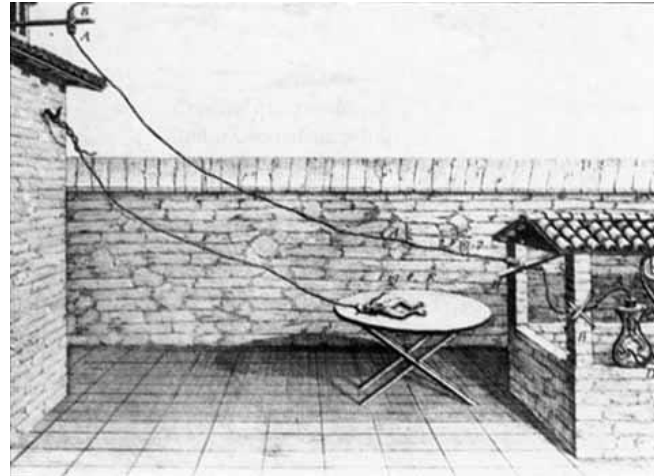
Thales describes static electricity  
“electron”





# Early Science

1771  
Luigi Galvani, Bologna  
“animal electricity”



In 1803:

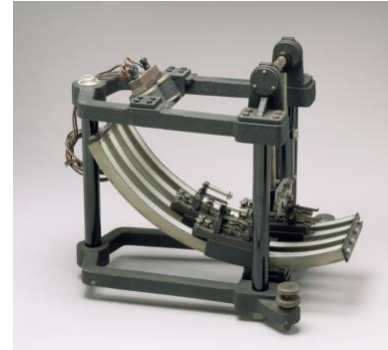
“On the first application of the process to the face, the jaws of the deceased criminal began to quiver, and the adjoining muscles were horribly contorted, and one eye was actually opened. ...

Mr Pass, the beadle of the Surgeons’ Company, who was officially present during this experiment, was so alarmed that he died of fright soon after his return home.”

<http://www.executedtoday.com/2009/01/18/1803-george-foster-giovanni-aldini-galvanic-reanimation/>

# Early Electrophysiology

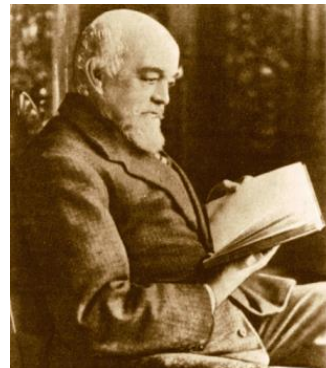
1842: Du Bois-Reymond, Berlin  
nerve action potentials neurons



1852: Helmholtz, Berlin  
speed of action potentials in frogs neurons



1875: Richard Caton, Liverpool  
first "ECoG" from animals



# Early EEG

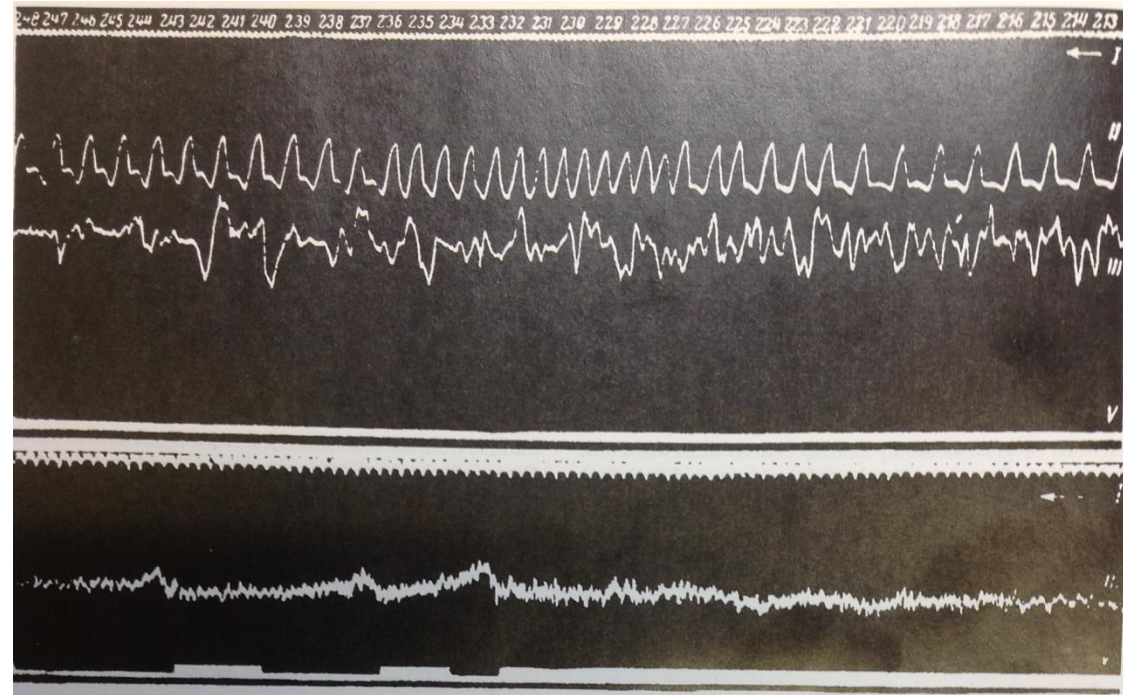
Time marker

Artery pulsation

Brain potential

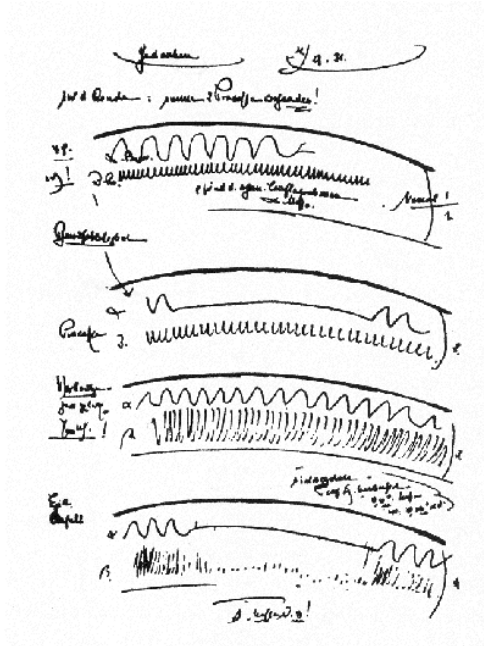
Response to sciatic nerve stimulation

Stimulation signal

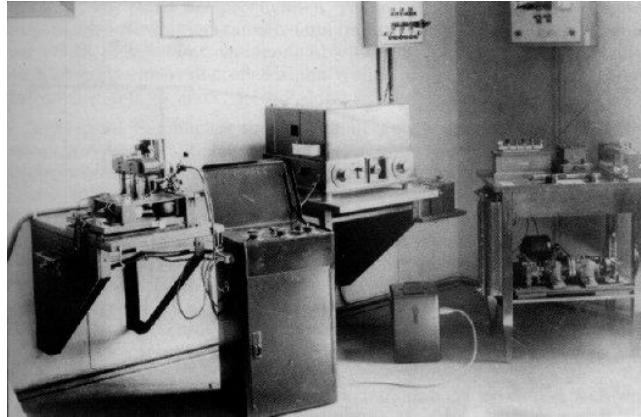


Pravdich-Neminsky, 1913

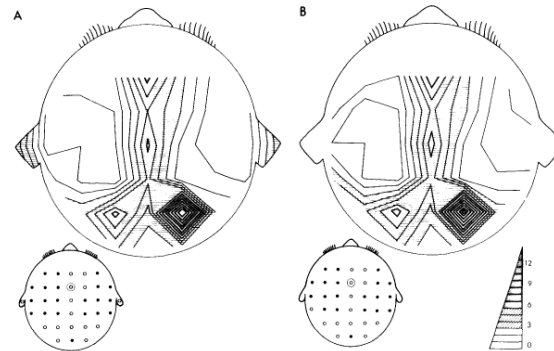
# Early EEG



Hans Berger, Jena 1924  
First Fourier Analysis of EEG: Berger&Dietsch 1931



1969/70: 32/48-channel EEG, "generators"



Lehmann, 1971

# Early ERPs

**A summation technique for detecting small signals in a large irregular background.** By G. D. DAWSON. *Neurological Research Unit, Medical Research Council, National Hospital, Queen Square, London, W.C. 1*

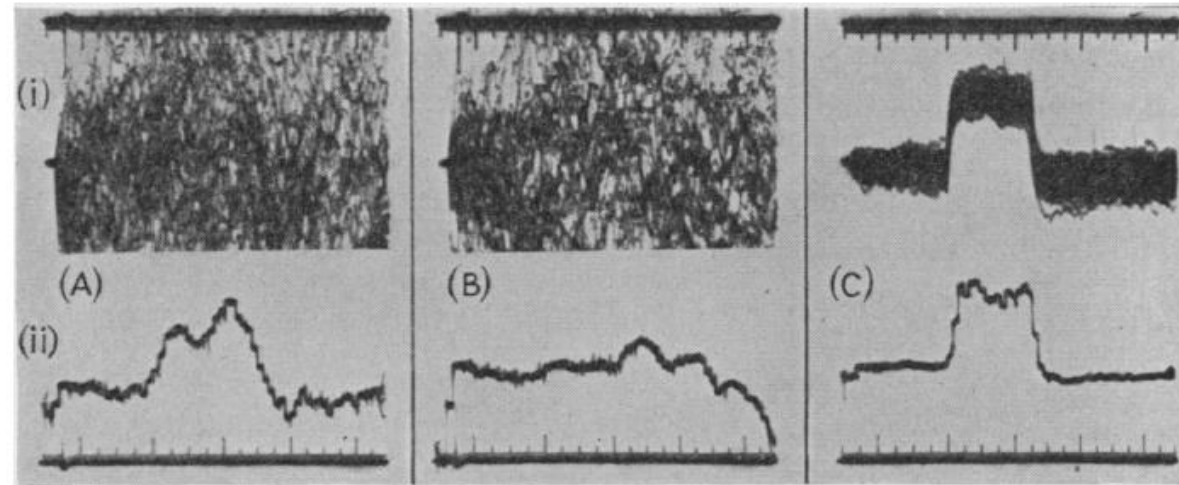


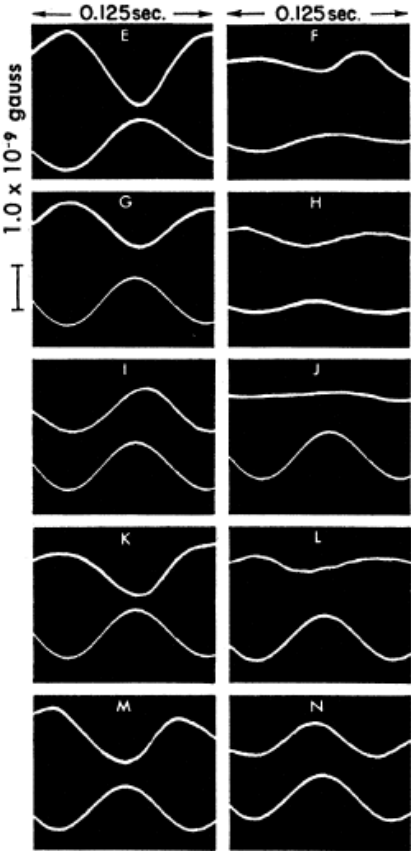
Fig. 1. An experiment to detect cerebral responses when the left ulnar nerve was stimulated at the wrist once per second. The upper line of traces shows sets of 55 records superimposed and the lower line the averages of these given by the machine. In A, from the contralateral scalp, there was one electrode on the midline and one over the right central sulcus. In B, from the ipsilateral scalp, the record was taken from the same midline electrode and one over the left central sulcus. In C is shown the result of making the electrode over the central sulcus positive to that on the midline by  $5 \mu\text{V}$ . The largest spikes in the time scales show intervals of 20 msec., and the stimulus was applied 5 msec. after the start of each sweep.

# First MEG: Pre-SQUID age

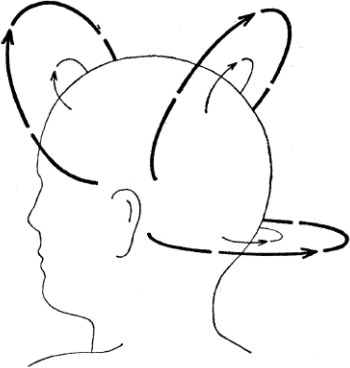
MEG pioneers MIT



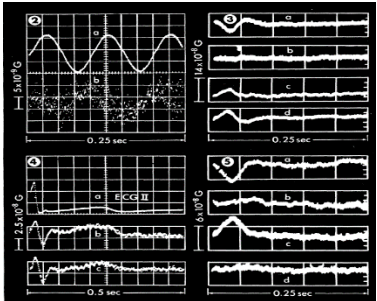
MEG, 1968



Alpha Rhythm



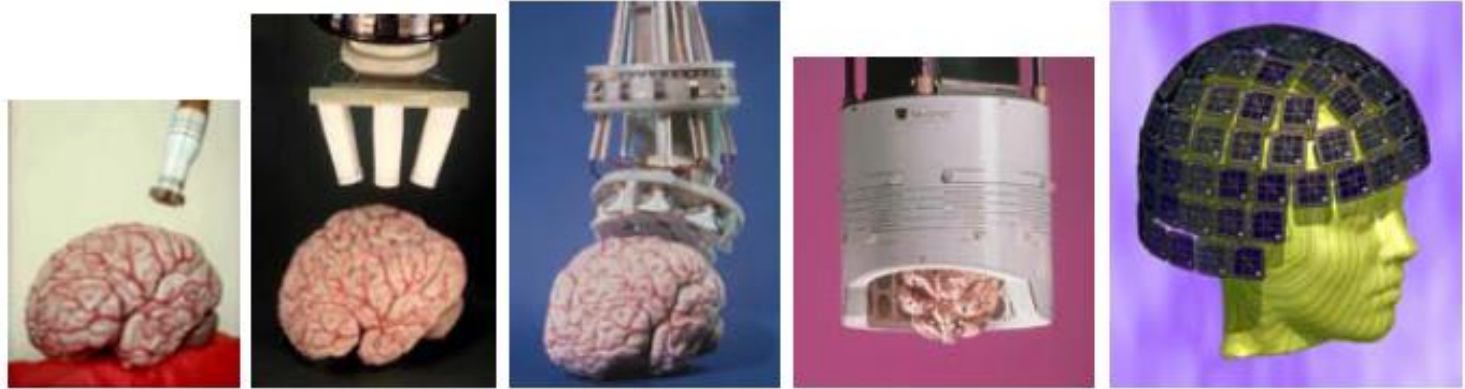
MCG, 1967/(63)



Cohen, Science 1967

Cohen, Science 1968

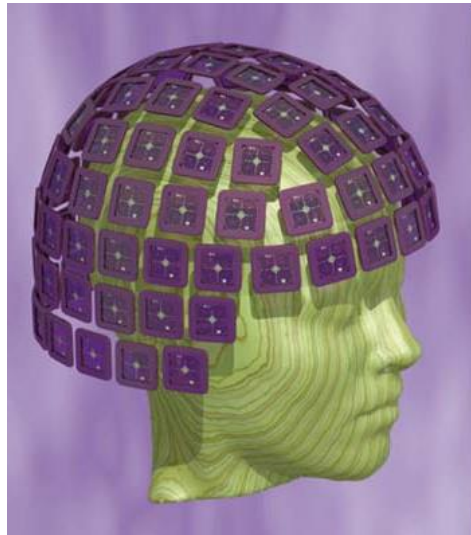
# The Fast Evolution of MEG



|                                |                                 |                                  |                                   |                                   |
|--------------------------------|---------------------------------|----------------------------------|-----------------------------------|-----------------------------------|
| 1983                           | 1986                            | 1989                             | 1991                              | 1997                              |
| by HUT                         | by HUT                          | by HUT                           | by Neuromag                       | by Neuromag                       |
| 4 channels                     | 7 channels                      | 24 channels                      | 122 channels                      | 306 channels                      |
| 30 mm in diameter              | 93 mm in diameter               | 125 mm in diameter               | whole head                        | whole head                        |
| (coverage: 7 cm <sup>2</sup> ) | (coverage: 68 cm <sup>2</sup> ) | (coverage: 123 cm <sup>2</sup> ) | (coverage: 1100 cm <sup>2</sup> ) | (coverage: 1220 cm <sup>2</sup> ) |
| Axial                          | Axial                           | Planar                           | Planar                            | Planar & Magnetometers            |
|                                |                                 |                                  | 12 Deliveries                     |                                   |

# MEG – The Present

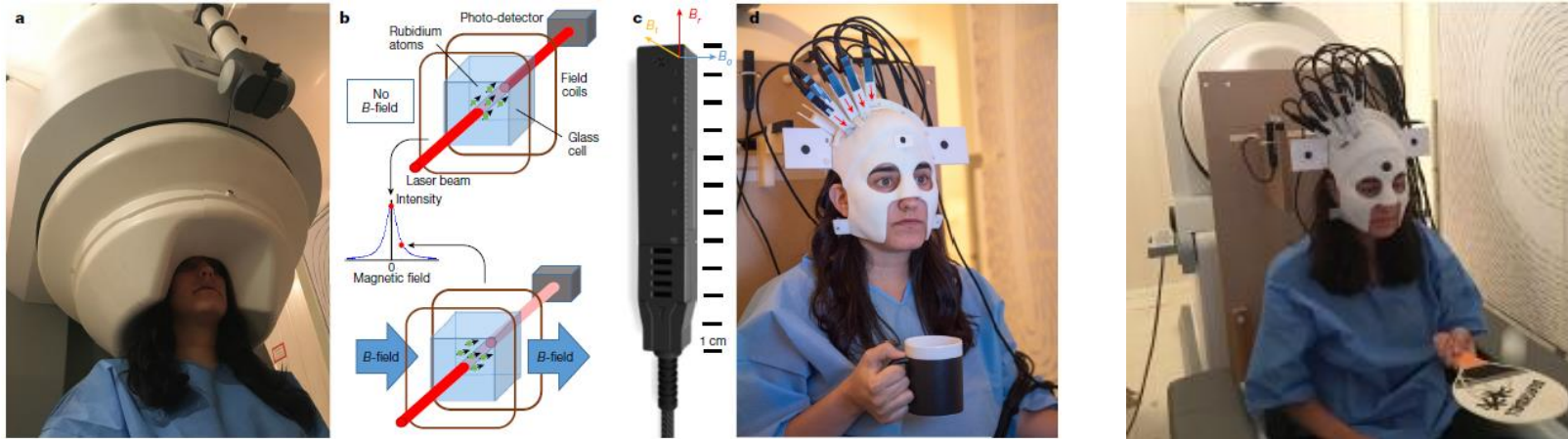
e.g. MEGIN Triux System  
306 MEG sensors (102 magnetometers, 204 gradiometers)  
64 EEG electrodes



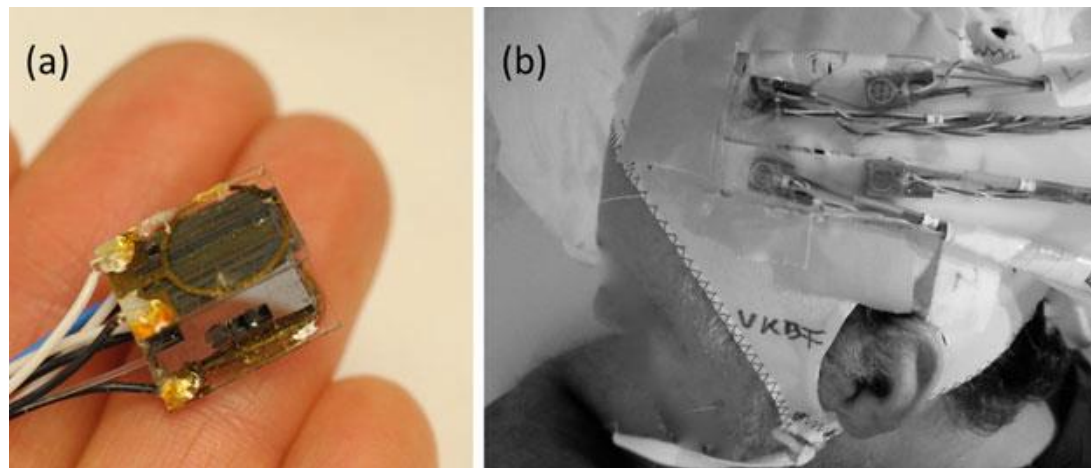


# MEG – The (Near) Future

## On-Scalp Optically Pumped Magnetometers



<https://twitter.com/wellcometrust/status/976534659436703744> Boto et al., Nature 2018

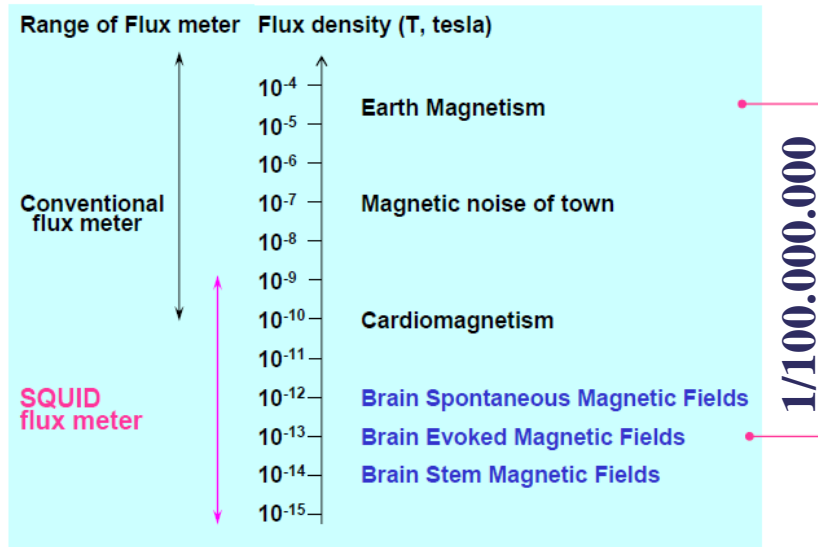


Knappe, Sander, Trahms, chapter in "Magnetoencephalography" by Supek & Aine (eds)

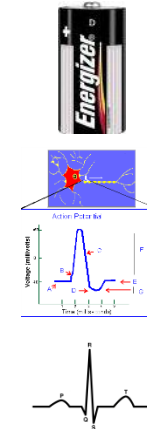
# The Measurement Of EEG/MEG Signals

# What EEG/MEG Are Measuring

## Magnetoencephalography (MEG)



## Electroencephalography (EEG)



Household Batteries  
~ 1-12 V

Cell Membrane Potentials  
~ 70 mV

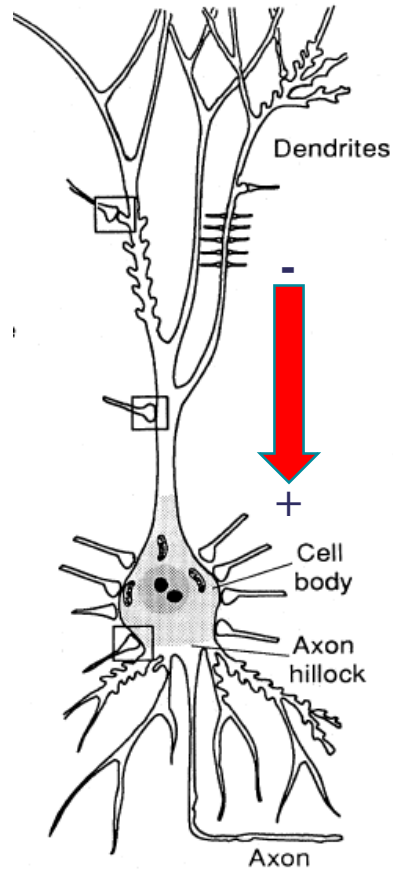
ECG:  
~ 1mV

Raw EEG: ~ 30  $\mu$ V  
Eye blinks: > 100  $\mu$ V

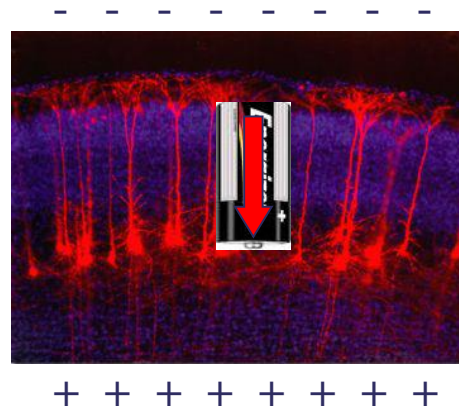
ERPs: ~ 0-10  $\mu$ V



# Main Generators of Electrical Activity in the Brain



- **Apical dendrites of pyramidal cells**
- **NOT action potentials** (too short-lived and quadrupolar)
- **EEG/MEG: same generators, different sensitivity**



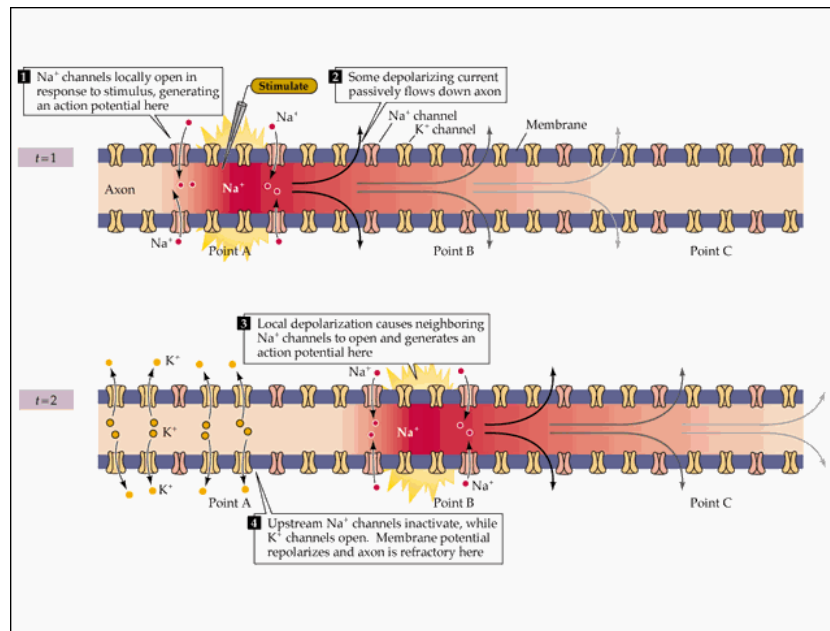
Dipolar currents

- ~ 1 Million synapses needed to activate simultaneously
  - Luckily: ~10000 cells per  $\text{mm}^2$ , ~ 1000 synapses per cell
- => several  $\text{mm}^2$  can produce measurable signal

# EEG/MEG Are Mostly Insensitive To Action Potentials

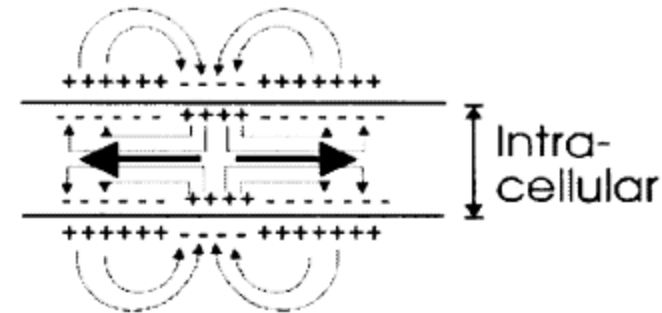
Action potentials are caused by active cellular mechanisms,  
not passive “Ohmic” currents.

(Very different speeds)



<http://www.arts.uwaterloo.ca/~bflaming/psych261/lec4se21.htm>

Action potentials are quadropolar



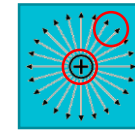
**Figure 1.1:** Schematic representation of an action potential  
Wieringa thesis, <http://www.medcat.nl/megeeg/chap1.htm>

Currents due to action potentials are very short-lived and asynchronous as well as “quadropolar” (i.e. two opposing dipoles).

# The Physics of EEG/MEG: Quasi-Static Approximations of Maxwell's Equations

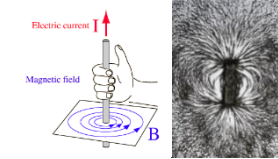
- The summed electric flux around a close surface is proportional to the total electric charge enclosed within this surface (Gauss's Law)

$$\nabla \cdot \mathbf{E} = \frac{\rho}{\epsilon_0} = 0 \text{ (for dipoles)}$$



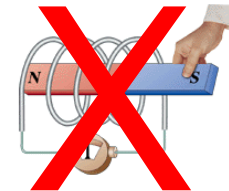
- Magnetic field lines are closed (Gauss's Law for magnetism)

$$\nabla \cdot \mathbf{B} = 0$$



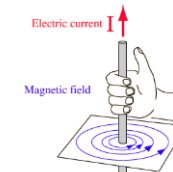
- We do not consider any inductive effects (Faraday's Law):

$$\nabla \times \mathbf{E} = 0$$



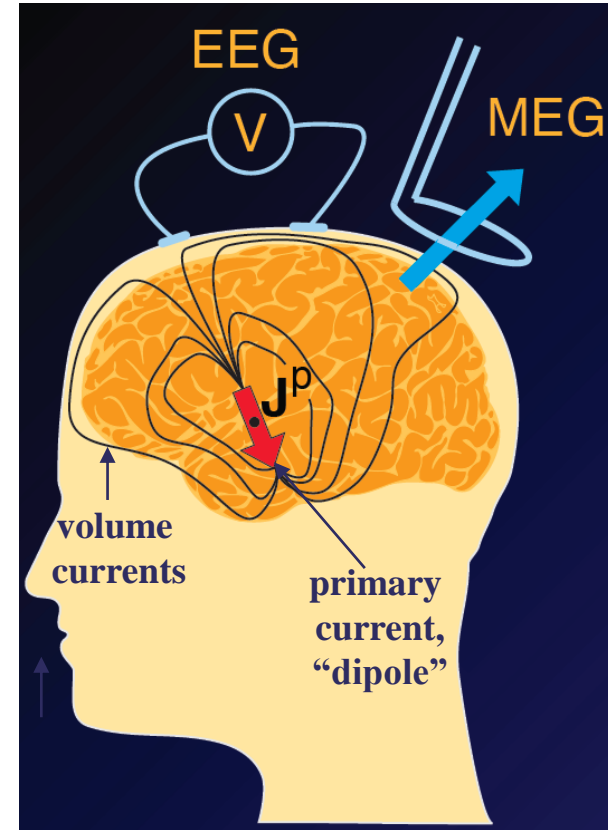
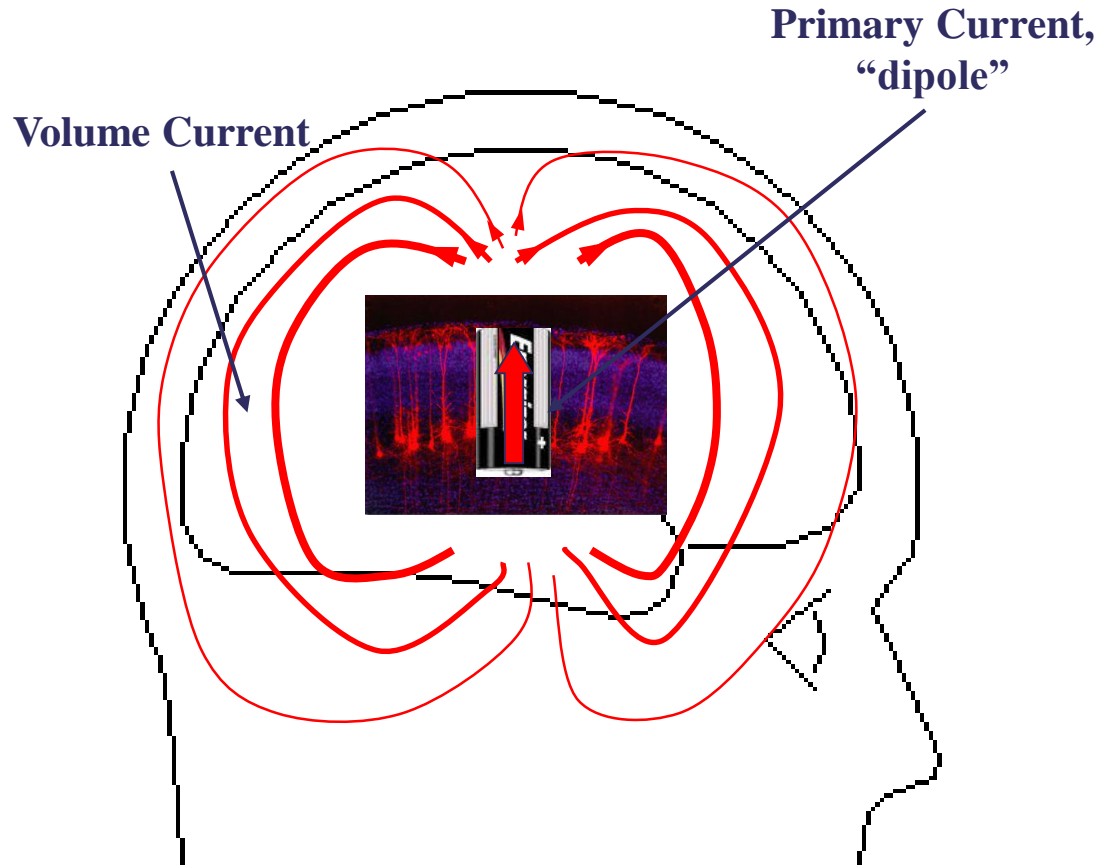
- Magnetic fields are only caused by static currents (Ampere's Law):

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{J}$$



**The relationship between EEG/MEG measurements and their brain sources is instantaneous (no “waves”).**

# Current Flow in the Head



<http://www.nmr.mgh.harvard.edu/meg/pdfs/talks/>

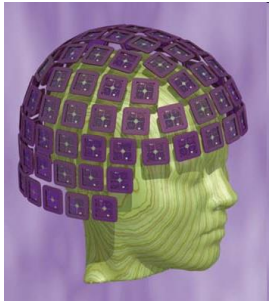
All effects are instantaneous.  
Volume currents affect both EEG and MEG –  
but EEG more than MEG

# Different Sensors and their Sensitivities (Leadfields)

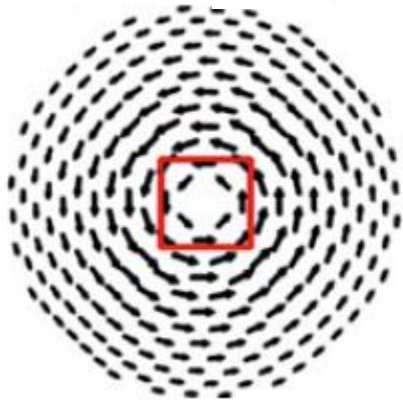
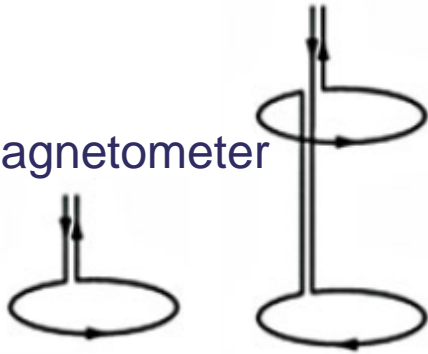
Leadfields are “sensitivity profiles” of individual sensors.

Each sensor is maximally sensitive to sources oriented along the arrows, and insensitive to sources perpendicular to the arrows.

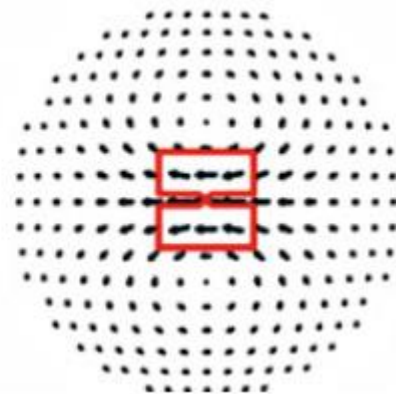
Axial Gradiometer



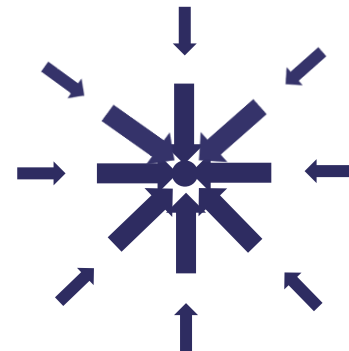
Magnetometer



Planar Gradiometer(s)



EEG Electrode





# The MEGIN Triux Neo System At CBU

306 channels in 102 locations

1 magnetometer and 2 planar gradiometers at each location

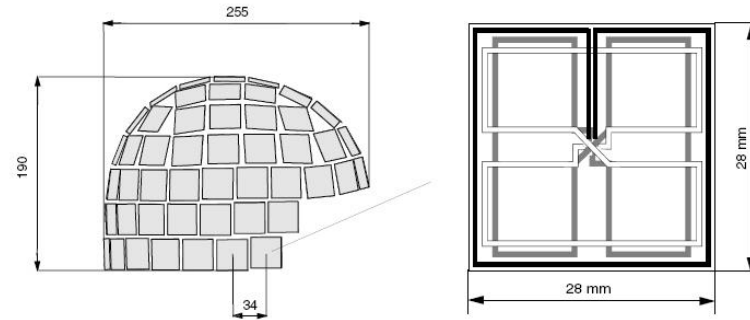
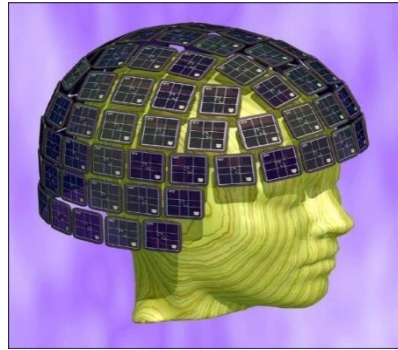
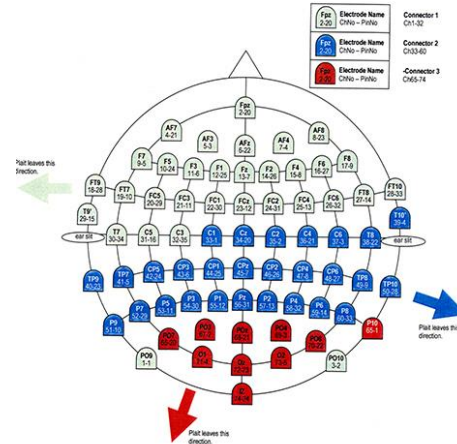
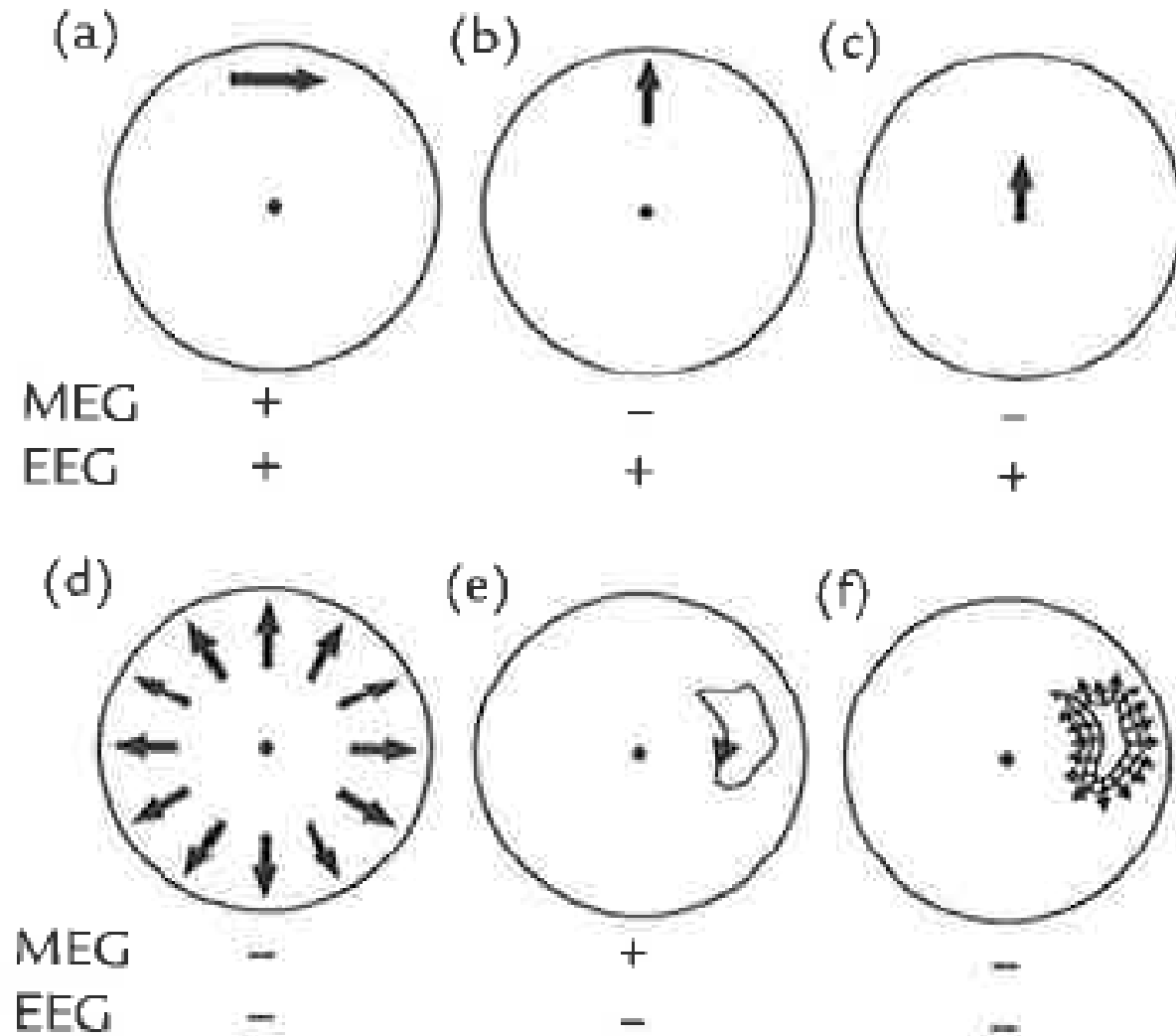


Figure 1.6. (left) Detector array, side view. Average distance between sensor elements : 34,6 mm. (right) Triple sensor detector unit.

64 EEG electrodes  
(plus EOG/ECG)



# EEG and MEG Are Differentially Sensitive To Radial and Tangential Sources



MEG is relatively insensitive to radial currents, and therefore also to deep currents.

Some complex source distributions may not produce EEG or MEG signals.





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**Thank you**