Recording and low-level processing of electrical brain activity

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BioComp 2019, Lille, May 13-15

why do we develop brain–computer interfaces?

talk outline

neuroprosthesis vs. brain–computer interface

neuroprosthesis

- prosthesis aiming at palliation of a sensory disability
  sensor → processing → electrical stimulation of nerve endings
  requires surgery (usually reversible)
- auditory neuroprosthesis: cochlear implant
  microphone → selective amplification → stimulation of auditory nerves
- visual neuroprosthesis
  camera → image → stimulation of retinal ganglion cells
  February 2014: FDA and CE agreements to the « Argus 2 » visual neuroprosthesis

brain–computer interface

a direct brain-computer interface is a device that provides the brain with a new, non-muscular communication and control channel (Wolpaw, 2002)

BCI timeline

- 1929 - electroencephalogram (Berger)
- 1965 - discovery of cognitive evoked potentials (Desmedt & Sutton)
- 1973 - brain–computer interface concept (Vidal)
- 1988 - first BCI using evoked potentials (Farwell & Donchin)
- 1991 - first BCI allowing a continuous 1D cursor control (Wolpaw)
- 2004 - 2D electrode matrix implanted in the motor cortex (BrainGate & Donoghue)
- 2013 - brain-to-brain interface between two rats (Nicolelis)
- 2015 - exoskeleton for persons with tetraplegia, Wimagine implant (Benabid)

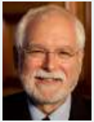

Berger


Desmedt


Vidal


Donchin


Wolpaw


Donoghue


Nicolelis


Benabid

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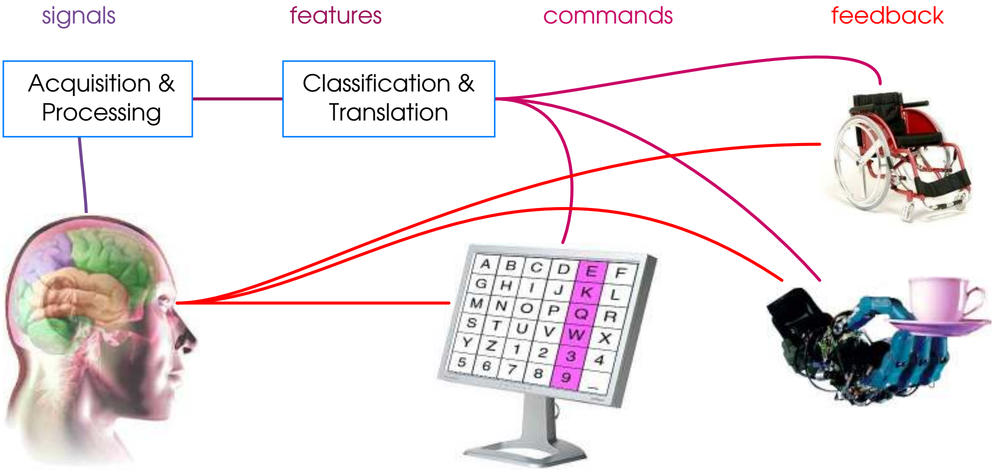
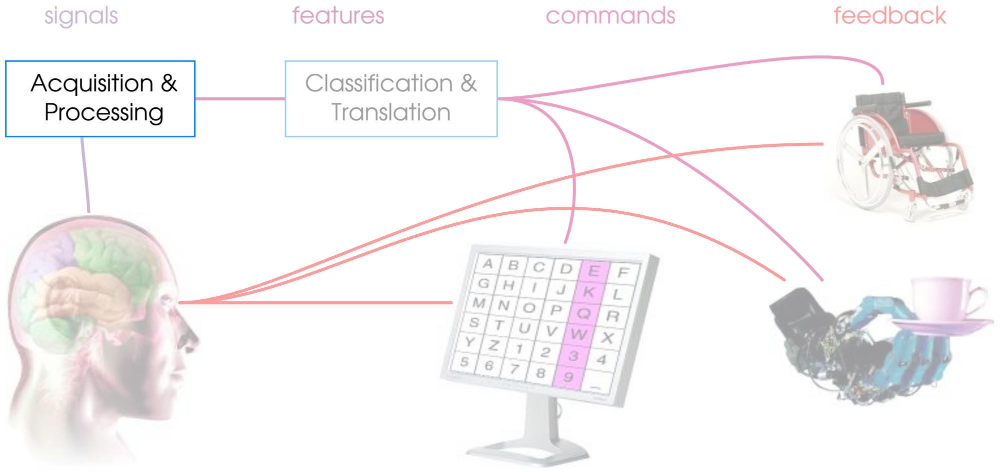
how does it work?



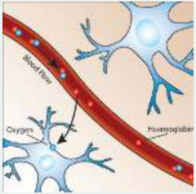
today's focus



measuring brain activity

metabolic or electrical activity

- blood flow and characteristics depends on the activity of neurons and other brain cells
- blood oxygenation level dependent (BOLD) imaging: fMRI
- oxy or deoxy-hemoglobin modifies near infrared spectrum properties: fNIRS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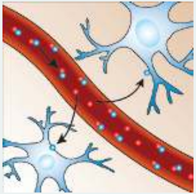
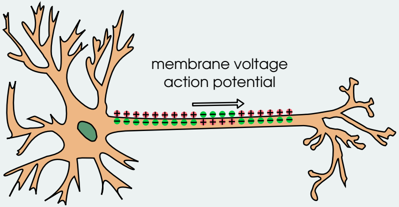
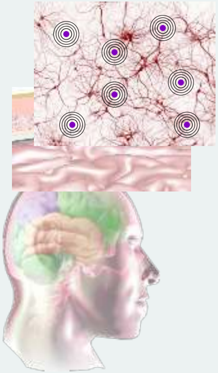

activated

- electrical activities of single neurons or of neural networks varies with brain state
- single unit (neuron) activity: recording ionic currents with patch-clamps
- short or long distance influence of electrical activity: extracellular recordings

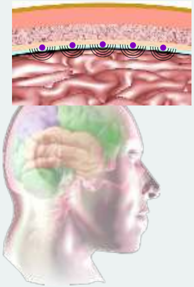


measuring brain electrical activity

extracellular recording

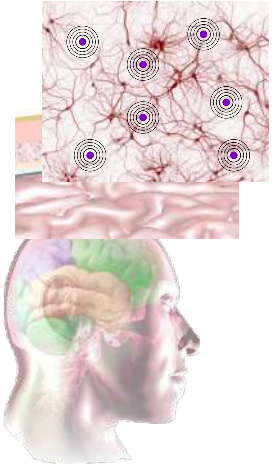


electro-corticography



electro-encephalography

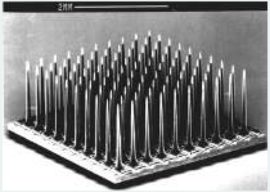
invasive intra-cranial recording (1/2)



implanted electrodes

single electrode or grid of electrodes implanted into the cortex

- excellent spatial resolution, single neuron or groups of limited size
- highly invasive approach, very delicate surgery
- correct stability, accurate recording during several months



“Utah” grid

integrated amplifiers

invasive intra-cranial recording (2/2)

ECoG: Electro-CorticoGram

grid of electrodes over/under the dura mater

- average spatial resolution, a few millimeters
- invasive approach, but relatively "simple" surgery
- excellent stability, accurate recordings during several years

sub-dural grid

non-invasive recording: EEG

EEG: Electro-EncephaloGram

set of electrodes over the scalp

- poor spatial resolution, a few centimeters
- non-invasive approach, a priori no risk
- limited recording duration, a few hours at the maximum

high-resolution EEG

Unicorn headset

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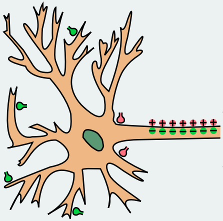
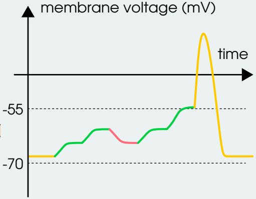
neurons: elementary sources

where does the voltage come from?

synaptic potentials

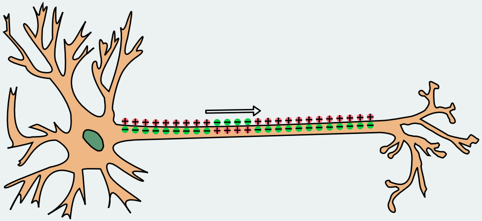
- voltage difference across the membrane of a post-synaptic neuron
- increases after action of excitatory synapses and decreases after action of inhibitory synapses





action potential (or spike, or nerve impulse)

- change of polarity across the membrane of the neuron axon that propagates down from the cell body
- very fast variation (1~2 ms)



basic model of local field potential

single electrode and single neuron

- the neuron generates a transmembrane current $I(t)$ that propagates in the brain matter
- the brain matter is considered isotropic and purely resistive, with conductivity σ
- the distance between the current source $I(t)$ and the electrode is d

then the voltage $V(t)$ measured by the electrode is given by: $V(t) = \frac{1}{4\pi\sigma}\frac{I(t)}{d}$

single electrode and multiple neurons

- neuron number k generates a transmembrane current $I_k(t)$
- the distance between current source $I_k(t)$ and the electrode is d_k

$$V(t) = \sum_{k=1}^{n} \frac{1}{4\pi\sigma}\frac{I_k(t)}{d_k}$$

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more realistic models

brain matter

- in fact σ varies with frequency and the brain matter acts like a low pass filter
- the power spectrum of signals has a $1/f$ shape at low frequencies and $1/f^3$ at high frequencies
- many models have been proposed to explain this behavior, but this is beyond the scope of this talk

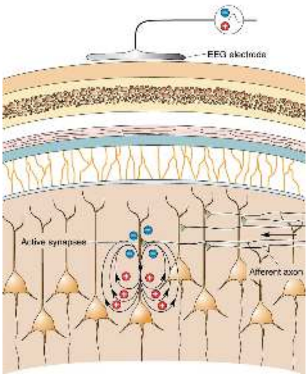
spikes vs. local field potential

in practice:

- current sources nearby the recording electrode produce a voltage with a time course similar to a pulse (spike) visible in the signal
- current sources far from the recording electrode produce an "average voltage" called local field potential (LFP).

but patterns appear in the LFP only when a significant number of sources have *correlated* activities (i.e. when neuron synaptic or post-synaptic potential variations are synchronized)

surface electro-encephalography (EEG)



Bear *et al.*, Neuroscience: Exploring the Brain

complex model

- surface EEG: combination of postsynaptic potentials of a very large number of cortical neurons (pyramidal cells) forming a group called macro-column (at least 10^5 neurons)
- the low-pass effect of brain matter, cerebrospinal fluid, dura mater, skull bone and finally skin, is extremely strong. Only low-frequency components can be recorded
- many noise sources can decrease the quality of EEG signals, but mainly electromagnetic noise and muscular activity (artifacts) are considered in general
- measurement quality also depends on the contact impedance of electrodes

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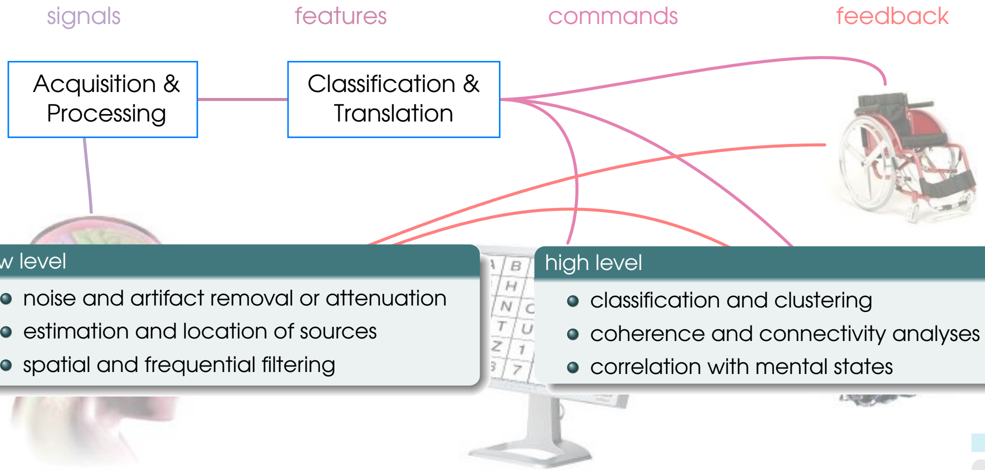
processing levels



low level

- noise and artifact removal or attenuation
- estimation and location of sources
- spatial and frequential filtering

high level

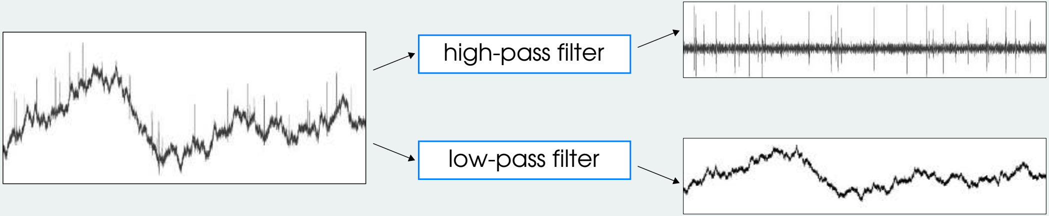
- classification and clustering
- coherence and connectivity analyses
- correlation with mental states

spikes and local field potential (LFP)

two different processing chains

simple assumption already mentioned: recorded signal is a combination of LFP in "low" frequencies and spikes in "high" frequencies

- low-pass filtering removes spikes and yields the LFP signal
- high-pass filtering removes LFP and yields the "spike train" signal



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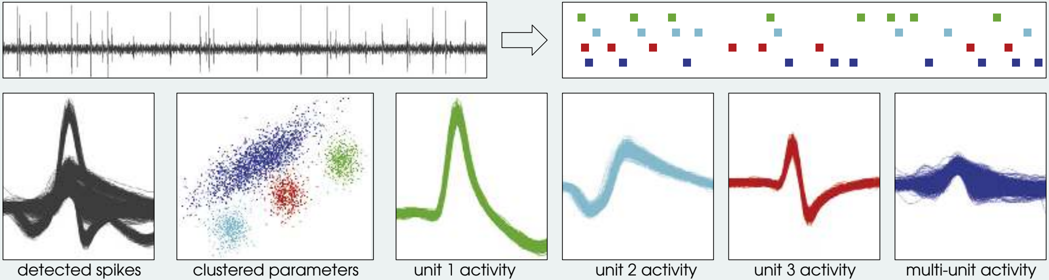
estimation of spike sources: “spike sorting”

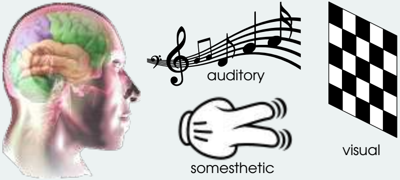
- assumption: each neuron brings a specific contribution to the composite measured voltage
- different parameters: distance, axon shape, myelin sheath shape and thickness, etc.
- result: spike “shapes” are different for different neurons: allows estimating single neuron activities
- alternate model: a third category of contribution is considered called “multi-unit activity”



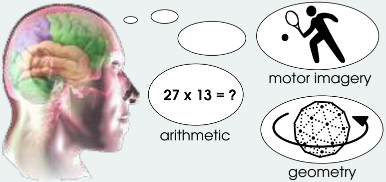
processing LFP and EEG signals

evoked vs. ongoing activity

- a specific brain activity is evoked by an external stimulus
- the "brain response" is supposed to be time-locked to the stimulus onset
- signal processing is generally performed in the original space and time domains

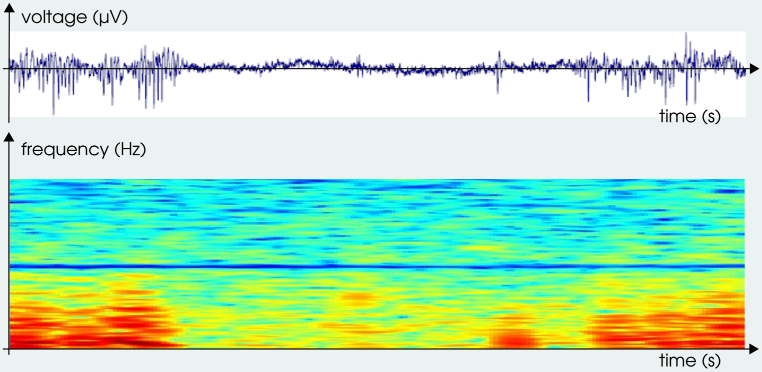


- brain activity is self-controlled or evoked by endogenous stimuli
- no time reference is available in the signals: time domain analysis is complex
- signal processing is performed in the frequency or spatio-frequency domains



example of LFP signal

- signal recorded in the primary motor cortex during hand movement



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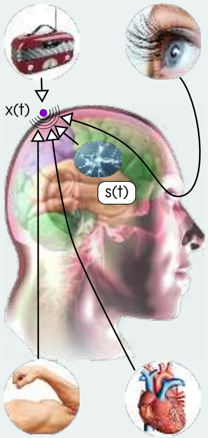
processing EEG signals



artifact removal

artifact sources:

- internal: eye movements, eye blinks, heart beats (EKG), electrical muscle activity (EMG)
- external or measurement related: electrode contact impedance, electro-magnetic noise, line (50 Hz)

additive direct model:

$$x(t) = \alpha s(t) + \sum_{j=1}^{J} \alpha_j n_k(t), \text{ where } n_j(t) \text{ is the } j^{th} \text{ artifact source}$$

solution of the inverse problem:

- for J artifact sources, record at least $J+1$ surface signals $s_i(t)$
- source “demixing” approach to estimate independent components, assuming that neural sources and artifact source are uncorrelated

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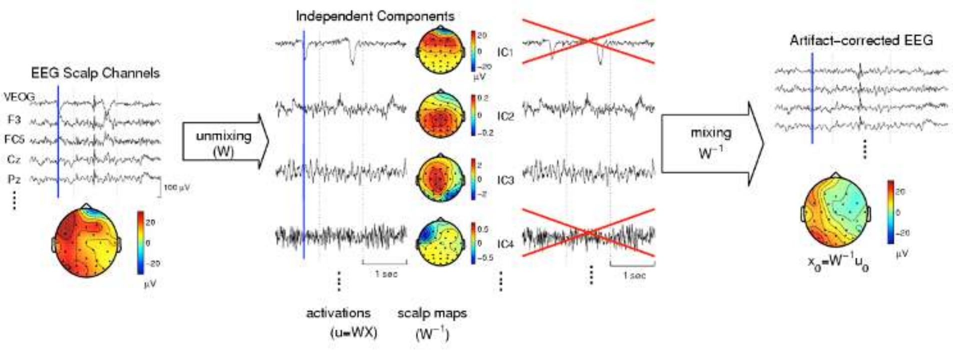
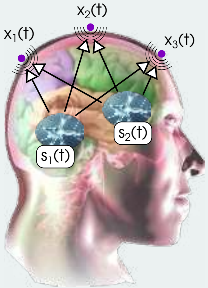
example of artifact removal on EEG signals

- EEG signals recorded on the scalp at various locations
- electro-oculogram recorded with an electrode on the upper eyelid



Institute of Engineering in Medicine (IEM), University of California, San Diego (UCSD)

processing EEG signals



estimating and locating sources

additive direct model, I measurements for J sources:

$$\text{for each } i \in (1 \cdots I),\ x_i(t) = \sum_{j=1}^{J} \alpha_{ij} s_j(t) + n_i(t)$$

$$\text{or } \mathbf{x}(t) = \mathbf{A}\mathbf{s}(t) + \mathbf{n}(t),\ \text{with}$$

$$\mathbf{x}(t) = (x_i(t)) \in \mathbb{R}^I,\ \mathbf{A} = (a_{ij}) \in \mathbb{R}^{I \times J},\ \mathbf{s}(t) = (s_j(t)) \in \mathbb{R}^J$$

many approaches to solving the ill-posed inverse problem:

- dipolar sources: estimate the positions and orientations of a small number of dipoles (ECD, MUSIC)
- distributed sources: estimate the amplitudes and orientations of dipoles on a grid (MNE, LORETA, sLORETA)

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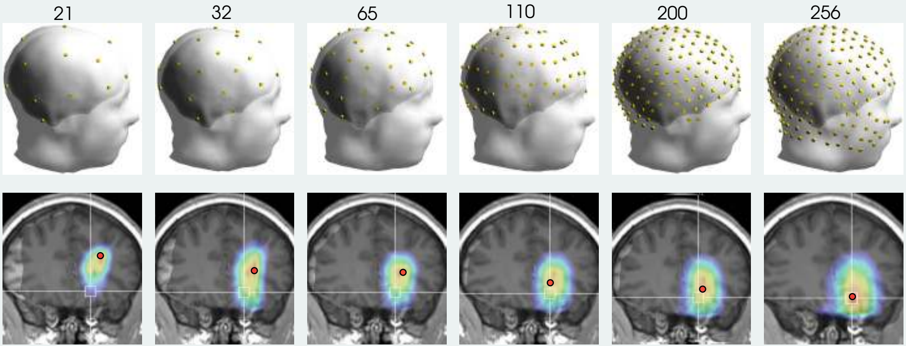
example of source localization on EEG signals

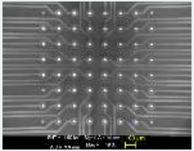
- high resolution (256) EEG signals, then different levels of subsampling to simulate lower resolution
- source localization with MUSIC (recursive multiple signal classification)



Isabelle Merlet, EEG source localization in epilepsy, 2018

increasing the number of channels and the information rate

bi-directional high-speed BCIs: closing the loop



diamond micro-electrodes

- many outputs from brain to actuators, ex: motion control with a large number of degrees of freedom
- many inputs from sensors to brain, ex: sensory feedback, proprioception, strength measurement
- bio-compatible implanted electrodes for recording as well as stimulating

signal processing challenge

- high speed processing: closer sources (ex: spikes) mean higher sampling and processing rates
- power consumption and power source: embedding processors in the recording or stimulating device is an issue

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