

# Brain Computer Interfaces

*Principles, Algorithms and Tools*

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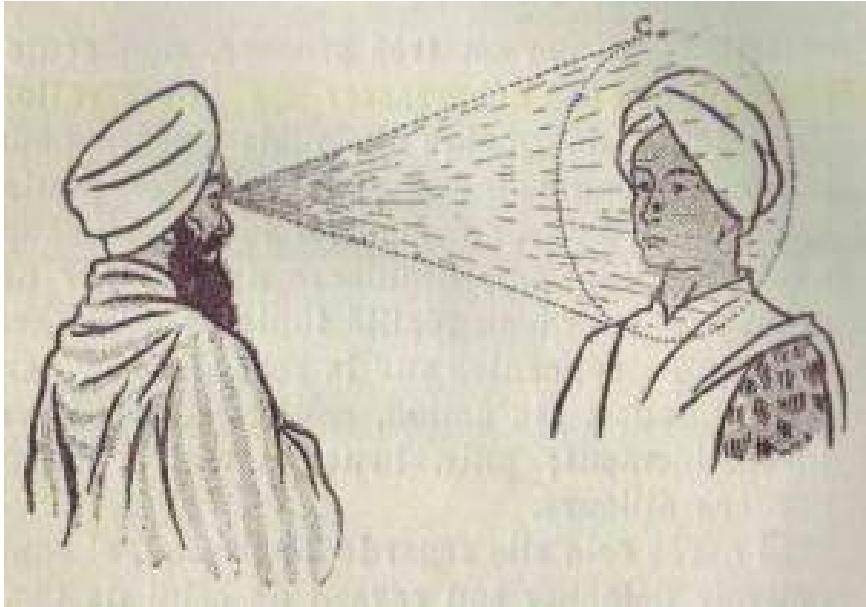
MSc DSAI

*Application of ML to MRI, electrophysiology and brain computer interfaces*

# Agenda

- A (very) brief historical perspective.
- What are Brain Computer Interfaces (BCI).
- Main principles.
- Study of some classical paradigms:
  - P300 speller.
  - Beta rebound.
  - Visually Evoked Potentials.
- Ethical issues.

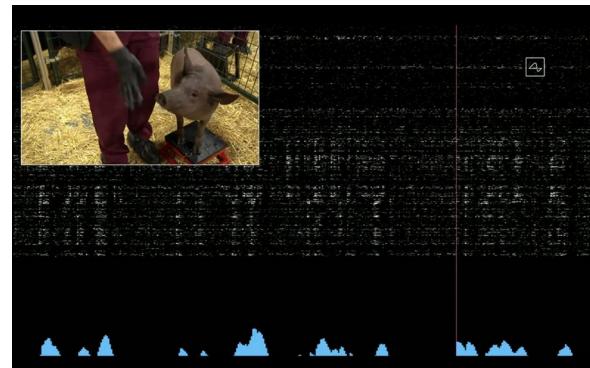
# An old fantasy of humanity...



**Magnetic encirclement**  
Hindu magnetic treaty ©ISI-CNV



*e-Mote fake advertisement – 2011.  
BBC real test in 2015.*



27/08/2020

# Game changers...

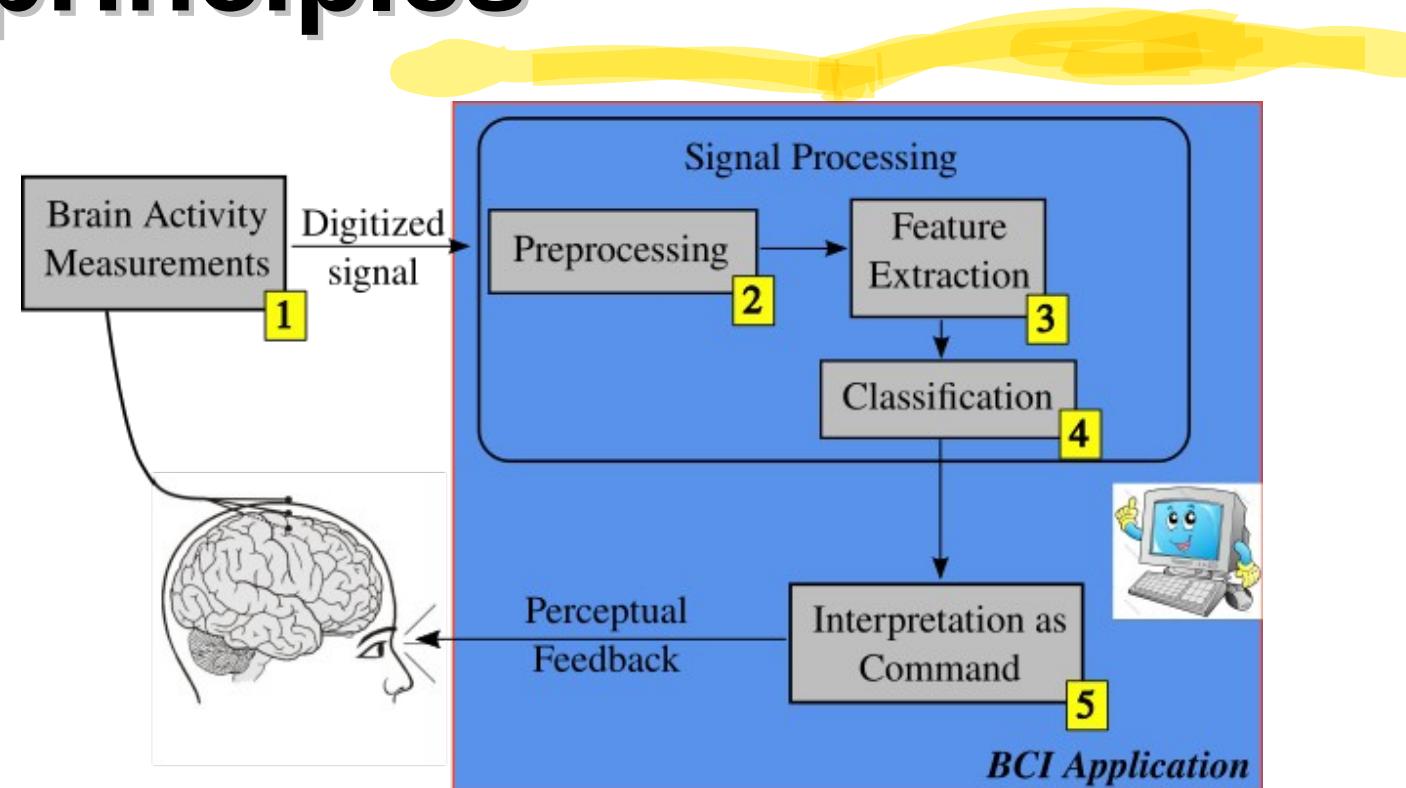
- Explosion of the techniques to measure the brain activity:  
EEG (1929), ECoG (early 1950s), MEG (1972), fMRI (1990), Optical Tomography (1993), ...  
→ Cognitive sciences: understanding of some brain processes.
- EEG biofeedback (1960-1970):
  - Voluntary control of brain rhythms ( $\alpha$  ,  $\mu$  ,  $\theta$ ).
  - Reduction of ictal activity.
  - 1973: **TOWARD DIRECT BRAIN-COMPUTER COMMUNICATION**

JACQUES J. VIDAL<sup>1</sup>

*Brain Research Institute,*

*University of California, Los Angeles, California*

# BCI: main principles

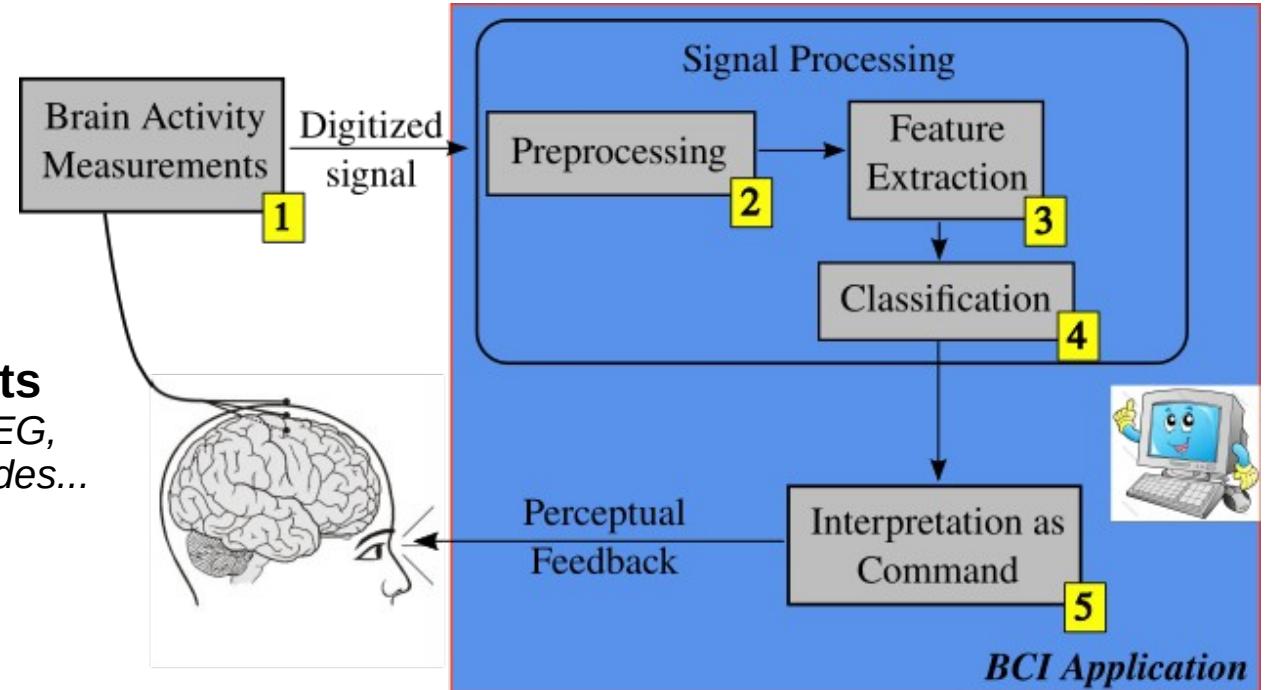


*A closed loop system between a subject (brain) and a computer (at least in principle...)*

# BCI: main principles

## 1 Brain Activity Measurements

Any non destructive type: *EEG, MEG, fMRI, ECoG, intra-cerebral electrodes...*

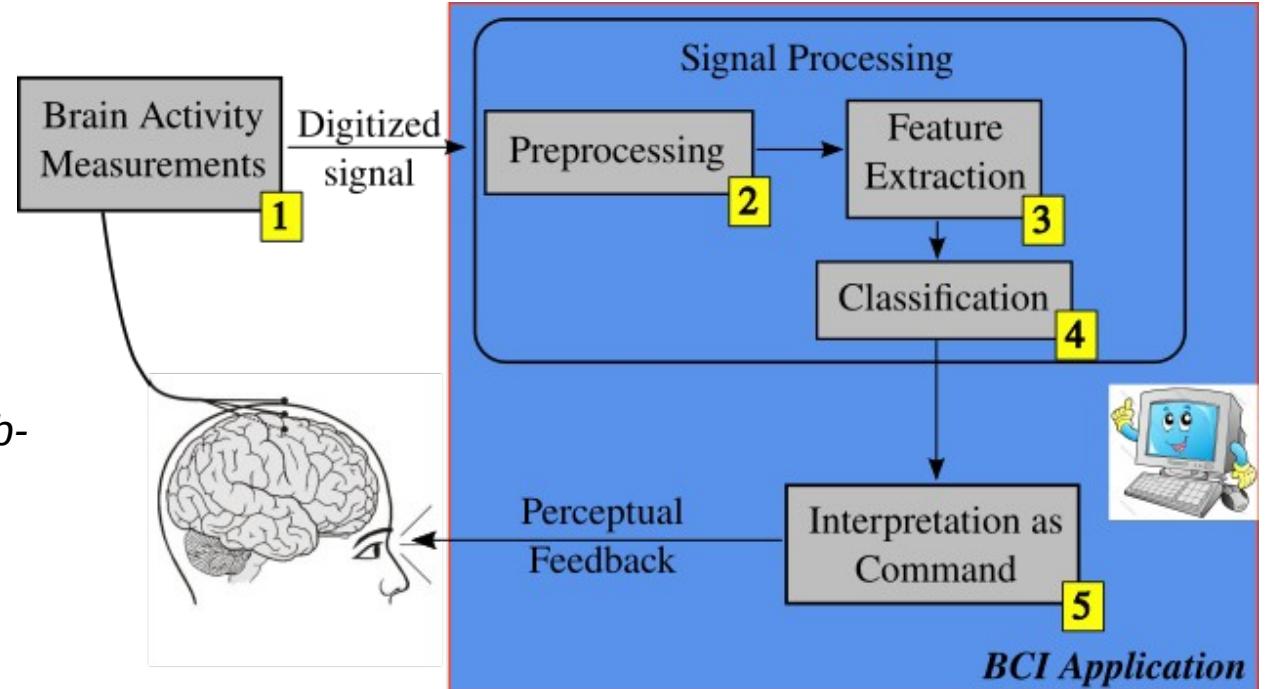


*A closed loop system between a subject (brain) and a computer (at least in principle...)*

# BCI: main principles

## 2 Preprocessing

Basic stuff: *channel selection, subsampling, filtering, ...*

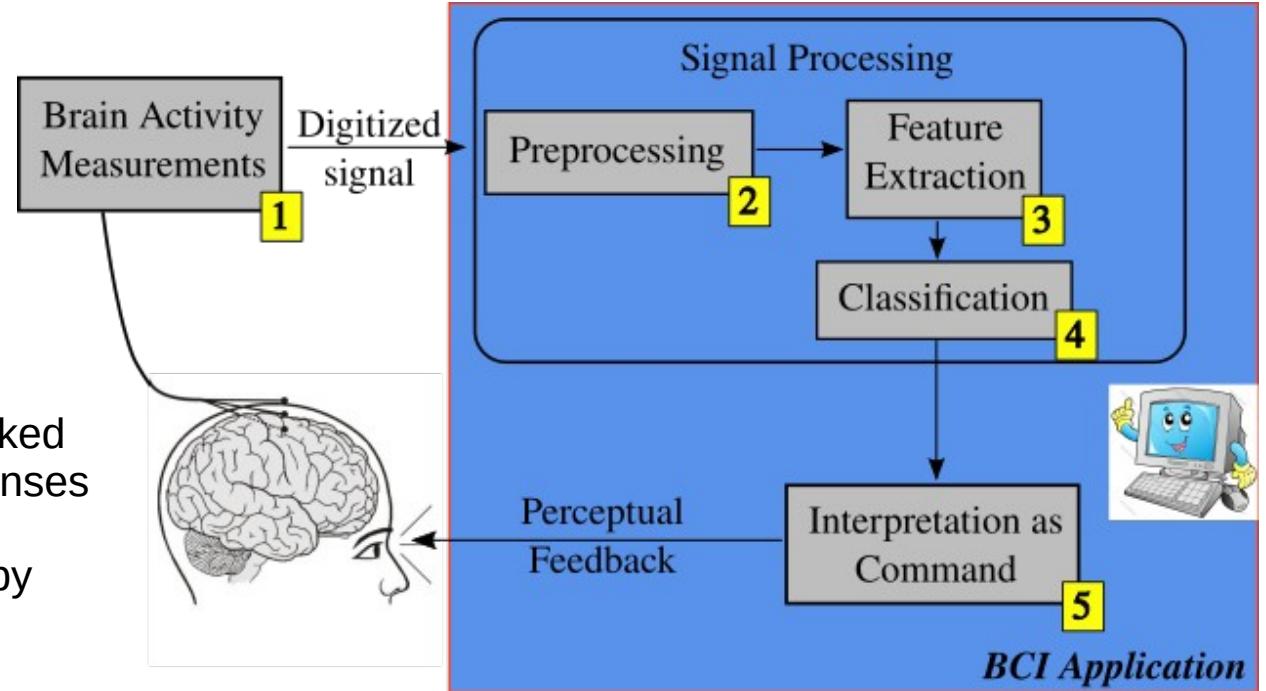


*A closed loop system between a subject (brain) and a computer (at least in principle...)*

# BCI: main principles

## 3 Feature Extraction

- Obtain a vector of numbers linked to neurological states or responses used by the system.
- User controlled or modulated by attention.

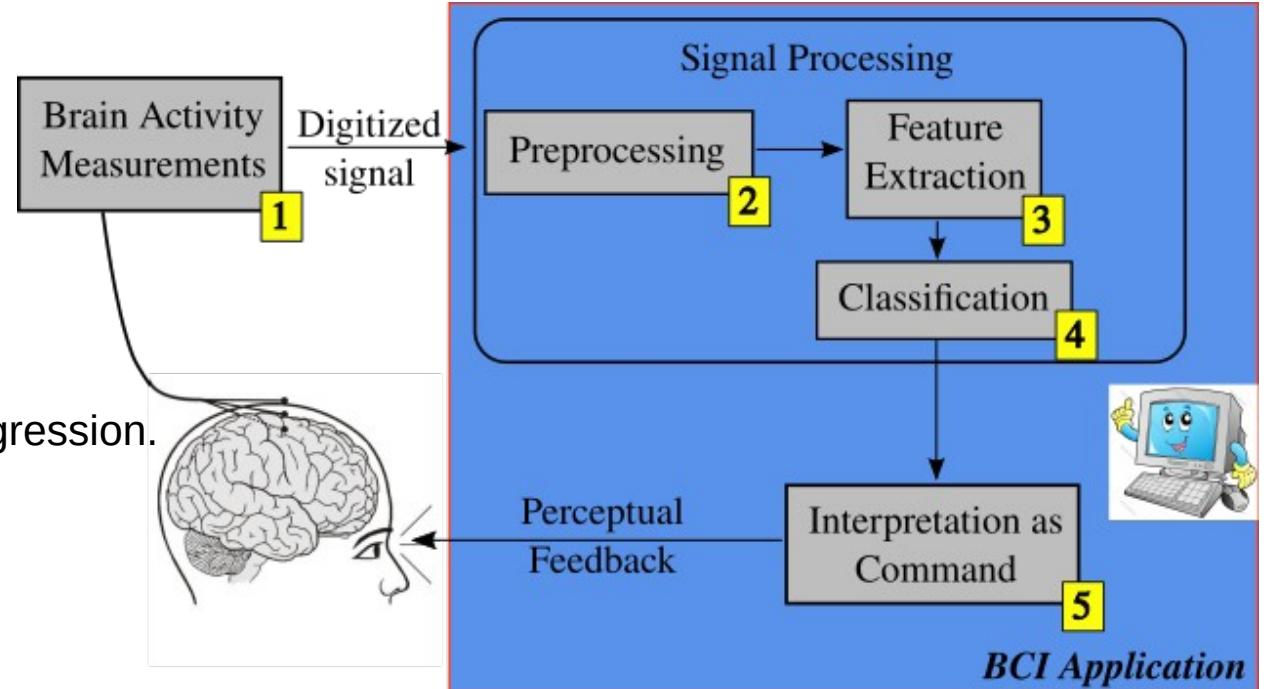


*A closed loop system between a subject (brain) and a computer (at least in principle...)*

# BCI: main principles

## 4 Classification

- Detection / Classification / Regression.
- Needs to be learnt.
- Training and testing phases.
- **Online** / Offline.

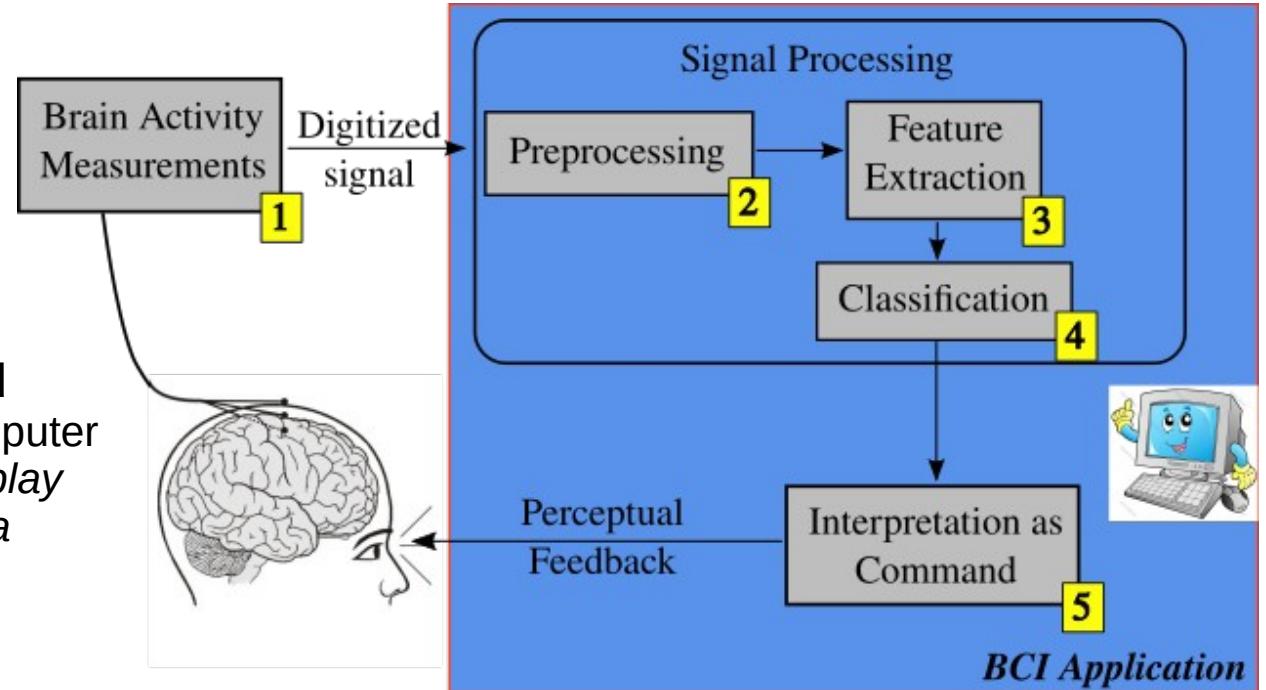


*A closed loop system between a subject (brain) and a computer (at least in principle...)*

# BCI: main principles

## 5 Interpretation as Command

The goal of the system. Any computer controlled action is possible: *display an image, play a sound, control a robot or an appliance, push an interface button, ...*



*A closed loop system between a subject (brain) and a computer (at least in principle...)*

# Activity types for BCI

- ✓ • Evoked or spontaneous.
- ✓ • Synchronous/Asynchronous (self-paced) protocols.
  - Visual, auditory, sensory, motor (real, imaginary or intentional), purely voluntary, mental states, high level.
  - Practical difficulties:
    - ▷ SNR
    - ▷ Variability:
      - For a same subject: intra / inter-session.
      - Inter-subjects.
    - ▷ Real time.

# Phenomenons

- VEP: Visual Evoked Potentials. Often Steady State SSVEP, but also CVEP.
- SCP: Slow Cortical Potentials.
- ERP: Event Related Potential, often P300. 
- ERD/S: Event Related (De)Synchronisation.
- MRP/LRP: Movement/Lateralized Readiness Potential.
- Self Controlled Brain Rhythms Modulation:  $\alpha$  waves...
- ERN: Error Related Negativity.
- VHFO: Very High Frequency Oscillations.

# Cerebral rhythms

- Delta (< 4 Hz): Deep sleep.
- Theta (4-7 Hz): Drowsiness.
- Alpha (8-16 Hz): State of diffuse awkeness.
- Mu (10-14 Hz): Motor rhythm.
- Beta (15-30 Hz): Normal activity state.
- Gamma (40 Hz): Perceptive link / Cognitive integration.

# Main challenges...

- Reliability and Limited communication capability.
- Real time processing.
- Training time and Human adaptation.
- Non invasive systems:

Noise, noise, noise...  
- Spatial resolution



Detectability / Accuracy / Speed.

- Invasive systems:

- Brain coverage / Number of electrodes.
- Tissue scars around electrodes.
- Costs (not only €, human).



Stability in time / High specificity.

# Main challenges...



- ✓ **Tedious Calibration**

- Search for features.
- Inter-subject + intra-session variability.

Technological

- ✓ **Low information transfert rate**

- Somewhat artificial applications.

Neurophysiological

- ✓ **Human learning needed for BCI use**

- Often time consuming.
- Fails for a fraction of the subjects  
(in particular for some sub-population like locked-in).

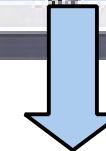
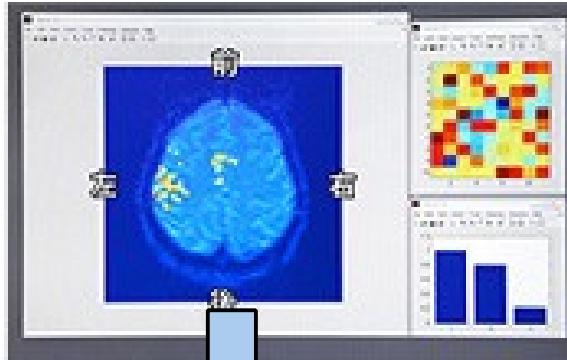
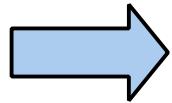
Ergonomics

# Example: *Roc-Paper-Scissors*

HRI (Honda) and ATR, May 2006.



Chi-Fou-Mi in fMRI



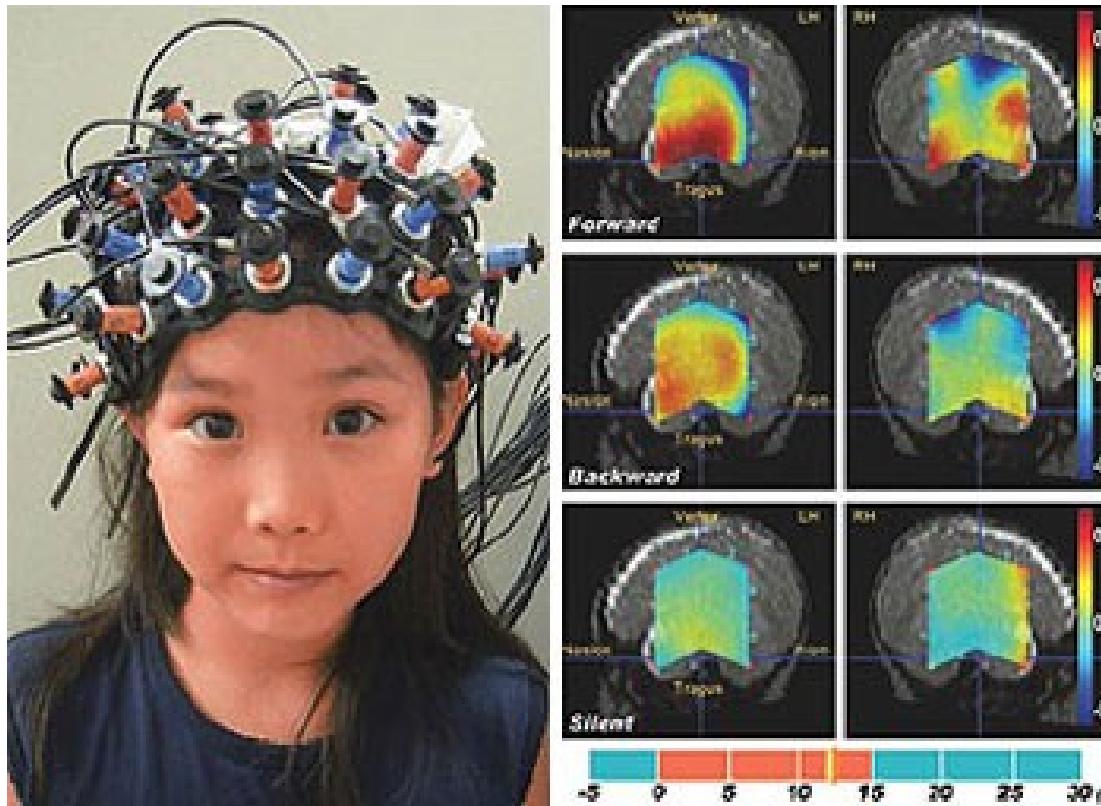
Robotic hand.



# Example: *On-Off Command*

Hitachi 2007 fNIRS

Start/Stop an electrical train.



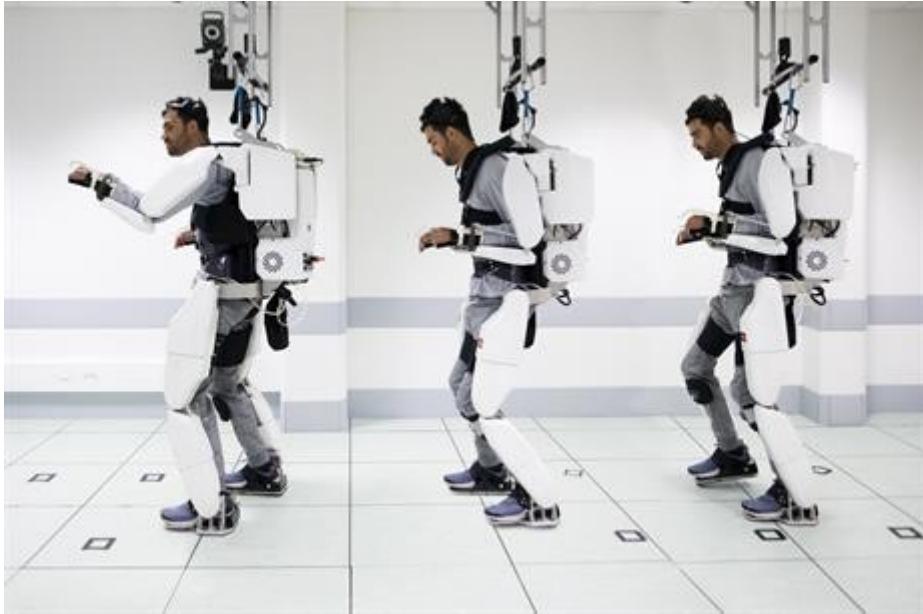
# Example: *Robotic dogs playing football*



EEG based  
Qinghua University  
June 2006

Source: People's Daily online.

# Example: Exosquelton

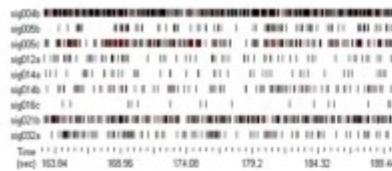


Clinatec (CEA, CHU Grenoble Alpes), 2019.  
Semi-invasive implant.  
Tetraplegic patient.

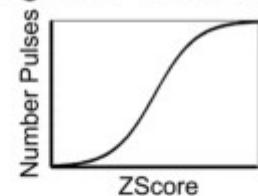


# Example: Network BCI

M1 neural ensemble



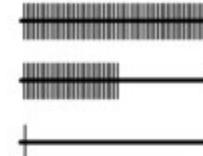
Sigmoid Transform



$$f(x)$$



ICMS

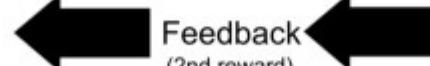


Brain-to-Brain transfer.  
Worked between US and  
Brazil !!!

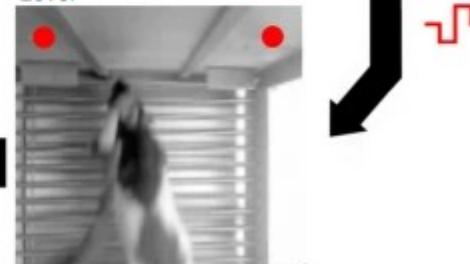
Correct Lever



Encoder



Correct Lever



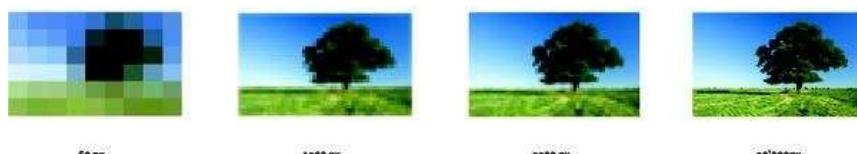
Decoder

A Brain-to-Brain Interface for Real-Time Sharing of Sensorimotor Information,  
Duke University, Nicolelis Lab,  
2013.

# Peripheral CNS implants...

Neuroprosthetics:

- Cochlear implants.
- Visual implants.
- Pain relief.
- Bladder control implants.
- ...



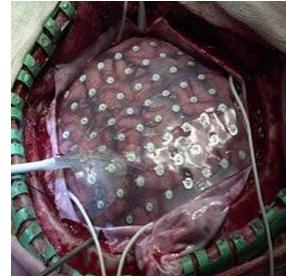
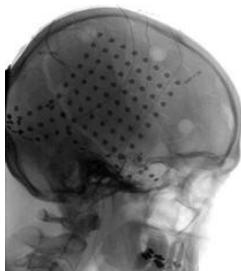
EPFL retinal implant (2018).

# Main Characteristics (1)

## Invasive

Subdural or intracortical electrodes.

- ✓ More focal than scalp electrodes.
- ✓ Less artifacted signal.
- ✗ Lower spatial coverage.
- ✗ Invasive, costly.



EcoG grid, photo by G. Schalk (Wadsworth center), K. Miller and J. Ojemann (U. of Washington).

## Non invasive

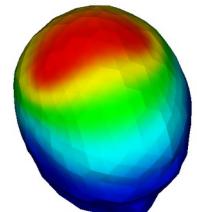
Scalp sensors (EEG, MEG, ...).

- ✓ Non invasive, cheap (EEG).
- ✓ High spatial coverage.
- ✗ Blurred spatial information.
- ✗ Artifacts.

low cost



EMOTIV EPOC



4.05e-05  
2.65e-05  
1.25e-05  
-1.25e-05  
-1.85e-05

# Main Characteristics (2)

## Online

- ✓ Feedback.
- ✓ “Real BCI”.
- ✗ Need for real time processing.
- ✗ Less sophisticated methods.

## Offline

- ✓ More sophisticated algorithms.
- ✓ Proof of concept.
- ✓ Easier and more tools available.
- ✗ “False BCI”.
- ✗ No subject feedback.



# Main Characteristics (3)

## Asynchronous (Self paced)

The subject decides when...

- ✓ Friendlier for the subject.
- ✓ Less tiring.
- ✗ More difficult for the computer.
- ✗ Higher demand on the signal processing.
- ✗ More training.
- ✗ Need for paradigms creating strong signals.

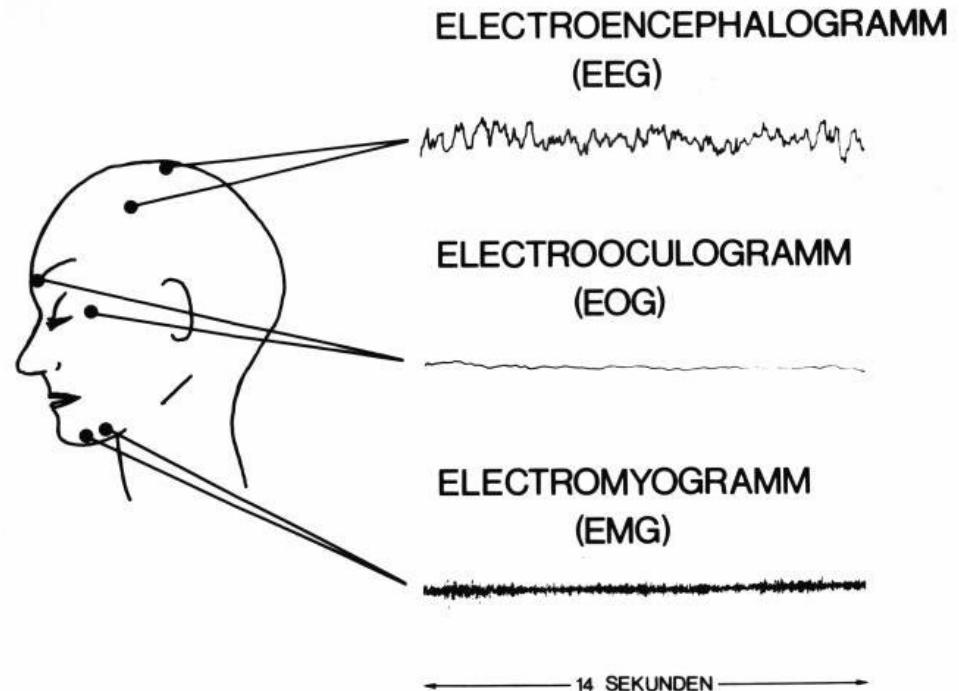
## Synchronous (Clocked)

The computer decides when...

- ✓ Simpler for the signal processing.
- ✓ The computer knows when to look.
- ✓ Ability to do multiple trials.
- Increase ~~Reduction~~ of signal to noise ratio,
- More paradigms can be used.
- ✓ Less training.
- ✗ Less comfortable for the subject.  
User concentration, effort.
- ✗ Non stoppable by the user.

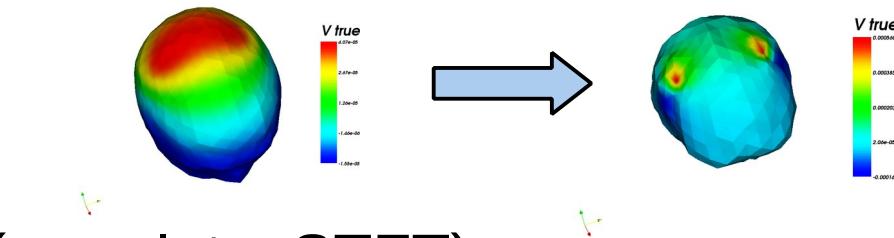
# Artifacts

- Main drawback of scalp vs intra EEG.
  - EMG, EOG
  - Patients with motor control problem.
- Artifact processing.
  - Rejection or not.
  - Suppression.
  - To be done in real time.



# Feature extraction

- Spatial signal improvement:
  - Laplacian.
  - Cortical mapping.
  - Source localization.
- Temporal analysis:
  - Time-frequency maps (wavelets, STFT).
  - Phase analysis.
  - ERD/ERS.
  - ICA / PCA.



# Classification

- Nearest Neighbors.
- Linear (Fischer) Discriminant Analysis (LDA).  
Quadratic DA.
- Common Spatial Patterns (CSP). Max variance.
- Perceptron / Neural Networks.
- Support Vector Machine (SVM).
- Self Organizing Maps..
- HMM, Temporal Hidden Markov Trees.
- Decision trees, Voting.
- ...

# Feedback

- Important for subject implication.
- Visual or auditory.
- Embodiment (robot, orthosis, neuroprosthesis).
- “Bidirectional” BCIs with neurostimulation.
- Ergonomics.
- Human learning theory.

# Applications

- Severe neuromuscular deficiencies:
  - Amyotrophic lateral sclerosis.
  - Brain stem vascular accidents (strokes).
  - Medullar wounds.
    - Neurorehabilitation, man-machine interface.
- Post-amputation treatment:
  - Proprioception, fantom pains.
  - Prosthesis control.
- Control of attention: Neurofeedback.
- Gaming.

# Tools

- Software



- Open hardware



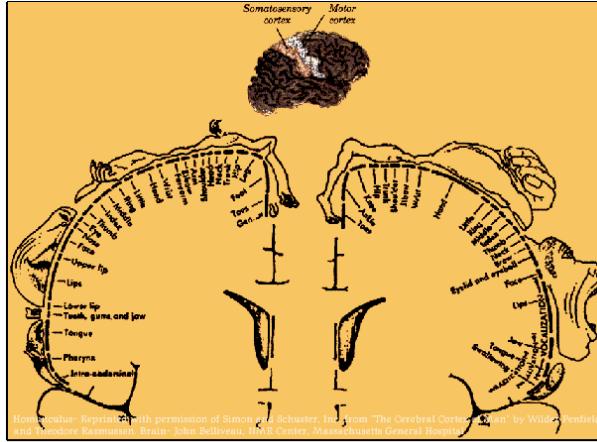
The Open Prosthetics Project

*Prosthetics shouldn't cost an arm and a leg.*

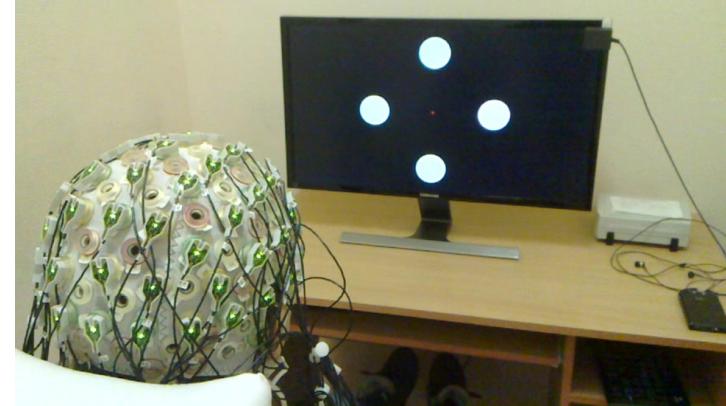
# Typical paradigms



P300 speller keyboard



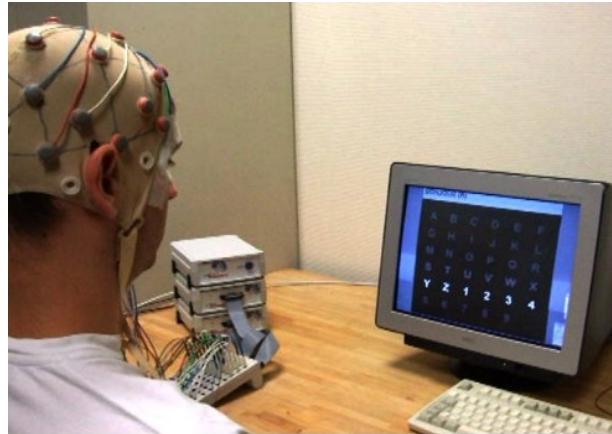
Motor imagination



Visually Evoked Potential

# P300 wave based paradigms

## P300 speller



A	B	C	D	E	F
G	H	I	J	K	L
M	N	O	P	Q	R
S	T	U	V	W	X
Y	Z	1	2	3	4
5	6	7	8	9	-

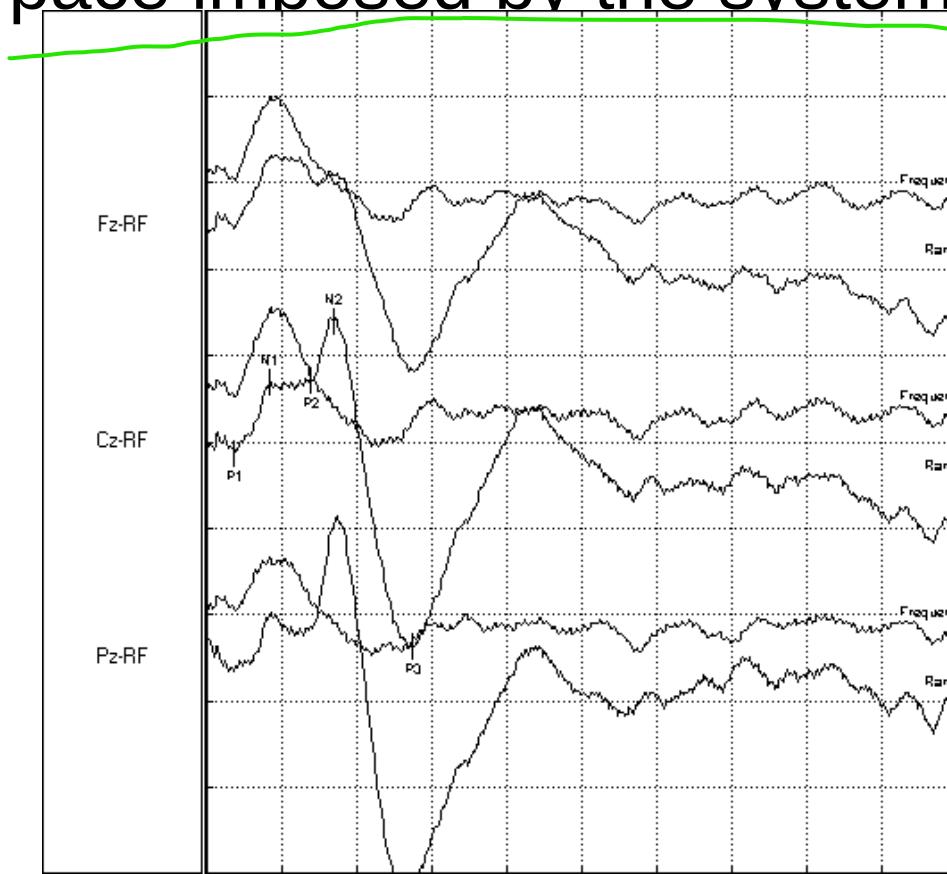
A	B	C	D	E	F
G	H	I	J	K	L
M	N	O	P	Q	R
S	T	U	V	W	X
Y	Z	1	2	3	4
5	6	7	8	9	-

- P300 wave linked to the **perception of a rare but expected event**.
- Can be visual or auditory.
- Random flashes of letters in groups.
- **Subject's attention** focused on a letter of his/her choice.
- Classification of EEG → intersection of groups.
- Single letter intersection between two groups (line / column).

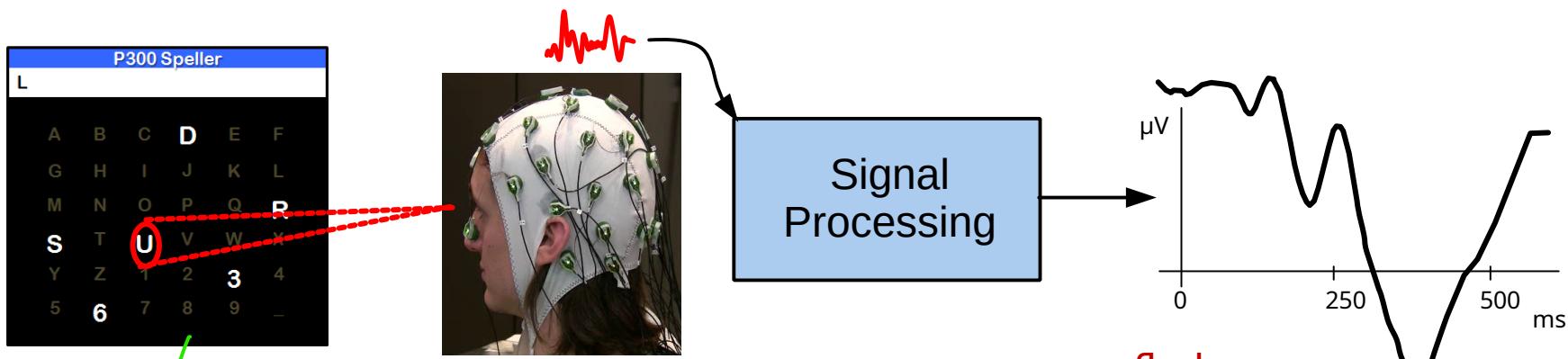
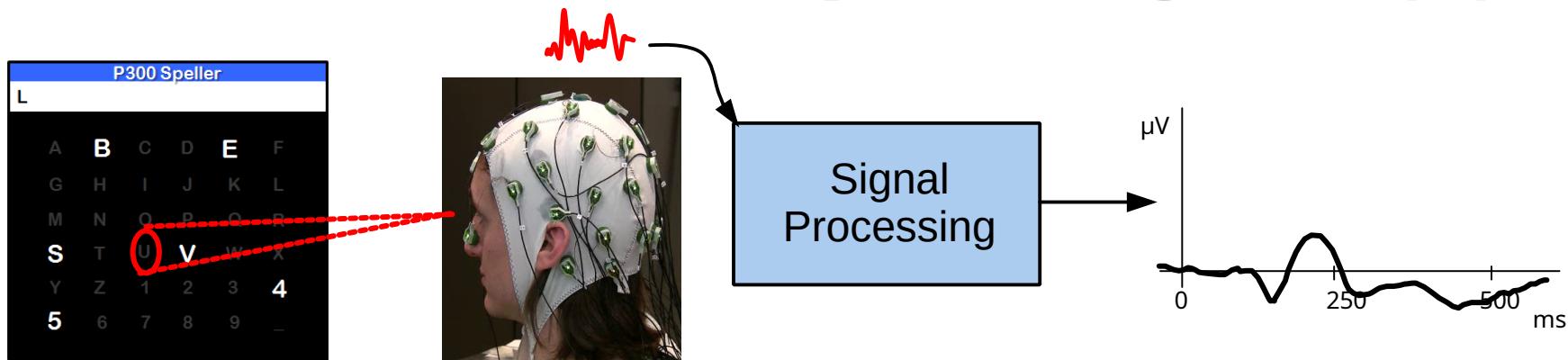
# P300 wave based paradigms (2)

Synchronous protocol: pace imposed by the system.

P300 / Non P300 waves



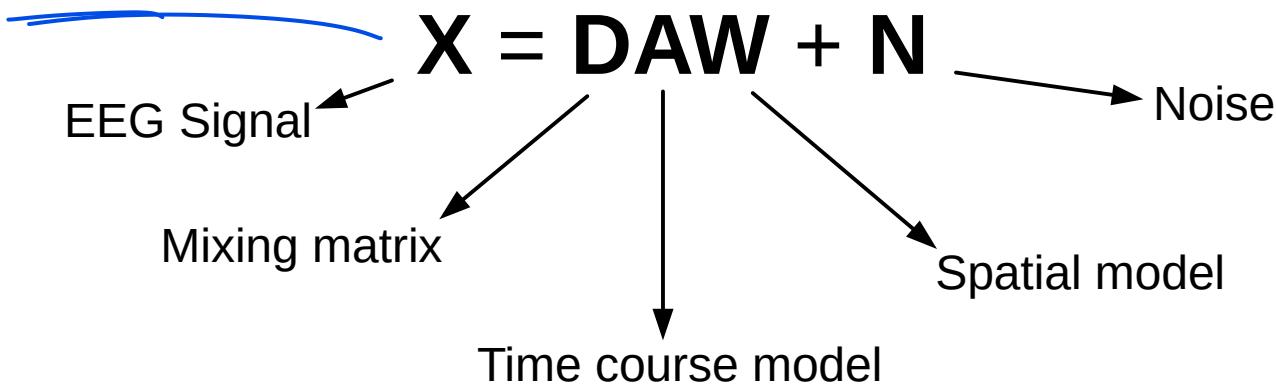
# P300 wave based paradigms (3)



With each « flash » of the desired letter,  
the interface should detect a P300 signal.

# P300 wave based paradigms (4)

XDAWN algorithm (Rivet et al, 2009):



## Training

$$X = D_t A_t W + D_{nt} A_{nt} W + N$$

- $D_t, D_{nt}$  → Given by the computer clock (Toeplitz matrices).
- $A_t, A_{nt}, W$  → Computed from calibration data.

# P300 wave based paradigms (5)

The P300 speller principle can be used in all cases involving commands based on multiple choices, not requiring a too fast choice:

- Keyboard.
  - Games.
  - Environment control.
- 
- Communication with Locked In subjects (auditive).

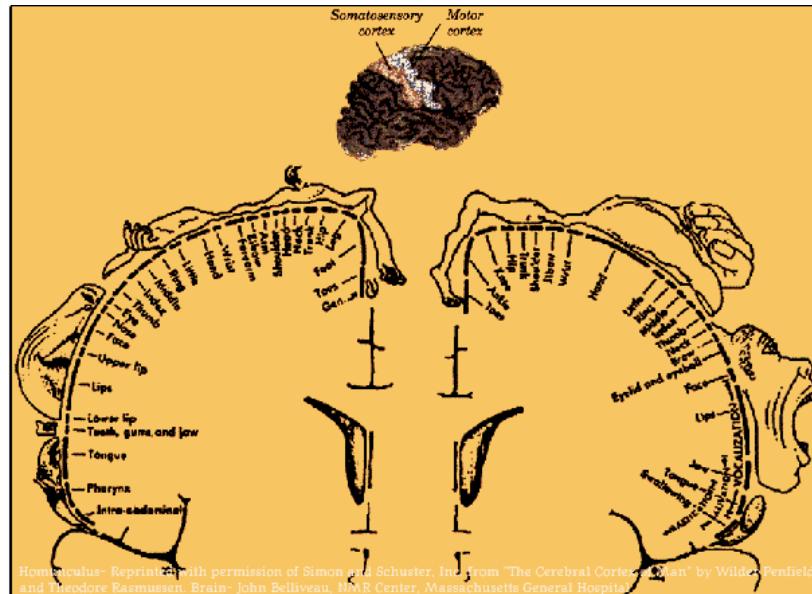


# P300 wave based paradigms (6)

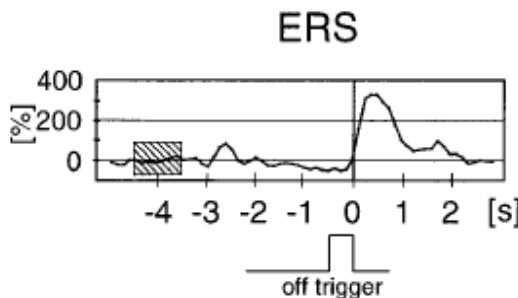
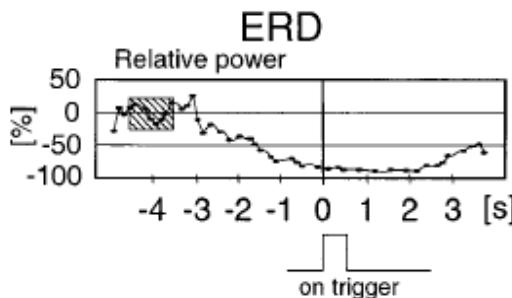
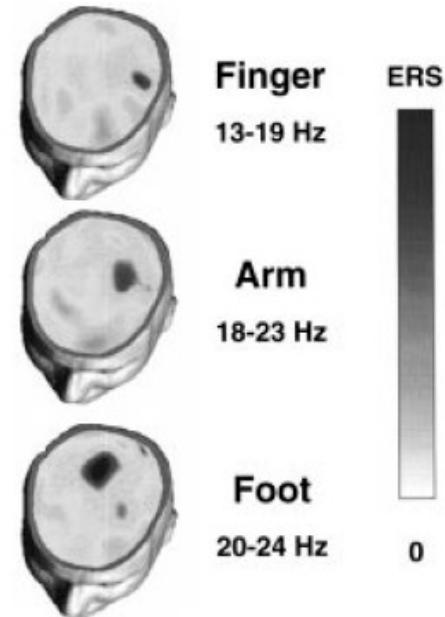
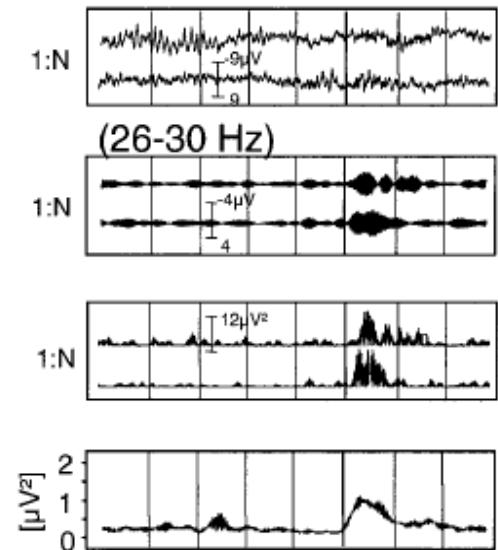
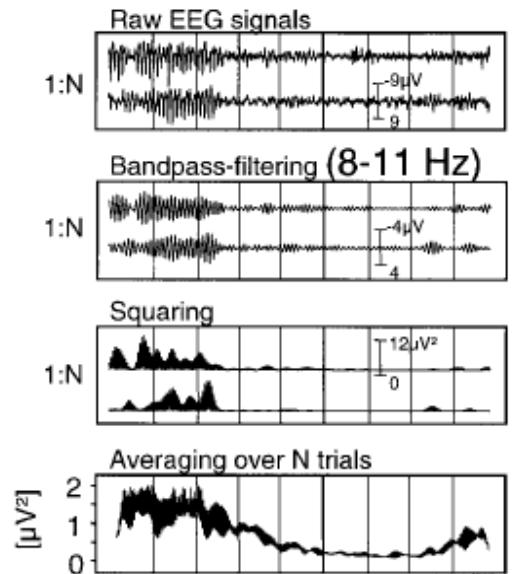


# Sensorimotor paradigms

- Real or imaginary activity.
- Event related Desynchronisation / Synchronisation (ERD / ERS).
- Topography characteristic of the body part.

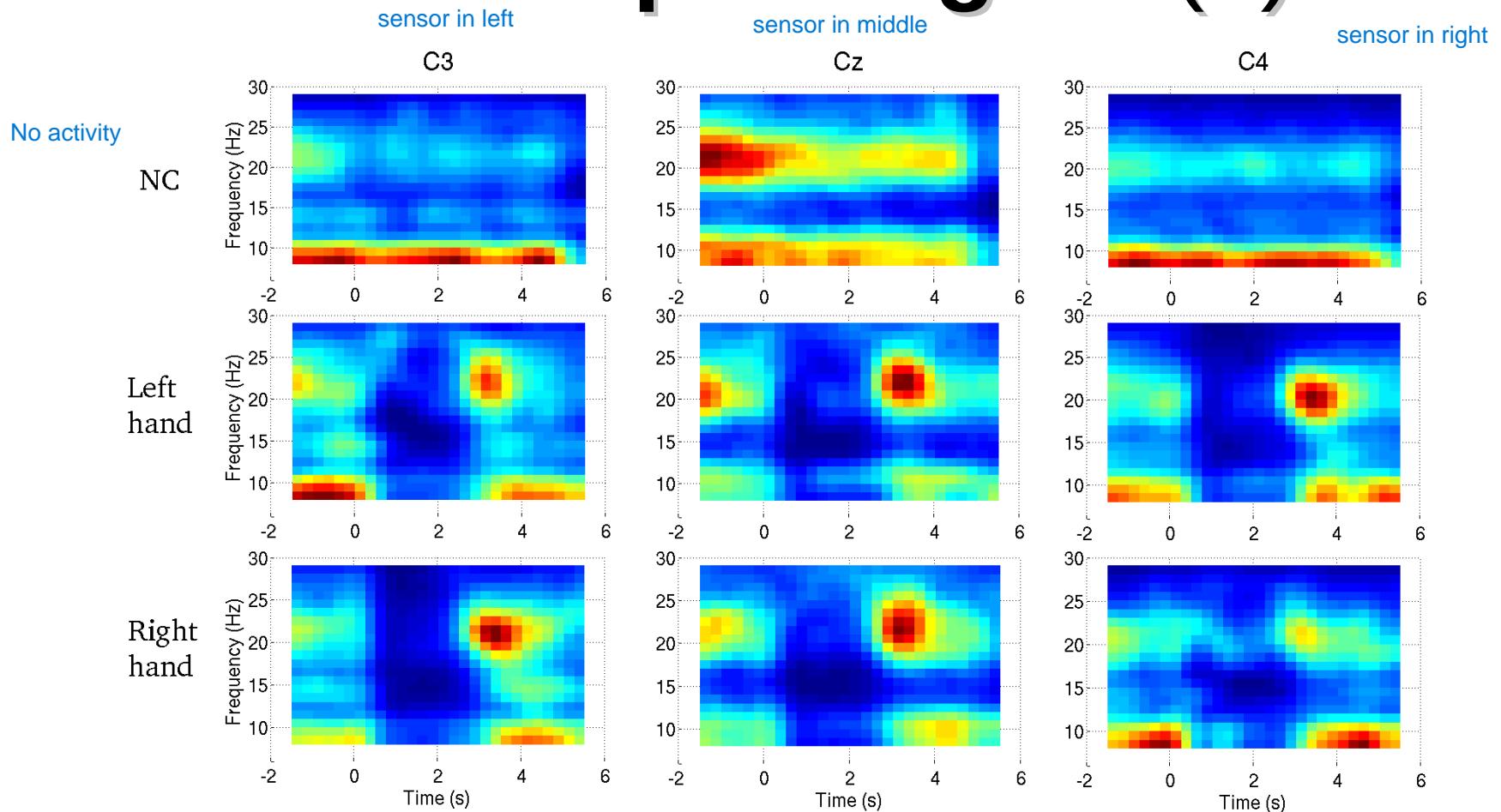


# Sensorimotor paradigms (2)



Pfurtscheller, 1999.

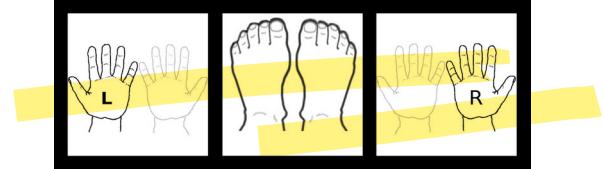
# Sensorimotor paradigms (3)



# Sensorimotor paradigms (4)

**Goal:** asynchronous commands, “self-paced”.

- Identify adequate motor tasks



- Detect the occurrence of such tasks in resting periods



Discrete command button

- Measure the task duration.



Continuous command cursor

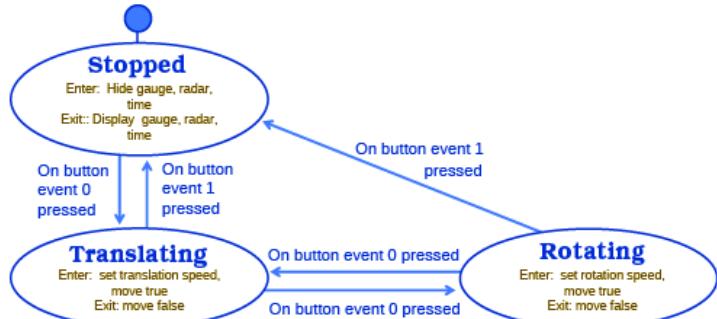
Note: non motor tasks are possible  
(mental calculus, 3D mental rotation, verbal tasks, ...).



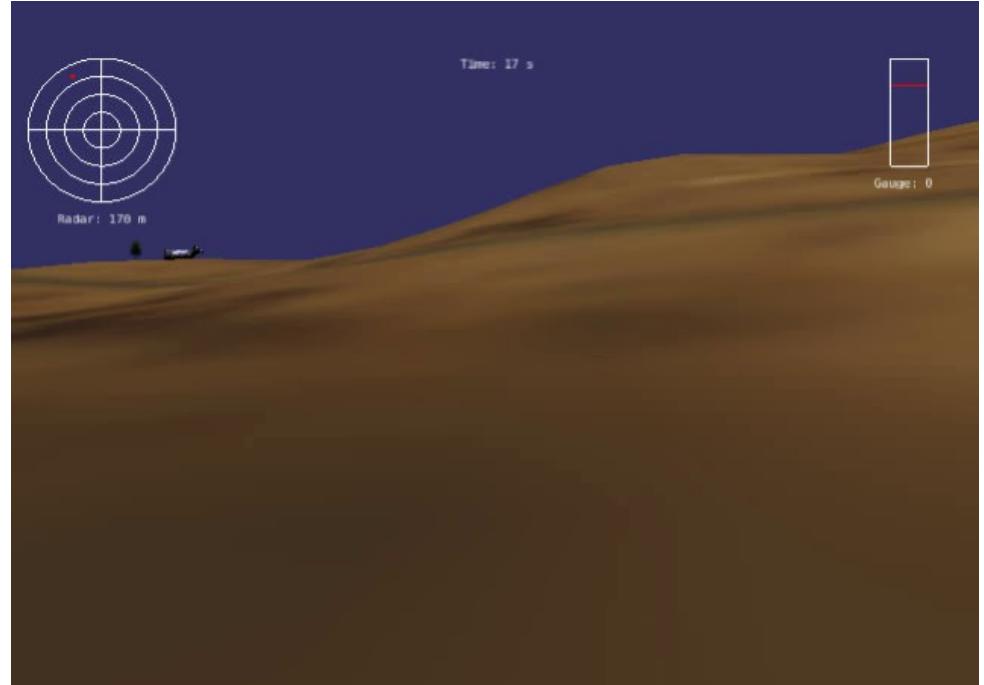
# Sensorimotor paradigms (5)

**Discrete command:** button based on beta rebound.

Application: **Navigation** in a virtual environment.



Logo turtle strategy.

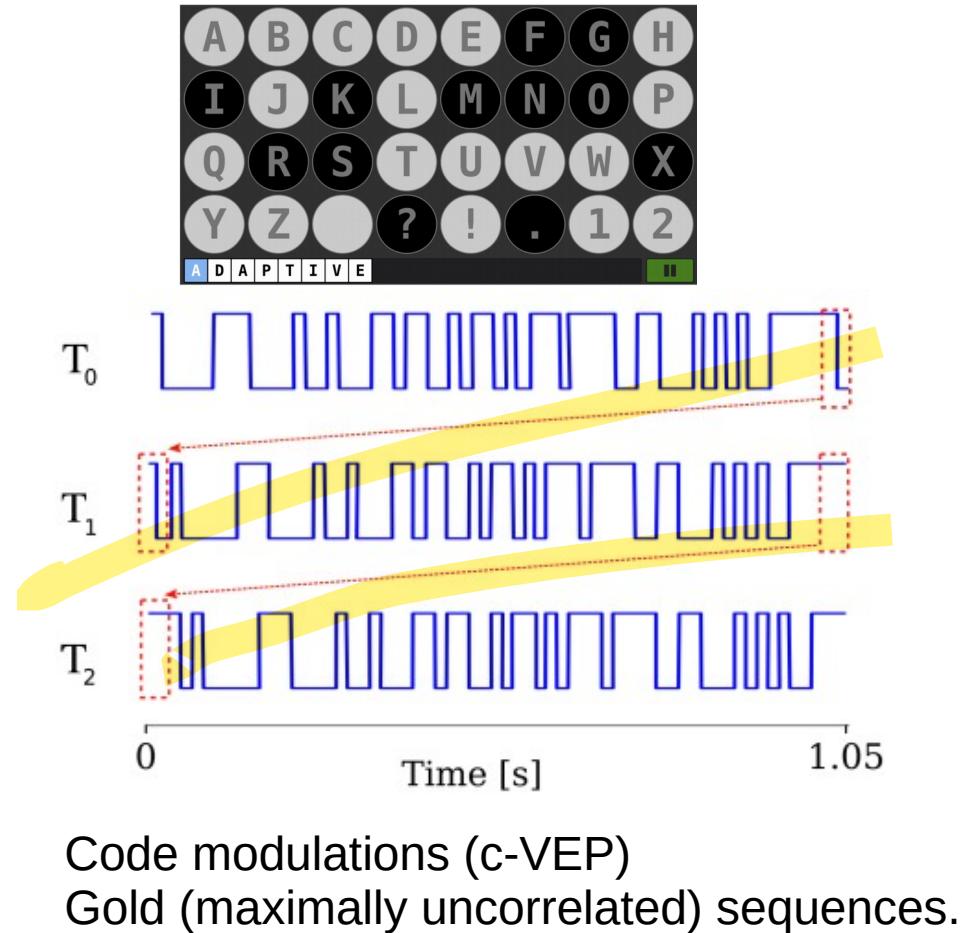


# Visually Evoked Potentials

Information encoded as:

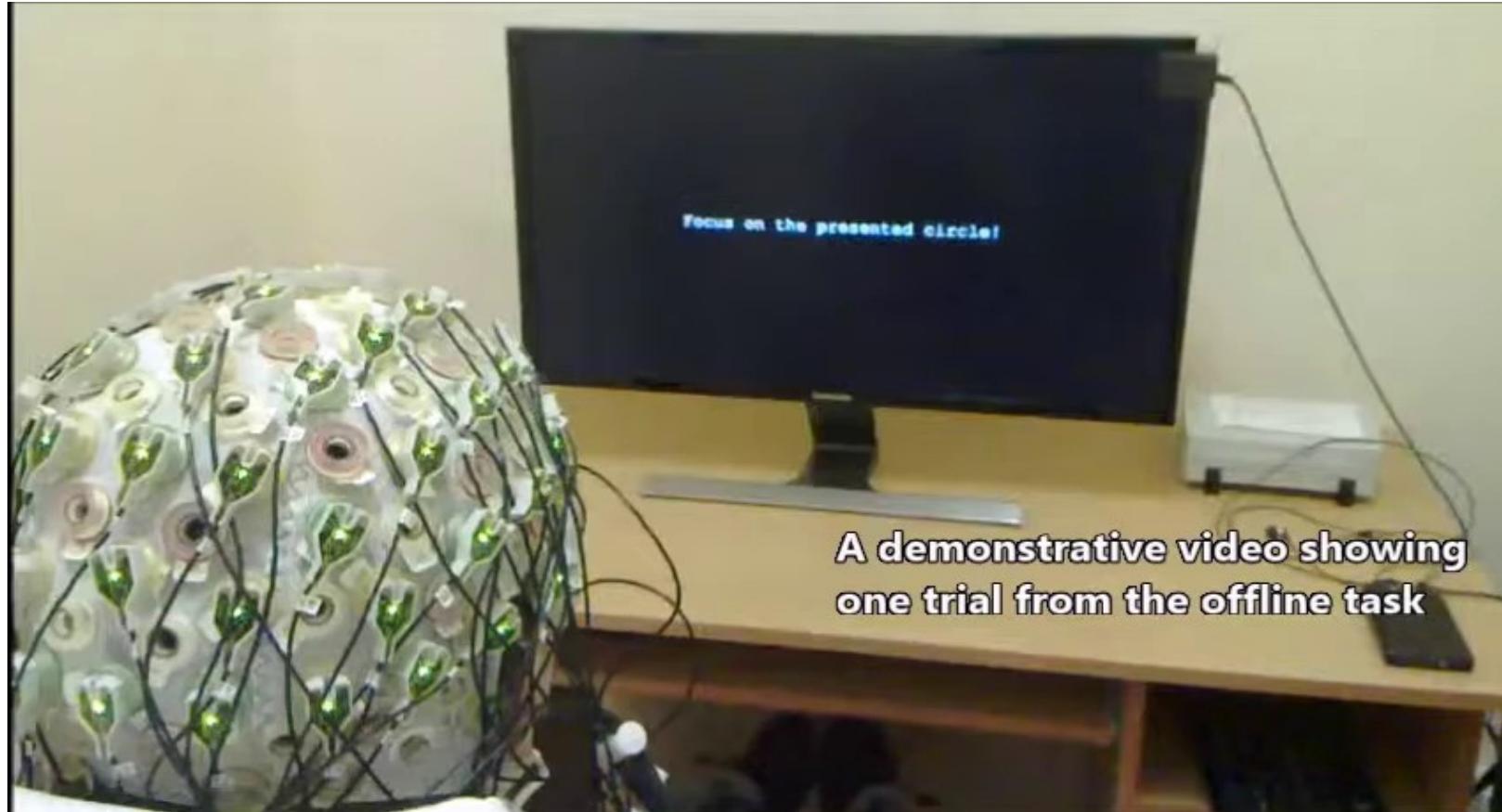


Frequencies (SSVEP)



Code modulations (c-VEP)  
Gold (maximally uncorrelated) sequences.

# Visually Evoked Potentials (2)



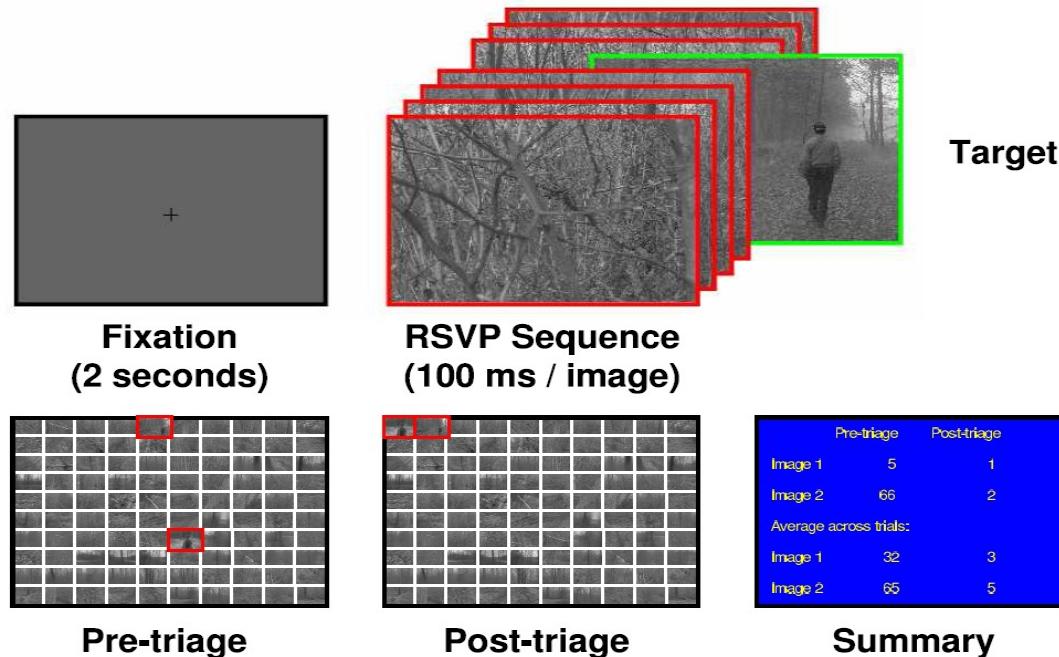
A demonstrative video showing  
one trial from the offline task

# Ethical issues

- Augmented human.
- Instrumentalisation.
- Brain “reading”.
- Reliability: wrong message or command.

# Ethical issues

Cortically Coupled Computer Vision for Rapid Image Search.



# Thank you !!!

