Brain Computer Interfaces

Principles, Algorithms and Tools

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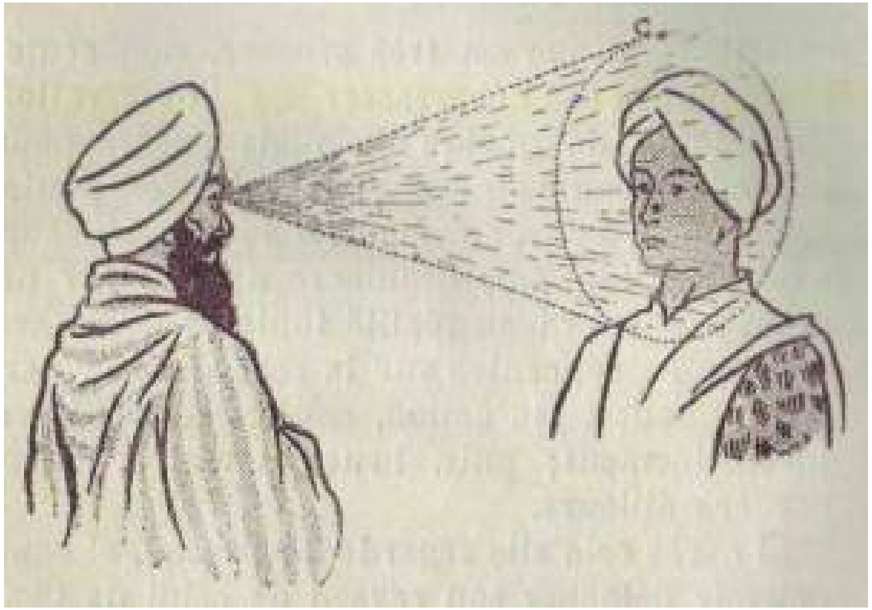
Application of ML to MRI, electrophysiology and brain computer interfaces

Agenda

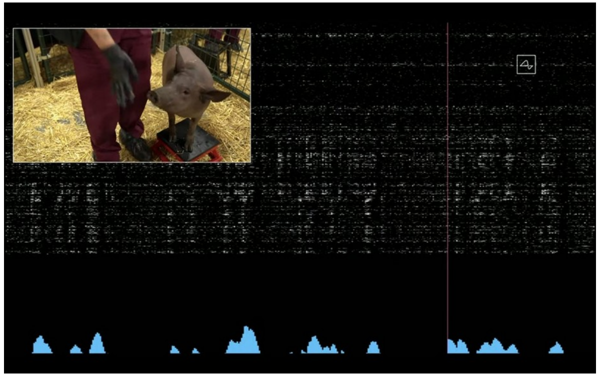
- A (very) brief historical perspective.
- What are Brain Computer Interfaces (BCI).
- Main principles.
- Study of some classical paradigms:
  - P300 speller.
  - Beta rebound.
  - Visually Evoked Potentials.
- Ethical issues.

An old fantasy of humanity...



Magnetic encirclement
Hindu magnetic treaty ©ISI-CNV

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



NEURALINK

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.

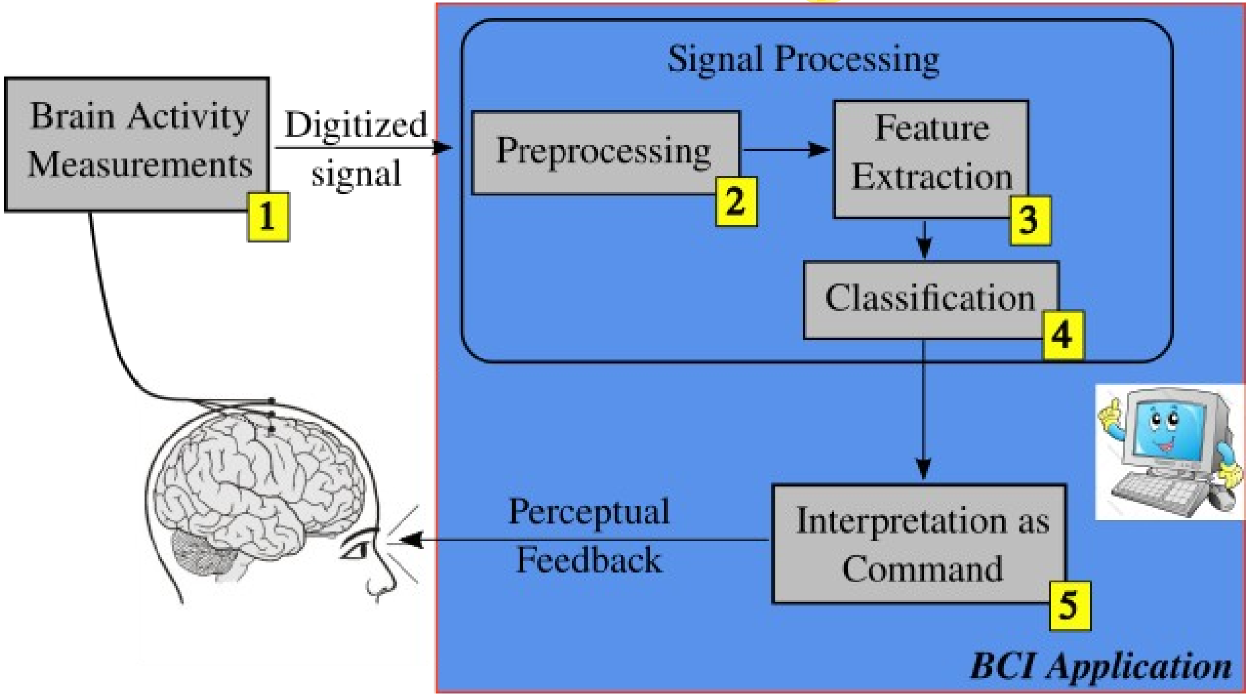
- EEG biofeedback (1960-1970):
  - Voluntary control of brain rythms (α , μ , θ).
  - Reduction of ictal activity.
  - 1973:

TOWARD DIRECT BRAIN-COMPUTER COMMUNICATION

JACQUES J. VIDAL[1]

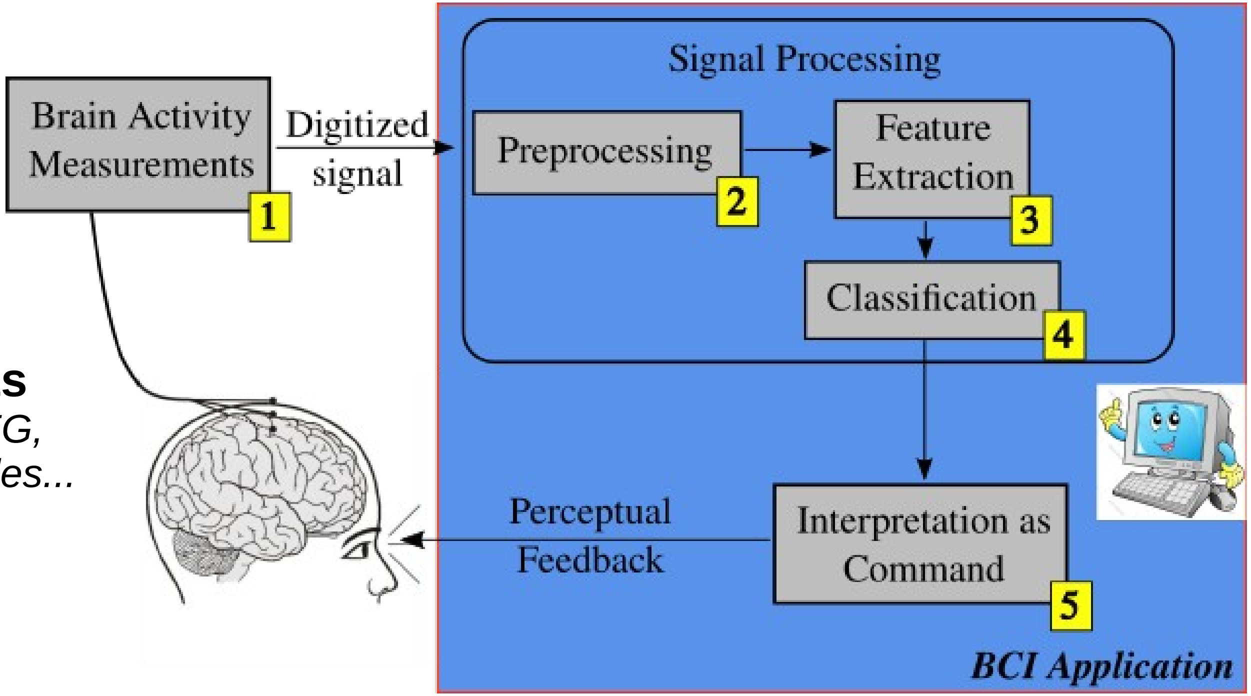
Brain Research Institute,
University of California, Los Angeles, California

BCI: main principles



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

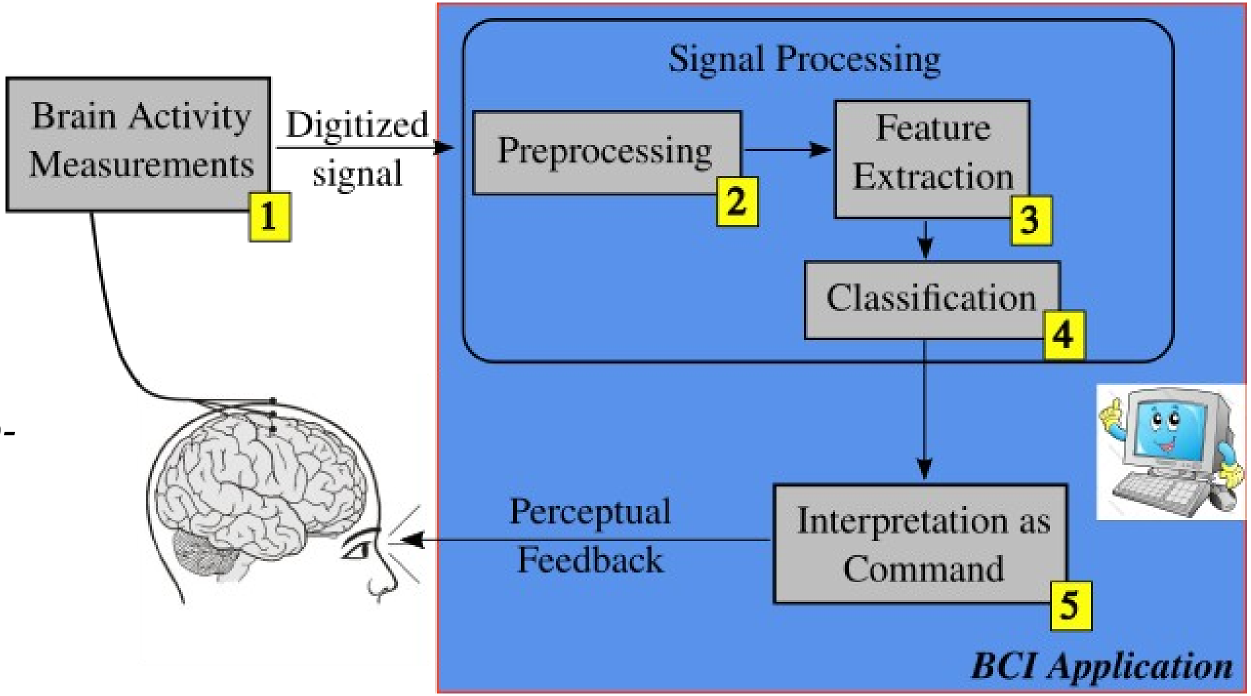
BCI: main principles



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…)

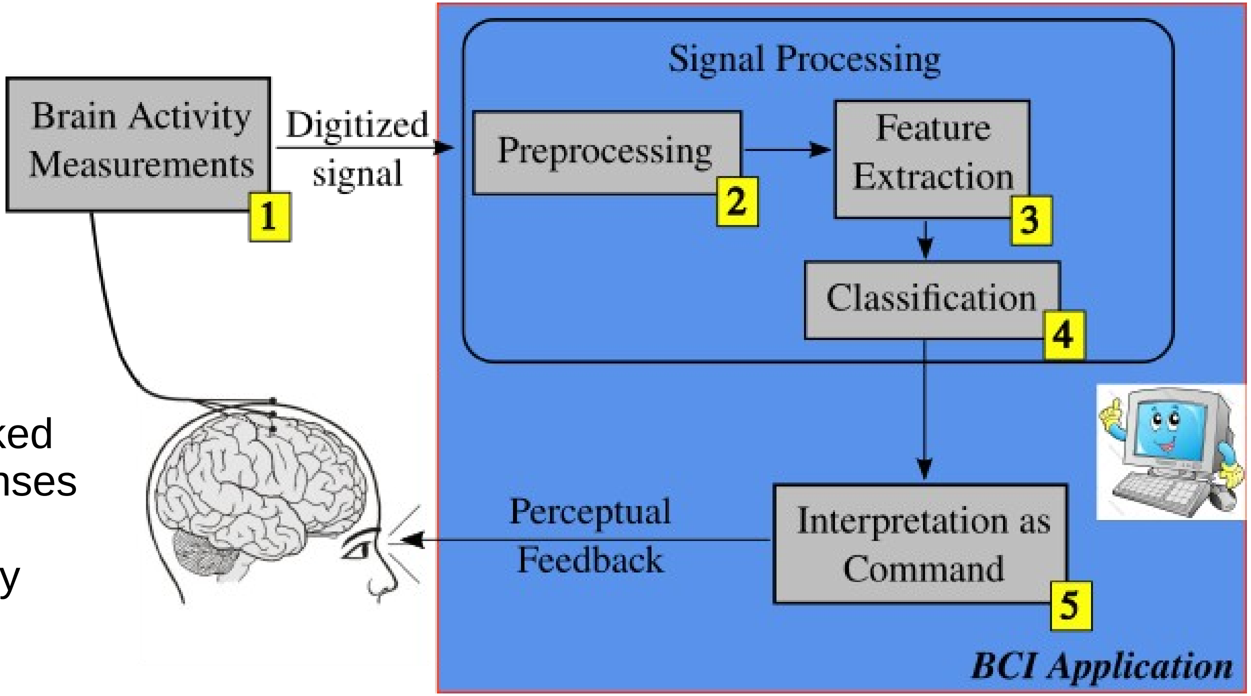
BCI: main principles



2 **Preprocessing**
Basic stuff: *channel selection,sub-sampling, filtering, ...*

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

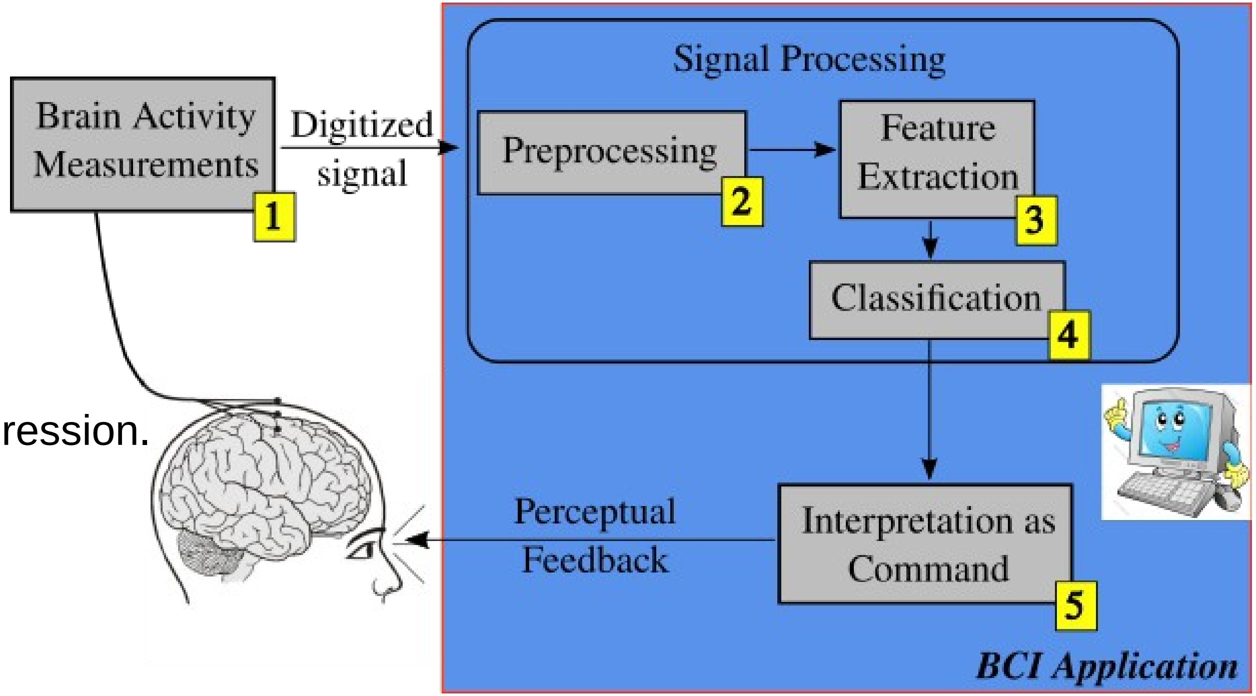
BCI: main principles



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

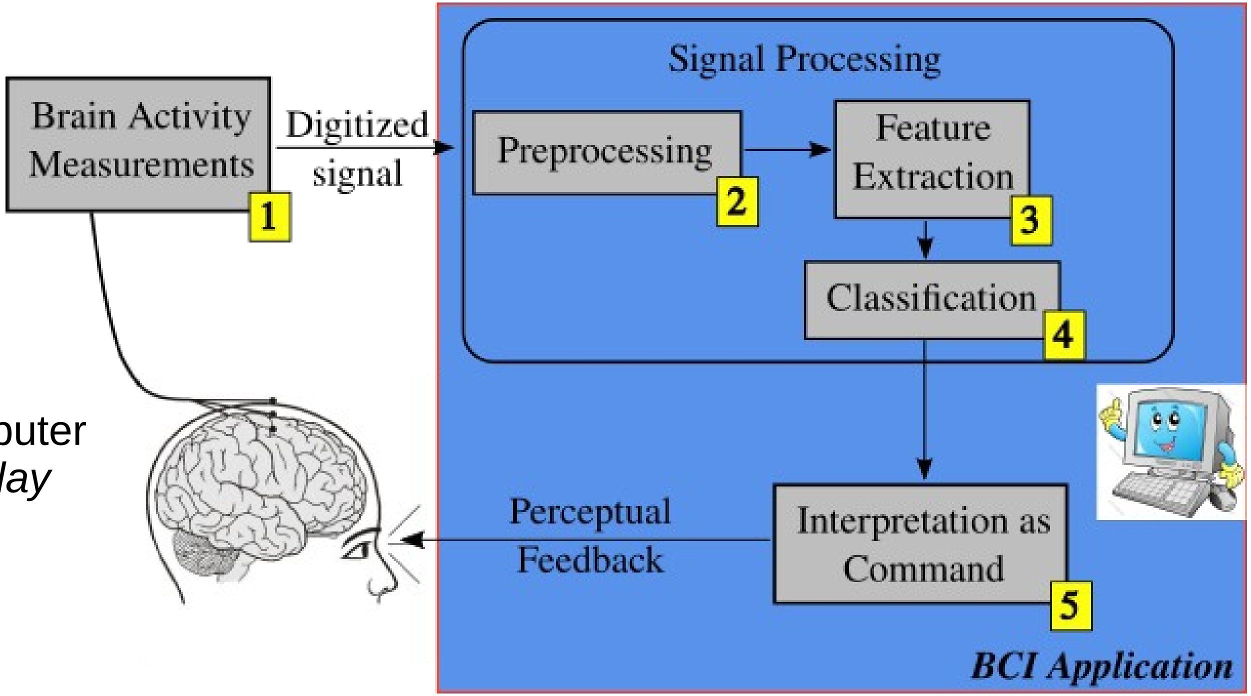


4 **Classification**

- 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: α waves...
- ERN: Error Related Negativity.
- VHFO: Very High Frequency Oscillations.

Cerebral rythms

- Delta (< 4 Hz): Deep sleep.
- Theta (4-7 Hz): Drowsiness.
- Alpha (8-16 Hz): State of diffuse awakeness.
- 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

  $\Rightarrow$ Detectability / Accuracy / Speed.
- Invasive systems:
  - Brain coverage / Number of electrodes.
  - Tissue scars around electrodes.
  - Costs (not only €, human).

  $\Rightarrow$ Stability in time / High specificity.

Main challenges...

- **Tedious Calibration**
    - Search for features.
    - Inter-subject + intra-session variability.

Technological

- **Low information tranfert rate**
    - Somewhat artificial applications.

Neurophysiological

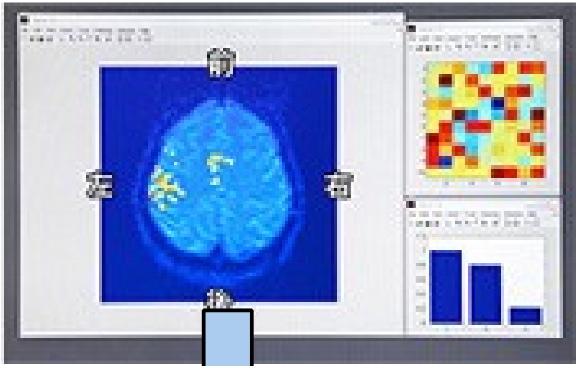
- **Human learning needed for BCI** use
    - Often time consuming.
    - Fails for a fraction of the subjects (in particular for some sub-population like locked-in).

Ergonomy

Example: ***Roc-Paper-Scisors***

HRI (Honda) and ATR, May 2006.

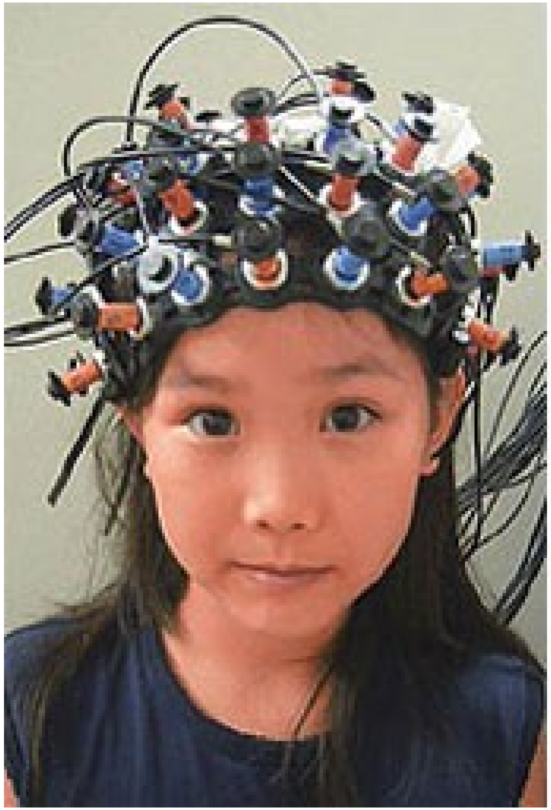
Chi-Fou-Mi in fMRI

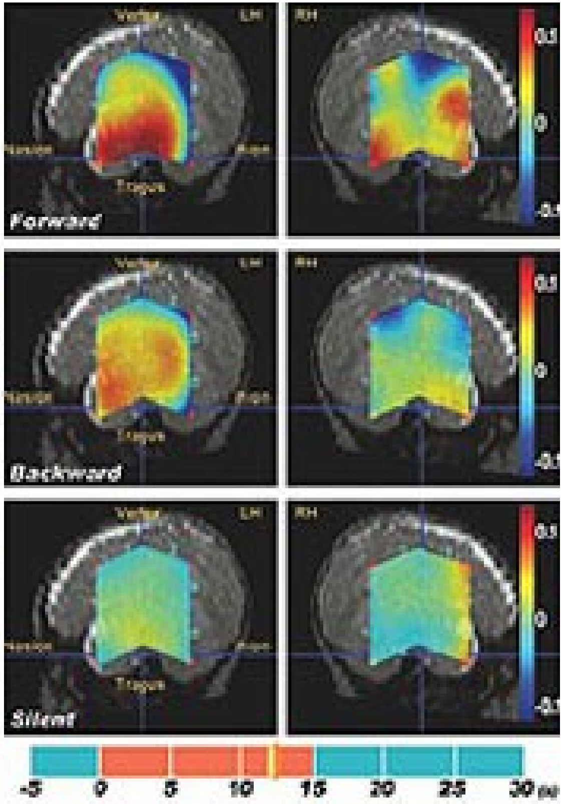


Robotic hand.

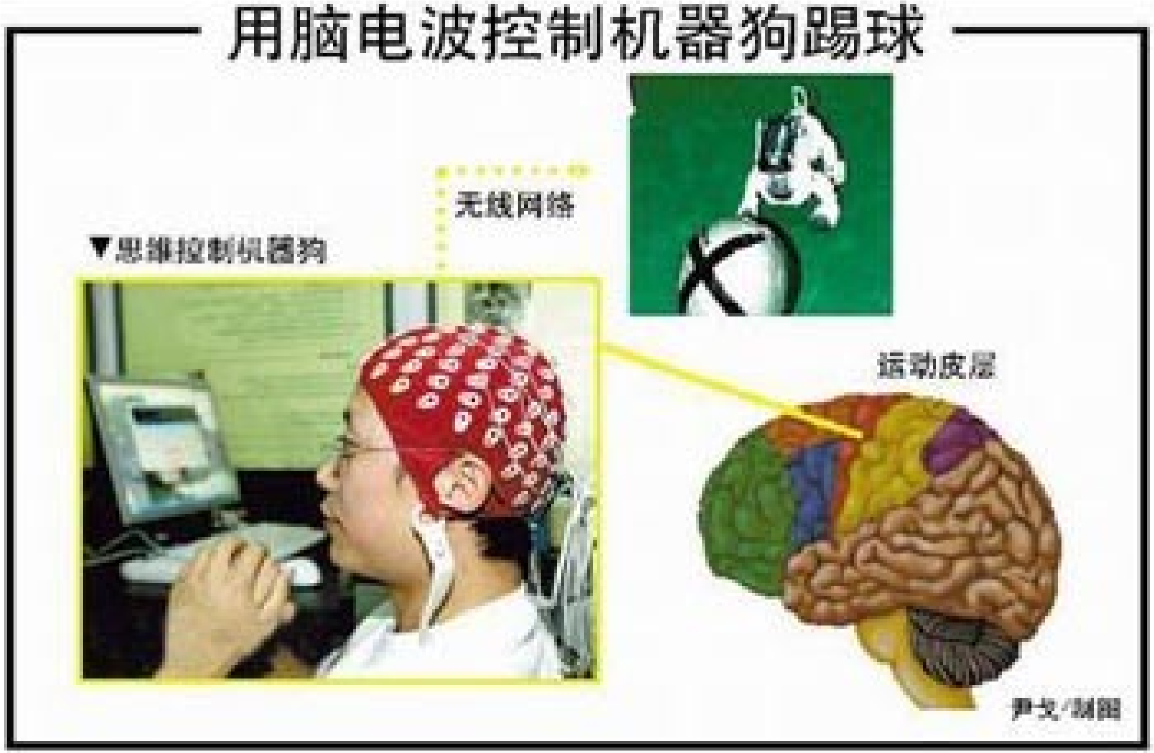
Example: *On-Off Command*

Hitachi 2007 fNIRS
Start/Stop an electrical train.



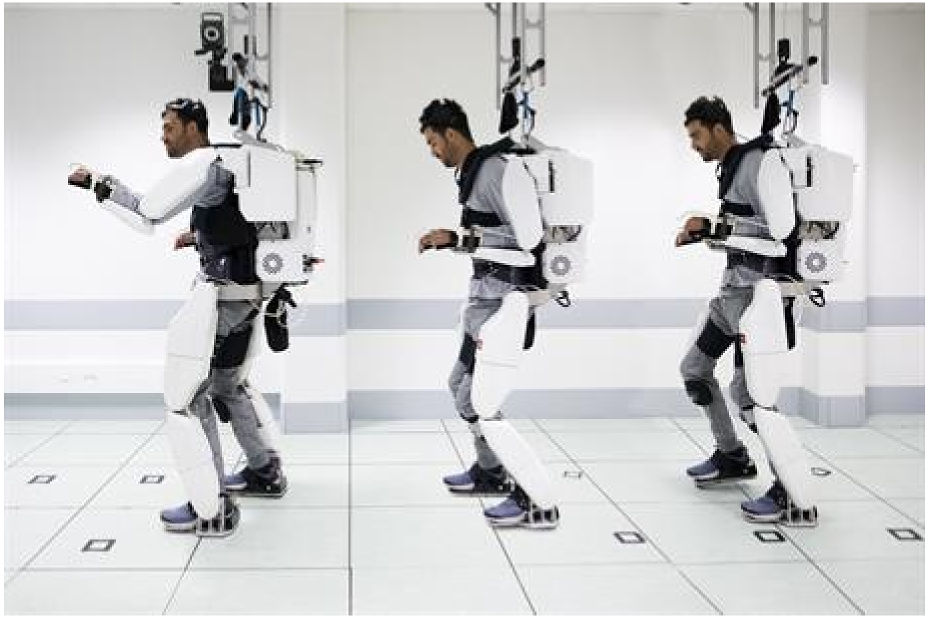


Example: *Robotic dogs playing football*



EEG based
Qinghua University
June 2006
Source: **People’s Daily online**.

Example: Exosquelton

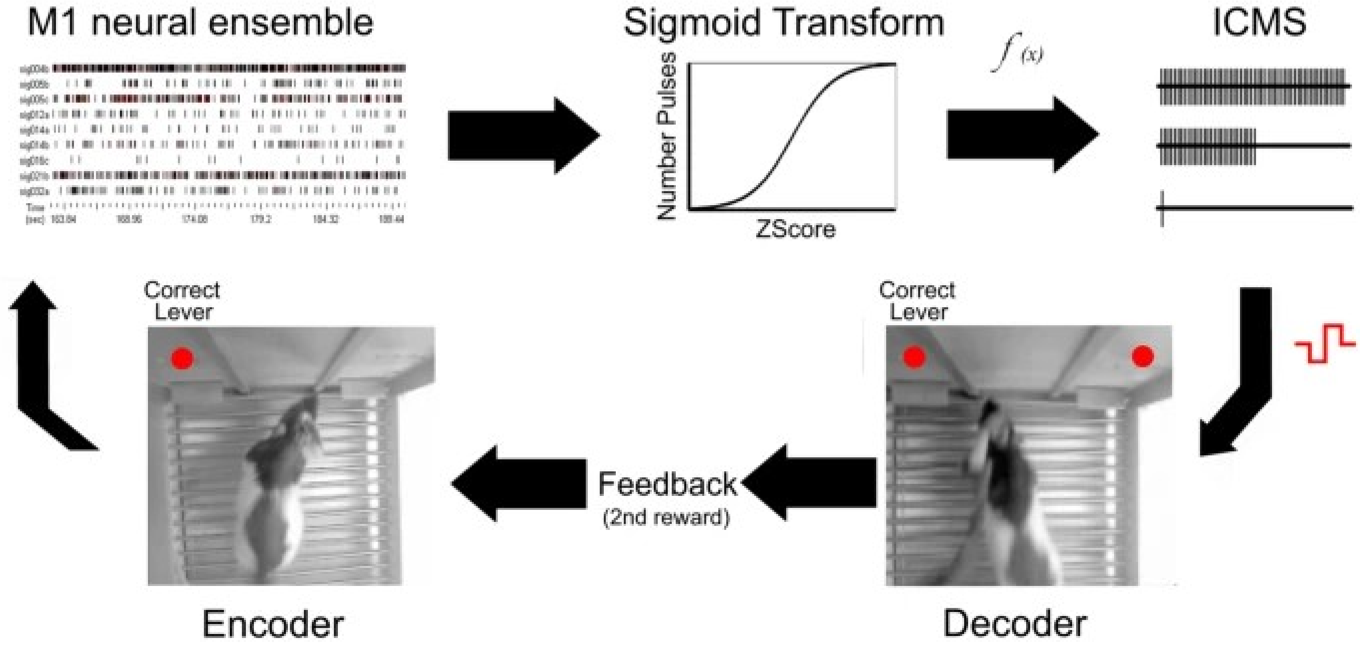


Clinatec (CEA, CHU Grenoble Alpes), 2019.

Semi-invasive implant.

Tetraplegic patient.

Example: Network BCI



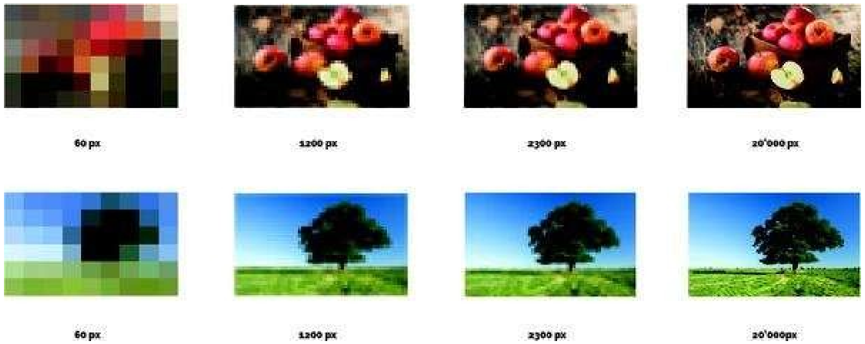
Brain-to-Brain transfer. Worked between US and Brazil !!!

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.
- Blader control implants.
- ...



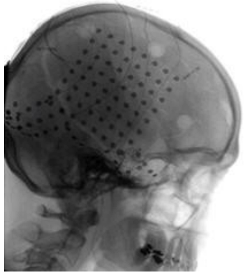
EPFL retinal implant (2018).

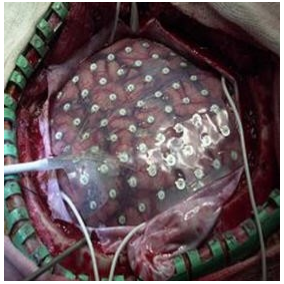
Main Characteristics (1)

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

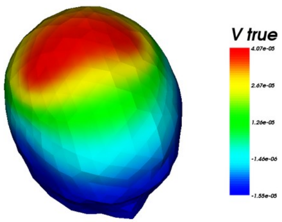
Scalp sensors (EEG, MEG, …).

- ✔ Non invasize, cheap (EEG).
- ✔ High spatial coverage.
- ✗ Blurred spatial information.
- ✗ Artifacts.

low cost

OpenEEG
openeeg.sourceforge.net
EEG for the rest of us!

EMOTIV EPOC



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.

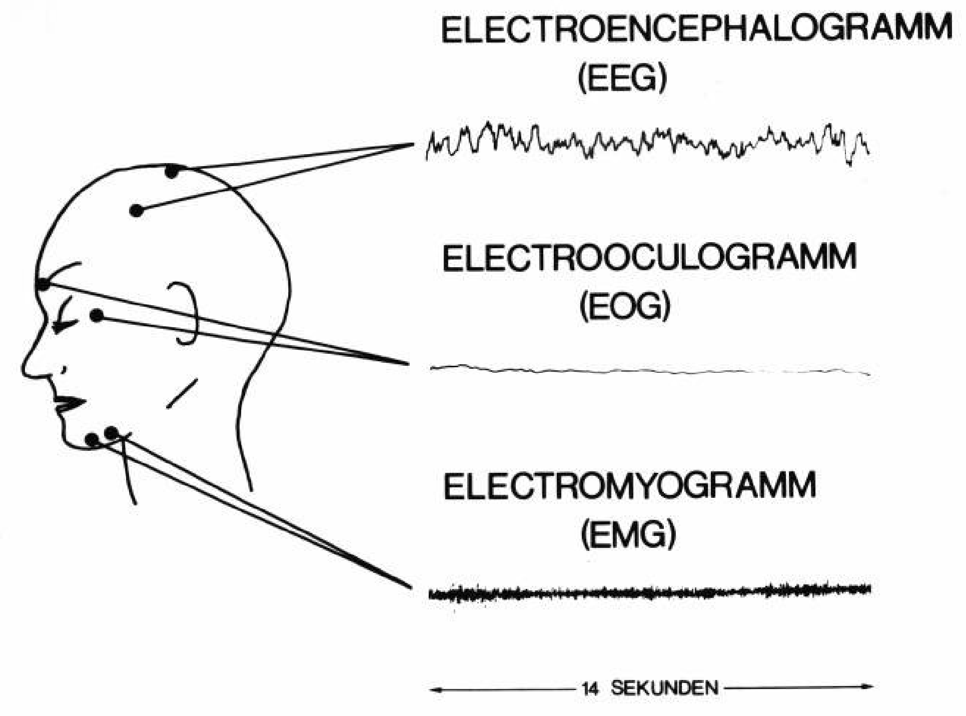
Synchronous (Clocked)

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.

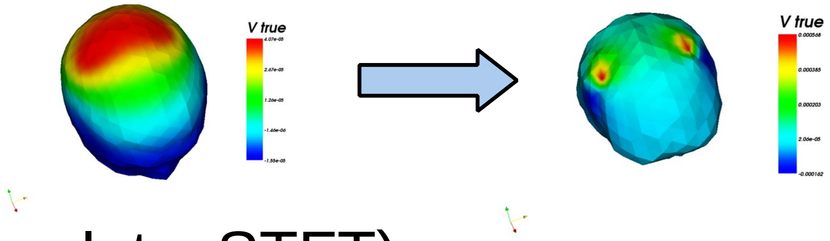
Artifacts

- 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 auditive.
- Embodiement (robot, orthesis, neuroprosthesis).
- “Bidirectional” BCIs with neurostimulation.

- Ergonomy.
- 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

BCI 2000

OpenVibe

FieldTrip

Timeflux

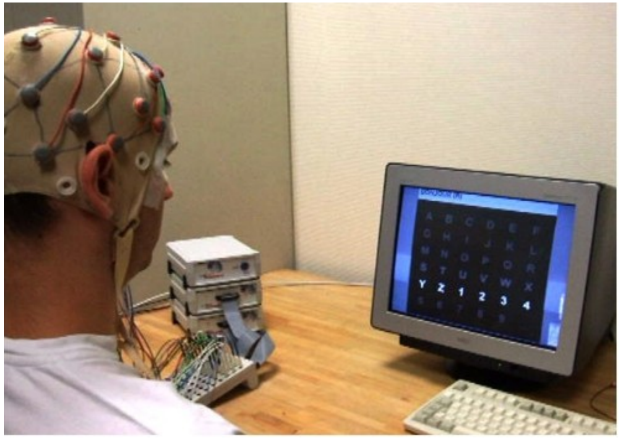
- Open hardware

OpenEEG
openeeg.sourceforge.net
EEG for the rest of us!

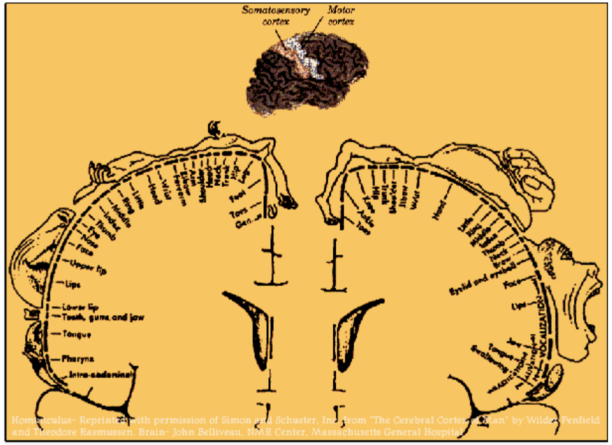
OpenBCI

The Open Prosthetics Project
Prosthetics shouldn't cost an arm and a leg.

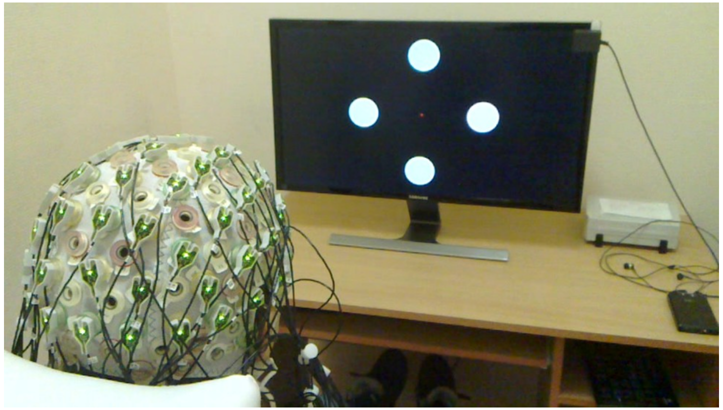
Typical paradigms



P300 speller keyboard



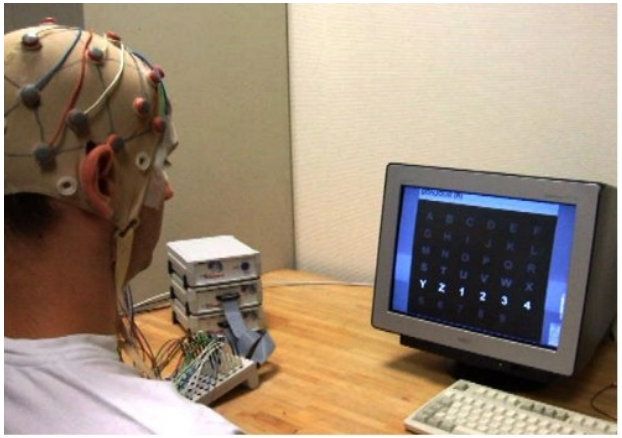
Motor imagination

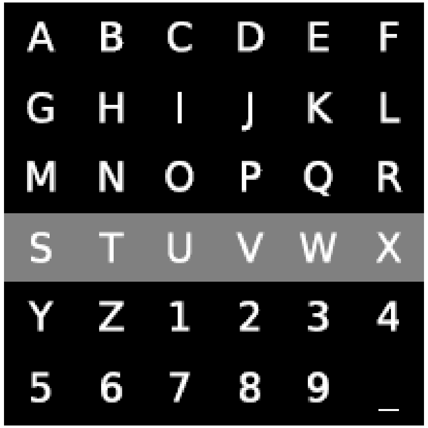


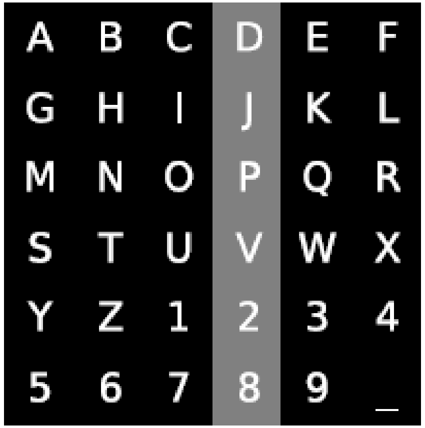
Visually Evoked Potential

P300 wave based paradigms

P300 speller





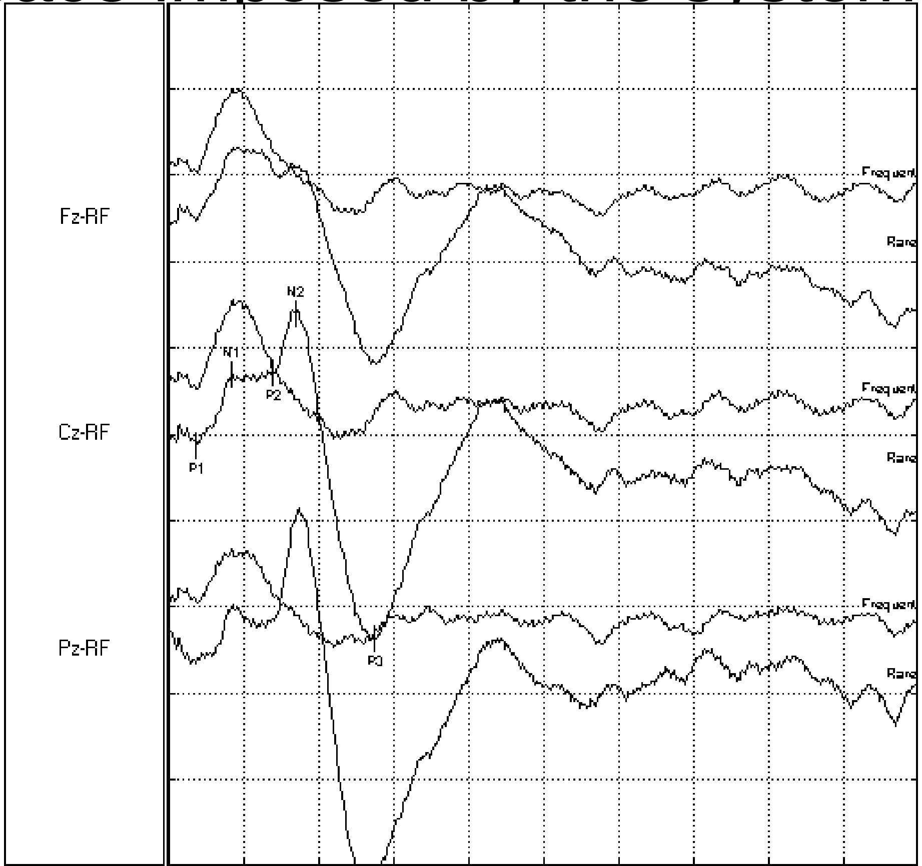


- P300 wave linked to the **perception of a rare but expected event.**
- Can be visual or auditive.
- Random flashes of letters in groups.
- **Subject's attention** focused on a letter of his/her choice.
- Classification of EEG → intersection of groups.
- Single letter intersection between two groups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

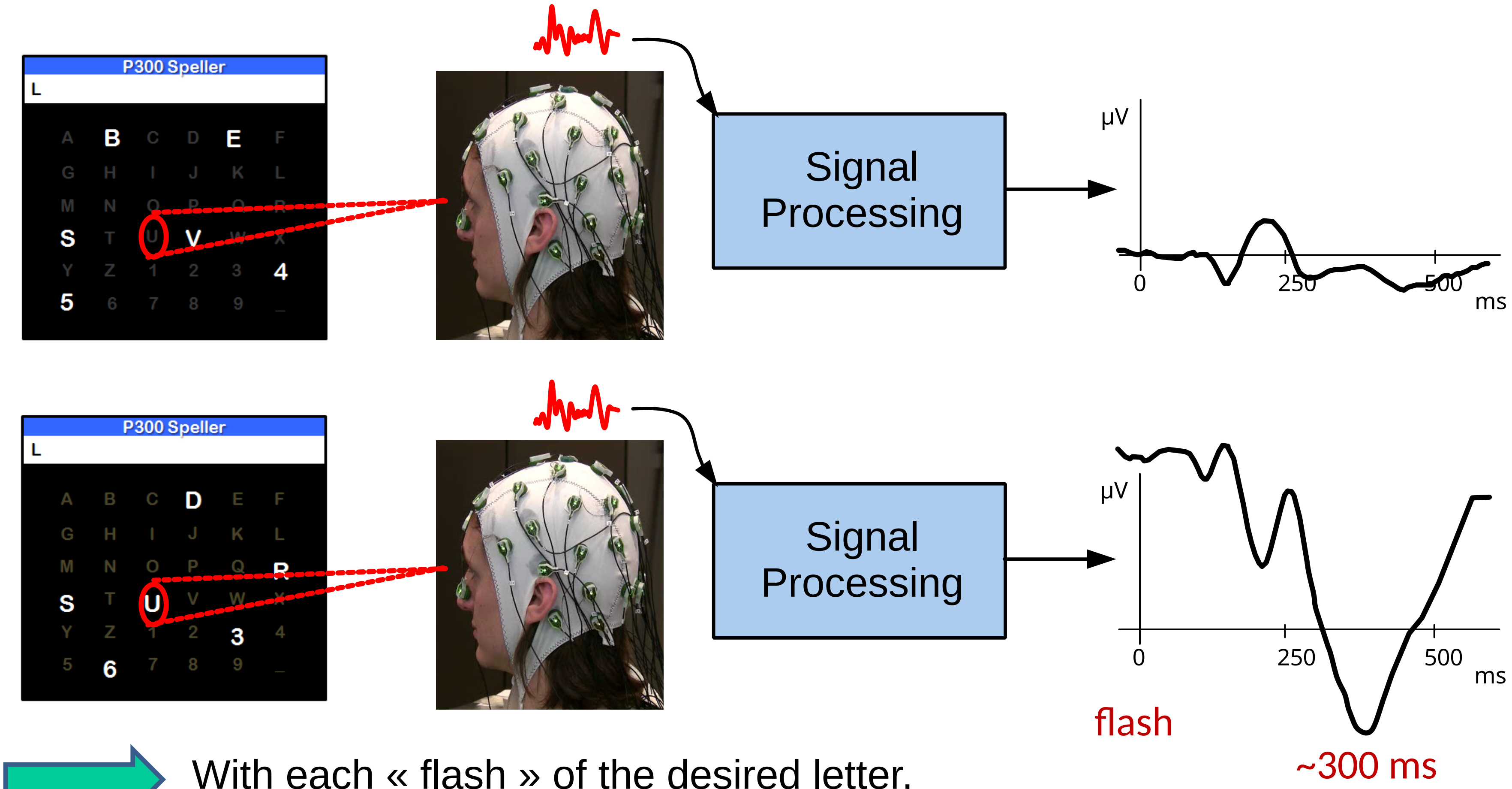
P300 wave based paradigms (2)

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 etal, 2009):

$$\mathbf{X} = \mathbf{DAW} + \mathbf{N}$$

EEG Signal

Mixing matrix

Time course model

Spatial model

Noise

Classification

$\hat{\mathbf{S}} = \mathbf{X}\mathbf{W}^T + \mathbf{N}\mathbf{W}^T$

$\hat{\mathbf{S}}$ is then compared to $\mathbf{A}_t$ or $\mathbf{A}_{nt}$.

Training

$$\mathbf{X} = \mathbf{D}_t\mathbf{A}_t\mathbf{W} + \mathbf{D}_{nt}\mathbf{A}_{nt}\mathbf{W} + \mathbf{N}$$

- $\mathbf{D}_t$, $\mathbf{D}_{nt}$ → Given by the computer clock (Toeplitz matrices).
- $\mathbf{A}_t$, $\mathbf{A}_{nt}$, $\mathbf{W}$ → Computed from calibration data.

P300 wave based paradigms (5)

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

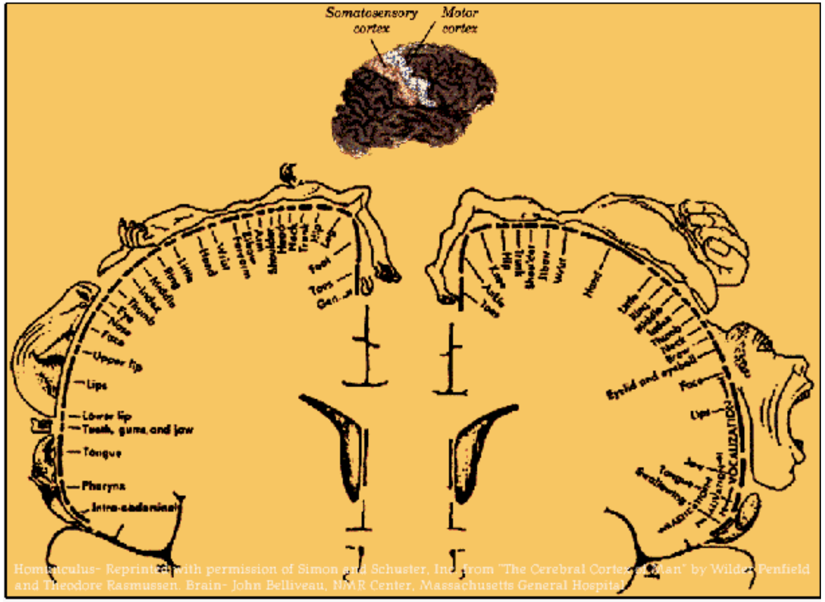
- Keyboard.
- Games.
- Environment control.

- Communication with Locked In subjects (auditive).

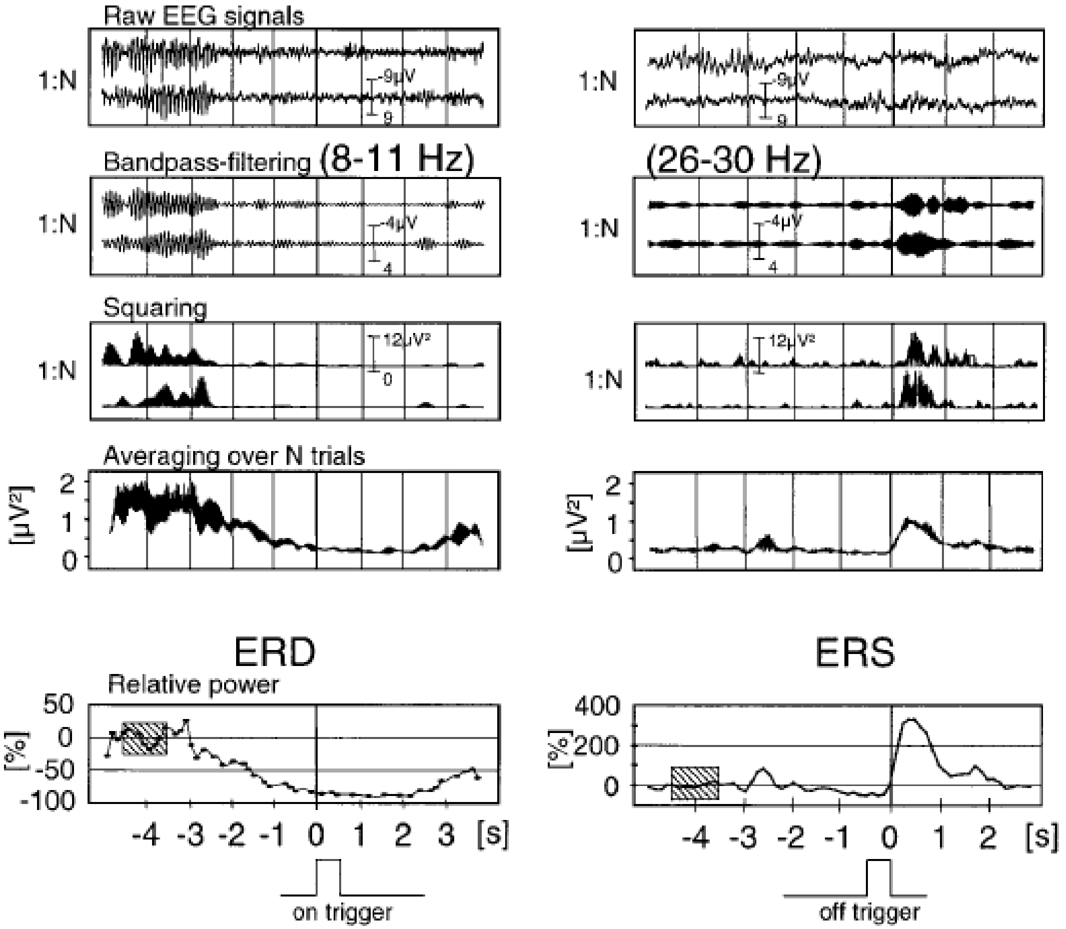
P300 wave based paradigms (6)

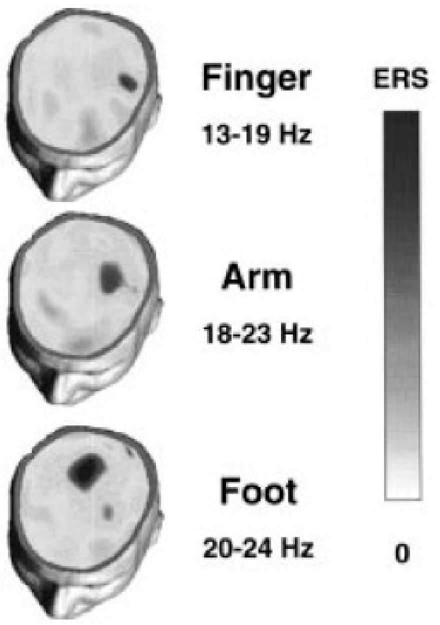
Sensorimotor paradigms

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



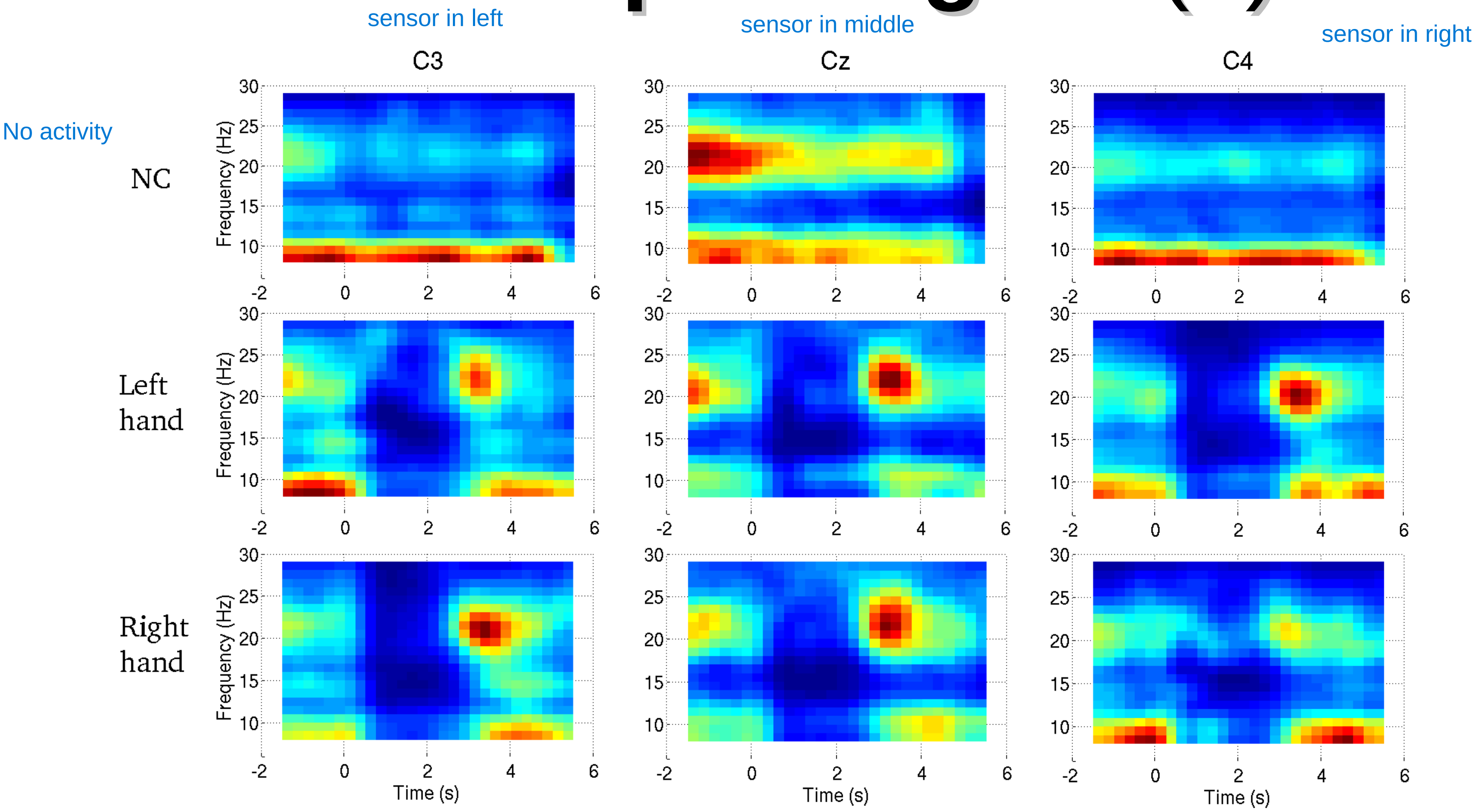
Sensorimotor paradigms (2)





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

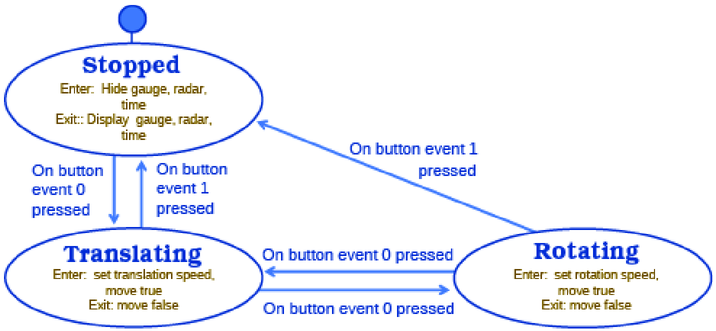
- Measure the task duration.

Continuous command cursor

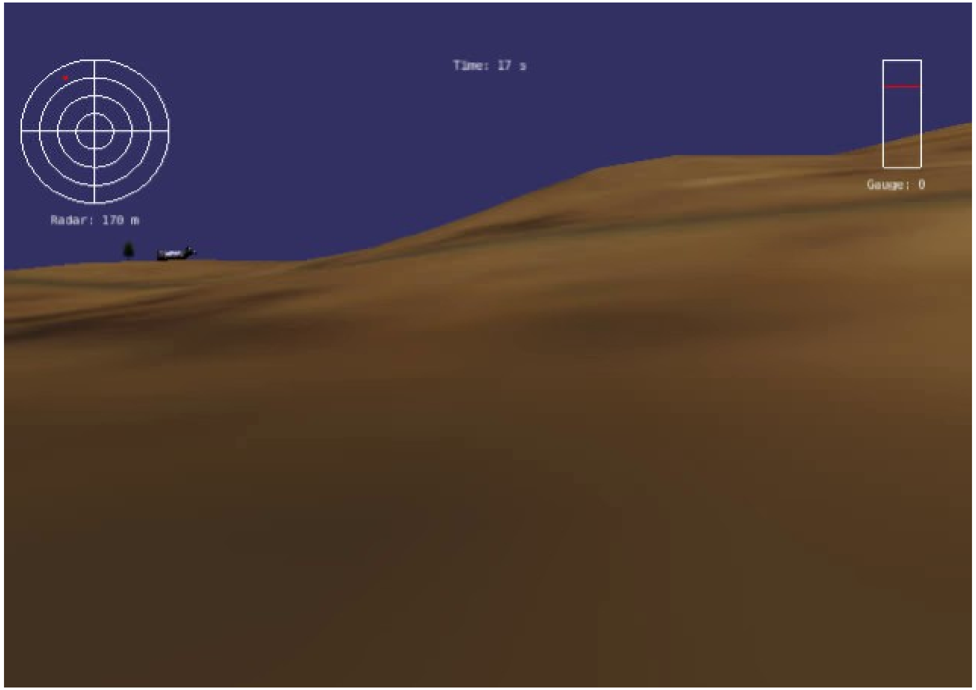
Note: non motor tasks are possible (mental calculus, 3D mental rotation, verbal tasks, …).

Sensorimotor paradigms (5)

Discrete command: button based on beta rebound.
Application: **Navigation** in a virtual environment.

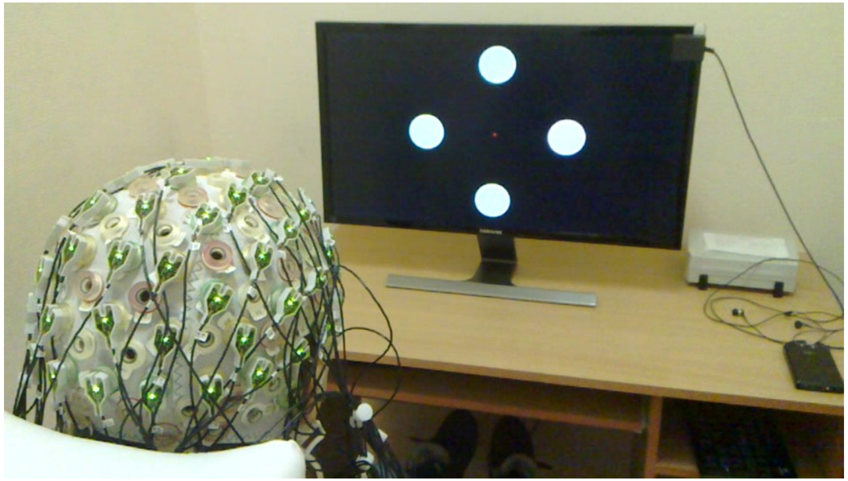


Logo turtle strategy.

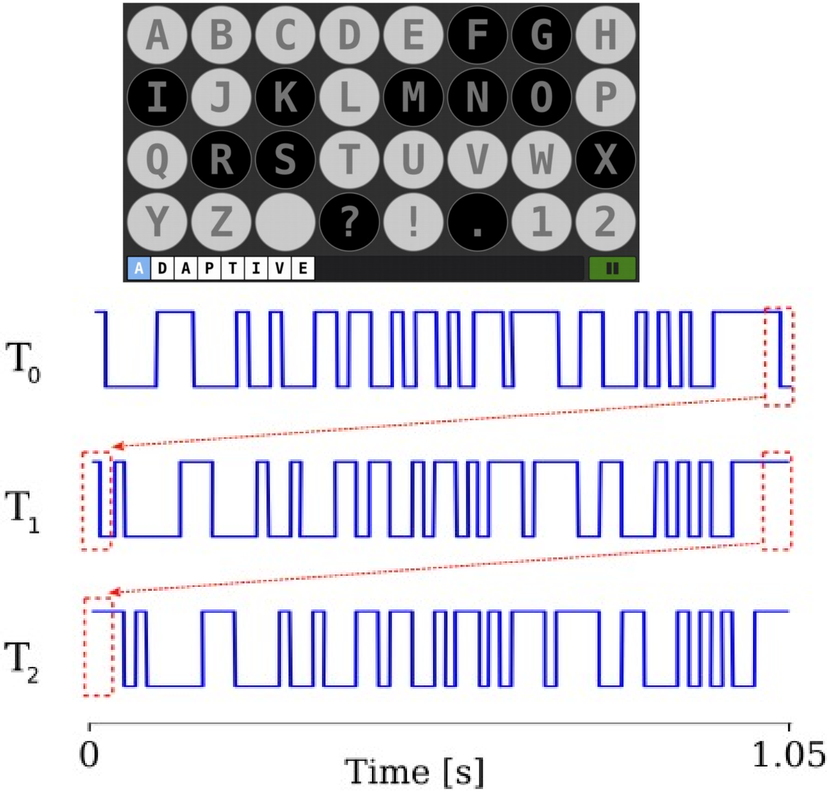


Visually Evoked Potentials

Information encoded as:

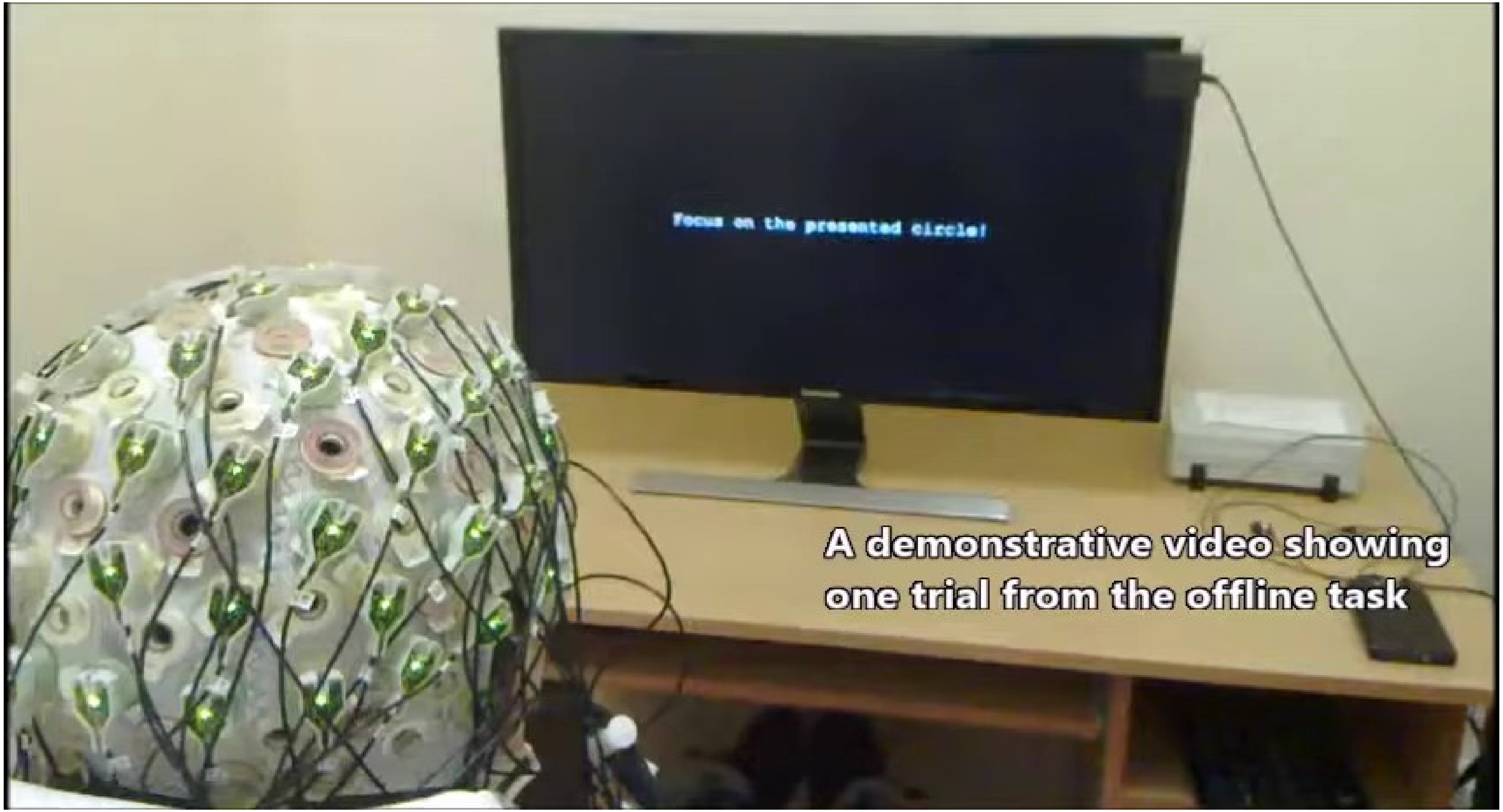


Frequencies (SSVEP)



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

Visually Evoked Potentials (2)

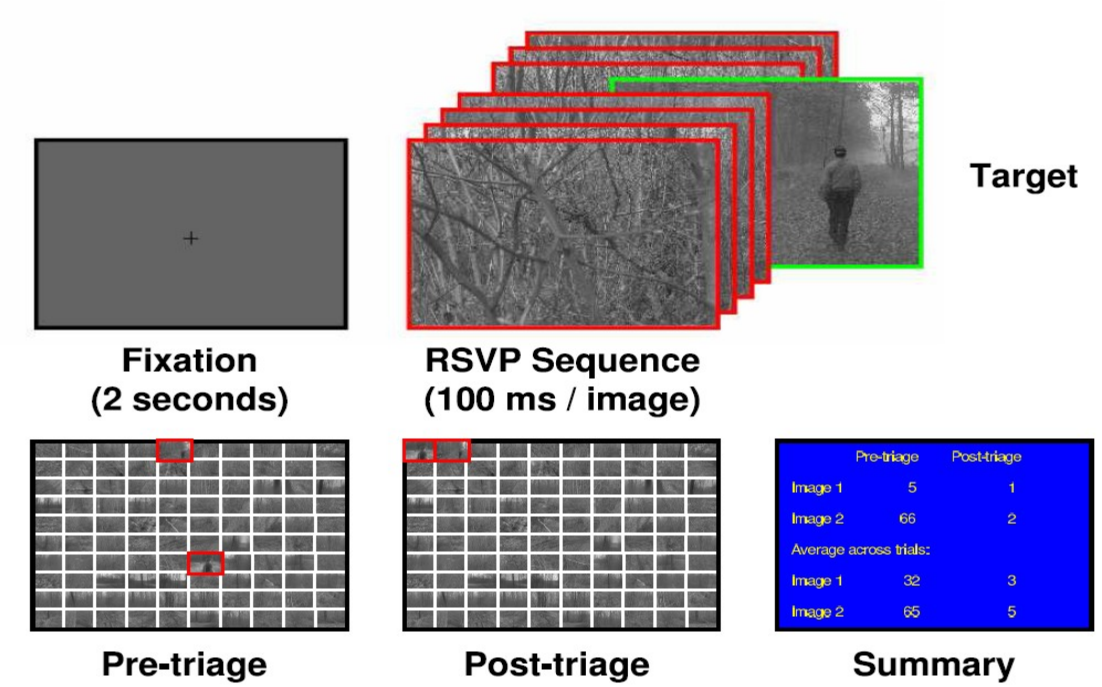


Ethical issues

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

Ethical issues

Cortically Coupled Computer Vision for Rapid Image Search.



DARPA: Neurotechnology for Intelligence Analysts

Thank you !!!