EEG TECHNIQUES FOR BRAIN COMPUTER INTERFACES

Basic Principles and Applications

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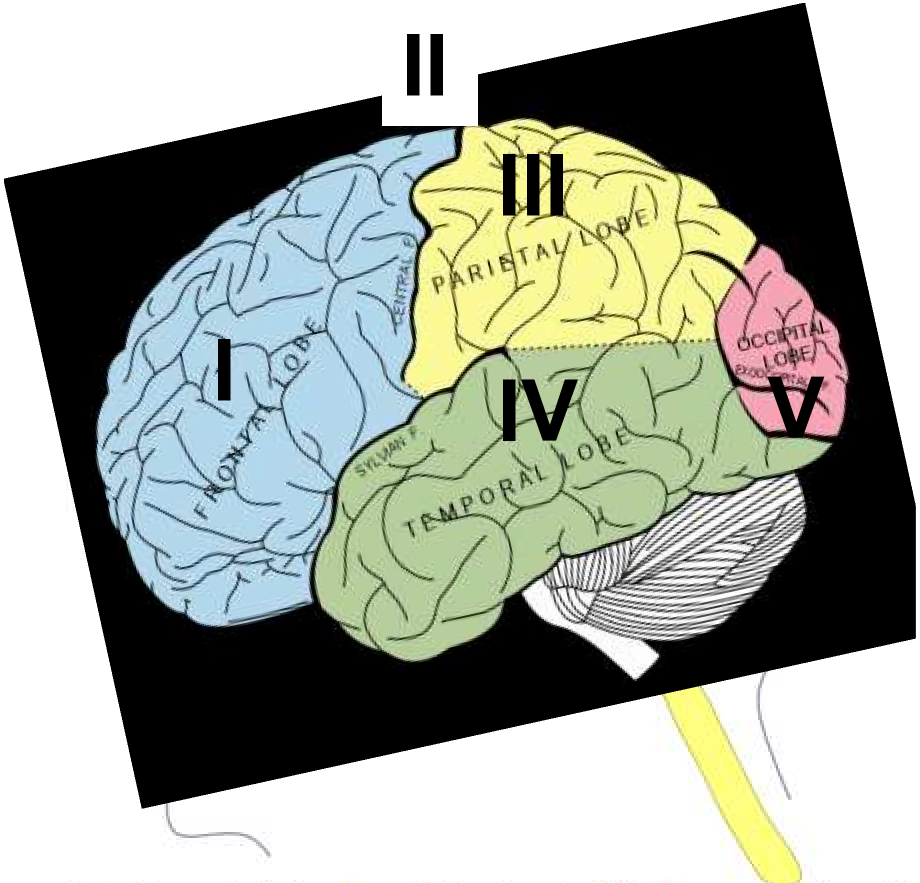
OUTLINE

- Brain Anatomy and Physiology (brief intro)
- Acquiring brain activity (EEG)
- EEG basis (Biological and Technical Principles)
- EEG phenomena usable for BCI
- Introduction on BCI
- EEG-based BCI paradigms
  - P300
  - Motor Imagery
- Applications

BRAIN ANATOMY



I Frontal Lobe (Motor / Higher Order Funct.

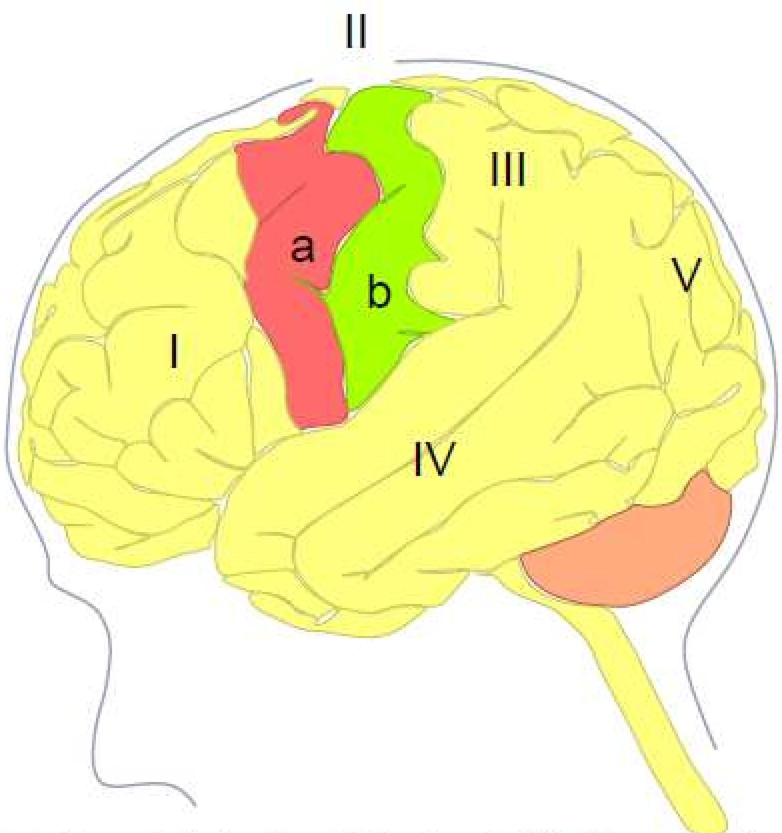
II Fissure of Rolando (Central Sulcus)

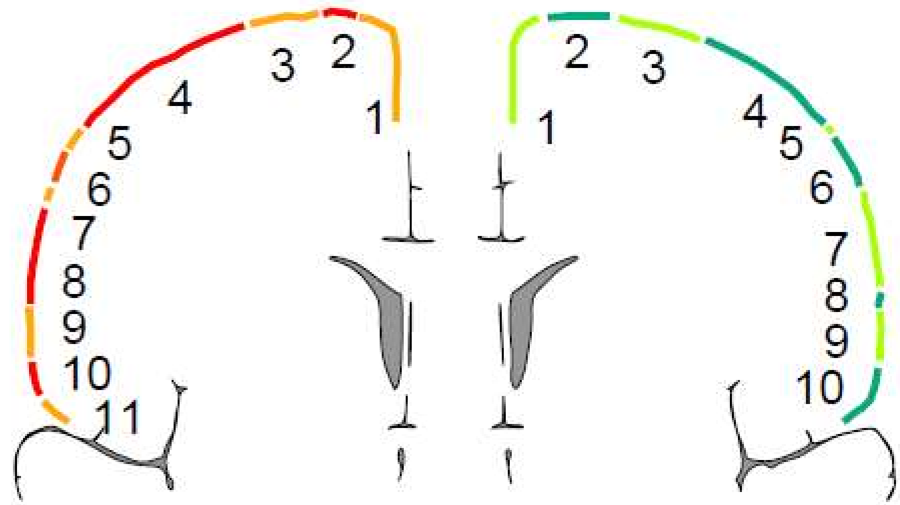
III Parietal Lobe (Sensation, Motor Control)

IV Temporal Lobe (Emotion, Hearing, Memory)

V Occipital Lobe (Vision, Color Recognition)

BRAIN ANATOMY





1 Foot, Leg
2 Trunk, Head
3 Arm
4 Hand, Fingers
5 Eye
6 Face
7 Lips
8 Jaw, Teeth
9 Tongue
10 Pharynx
11 Intra – abdominal

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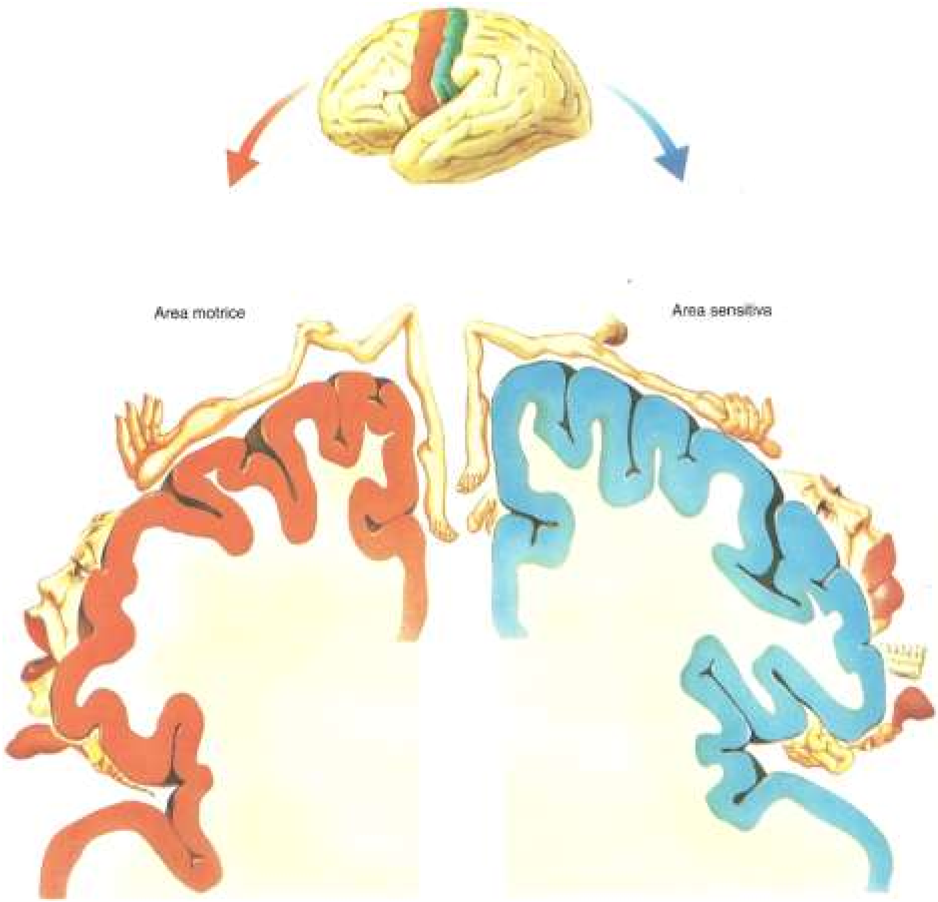
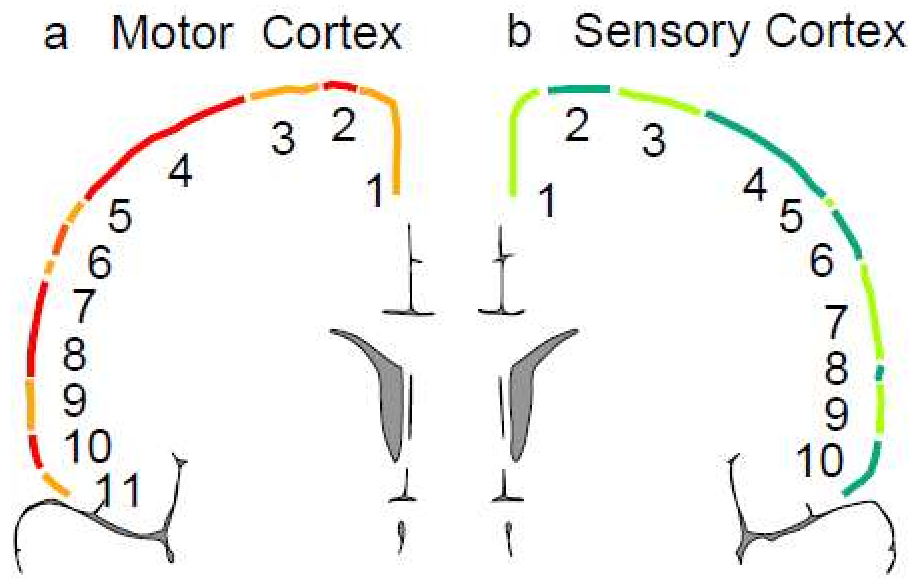
The Primary Somatic Sensory Cortex (Parietal Lobe) and the Primary Motor Cortex (Temporal Lobe) are the most important regions for BCI research.

BRAIN ANATOMY





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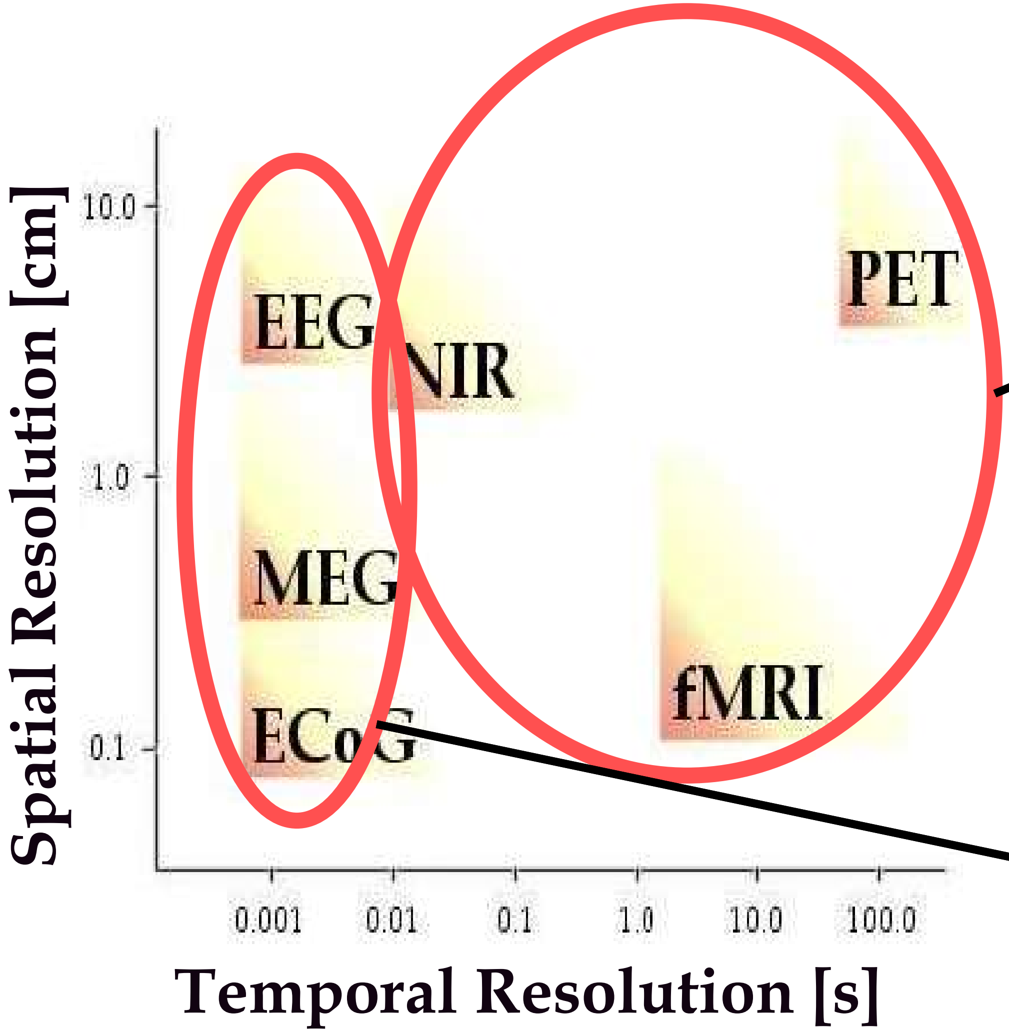
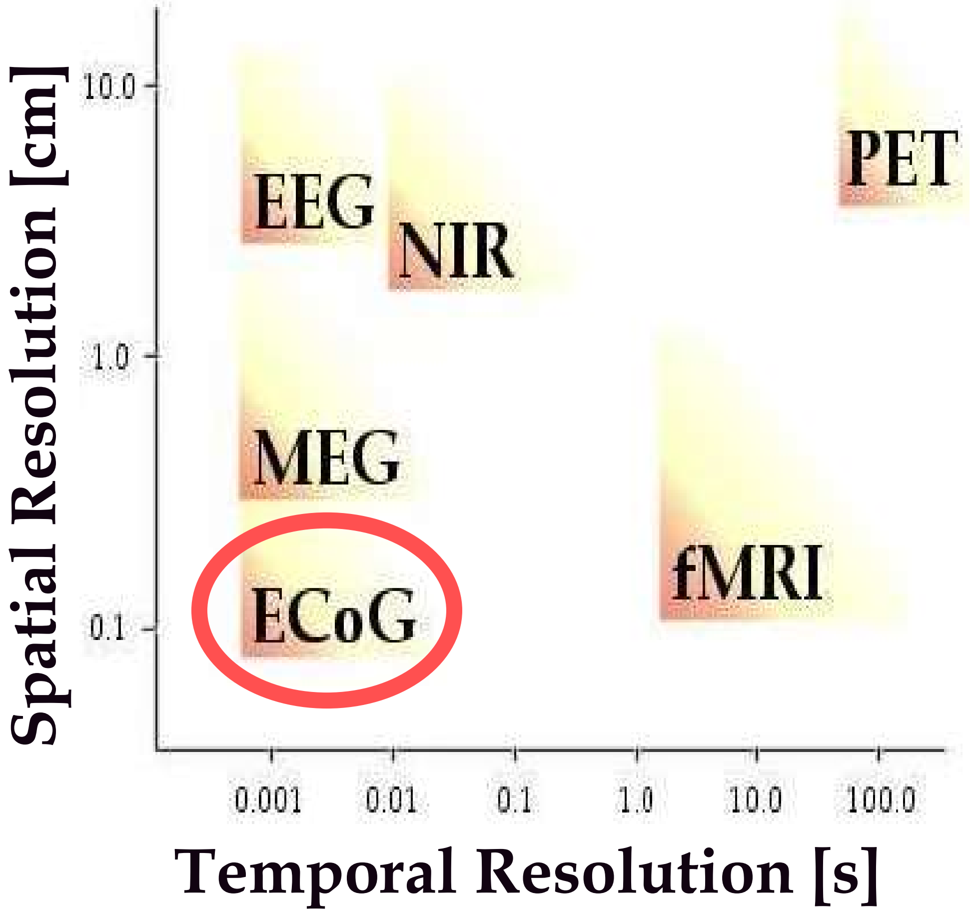
ACQUIRING BRAIN ACTIVITY



BASED ON THE BLOOD FLOW VARIATION

BASED ON THE MAGNETIC-ELECTRICAL ACTIVITY

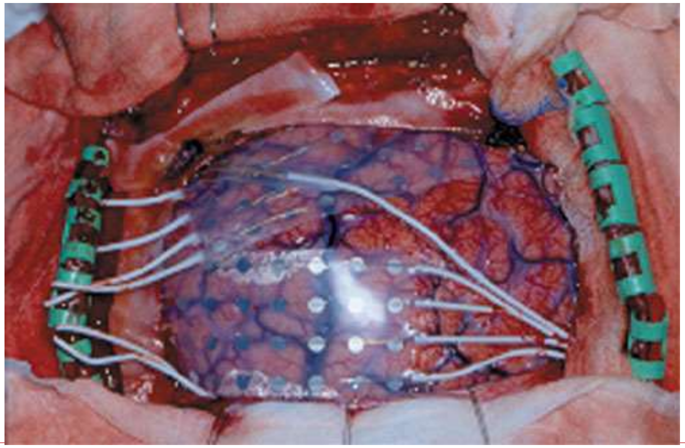
ACQUIRING BRAIN ACTIVITY



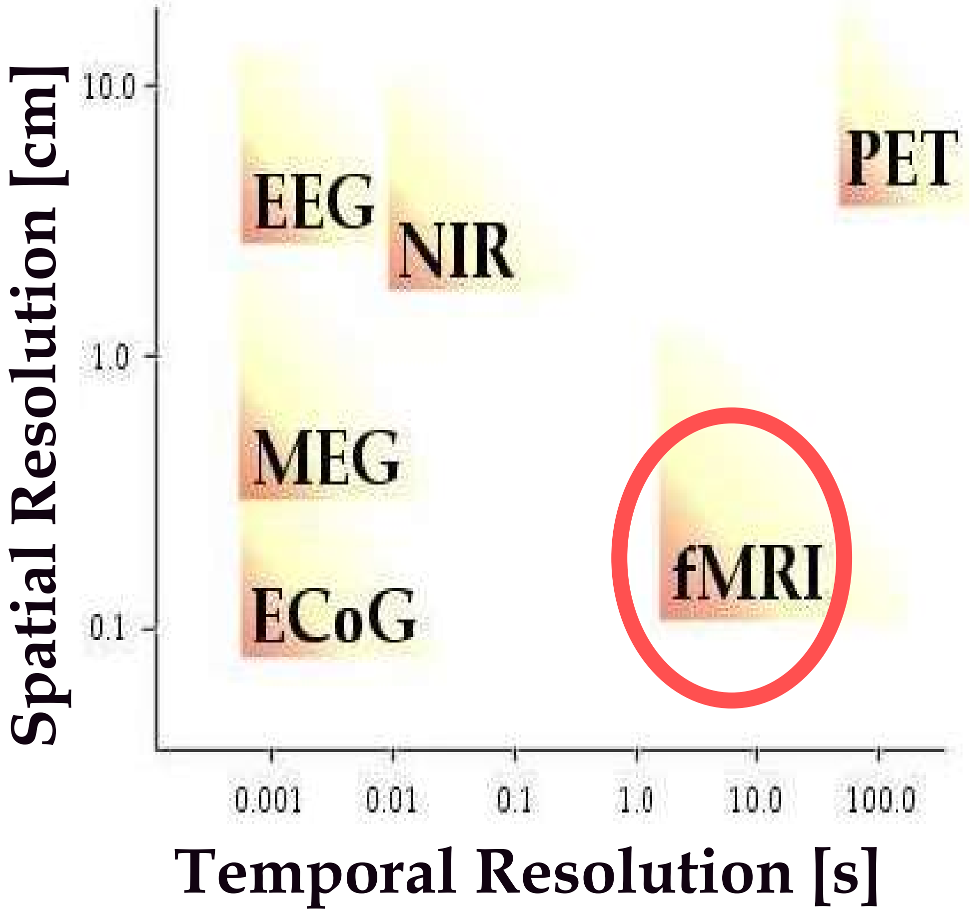
ElectroCorticoGraphy (ECoG)

Very good spatial and temporal resolution (firing of a single neuron)

INVASIVE
Surgical intervention



ACQUIRING BRAIN ACTIVITY

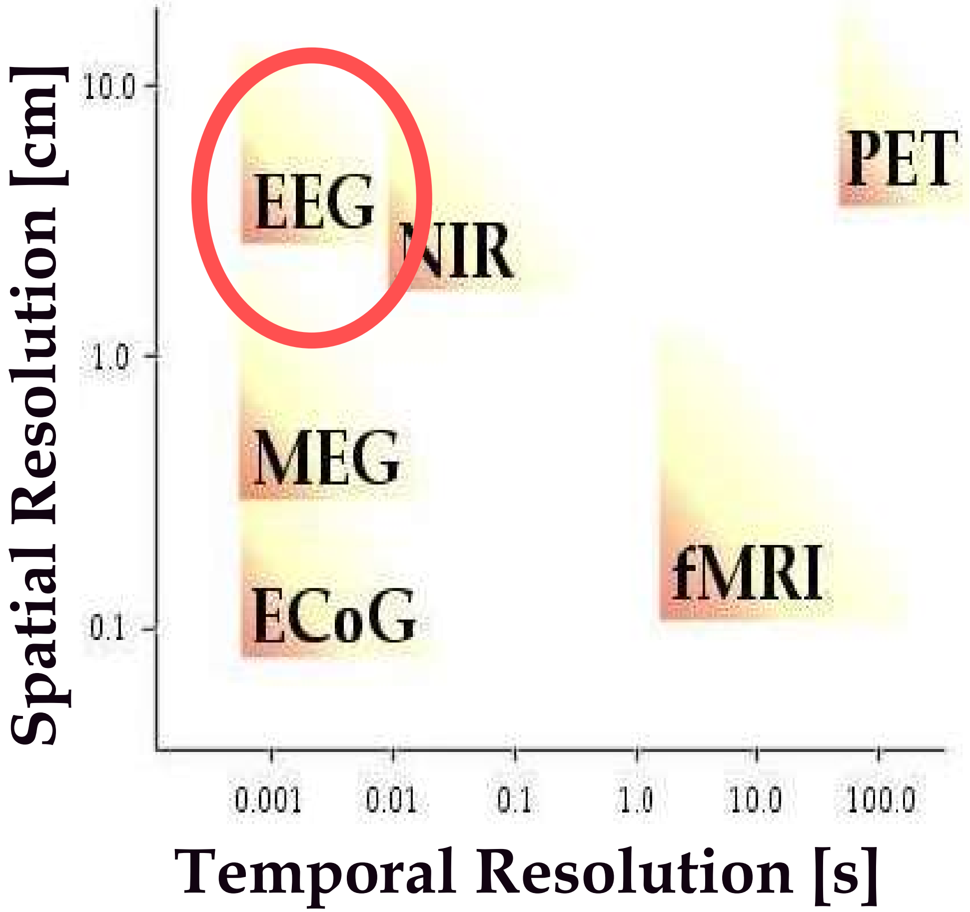


fMRI measures brain activity by detecting associated changes in blood flow.

fMRI presents a good Spatial Resolution (it is possible to map the brain to identify regions linked to critical functions such as speaking,moving,planning)

fMRI suffers from a low Temporal Resolution and an inherent delay, since it is based on a hemodynamic response rather than electrical signals.

ACQUIRING BRAIN ACTIVITY



EEG is the record of electrical activity of brain by placing the electrodes on the scalp.

Most widely used strategy for BCI applications

Good Temporal Resoltion

Several **portable**, **cheap systems** exist

Motion artifacts and interferences can be greatly reduced by employing active electrodes

EEG

- Electrical activity of neurons produces currents spreading through the head.
- These currents reach the surface of the scalp, in the form of voltage changes and magnetic fields, both of which can be measured non-invasively.
- Measured voltage changes at the scalp are called the *electroencephalogram* (EEG).

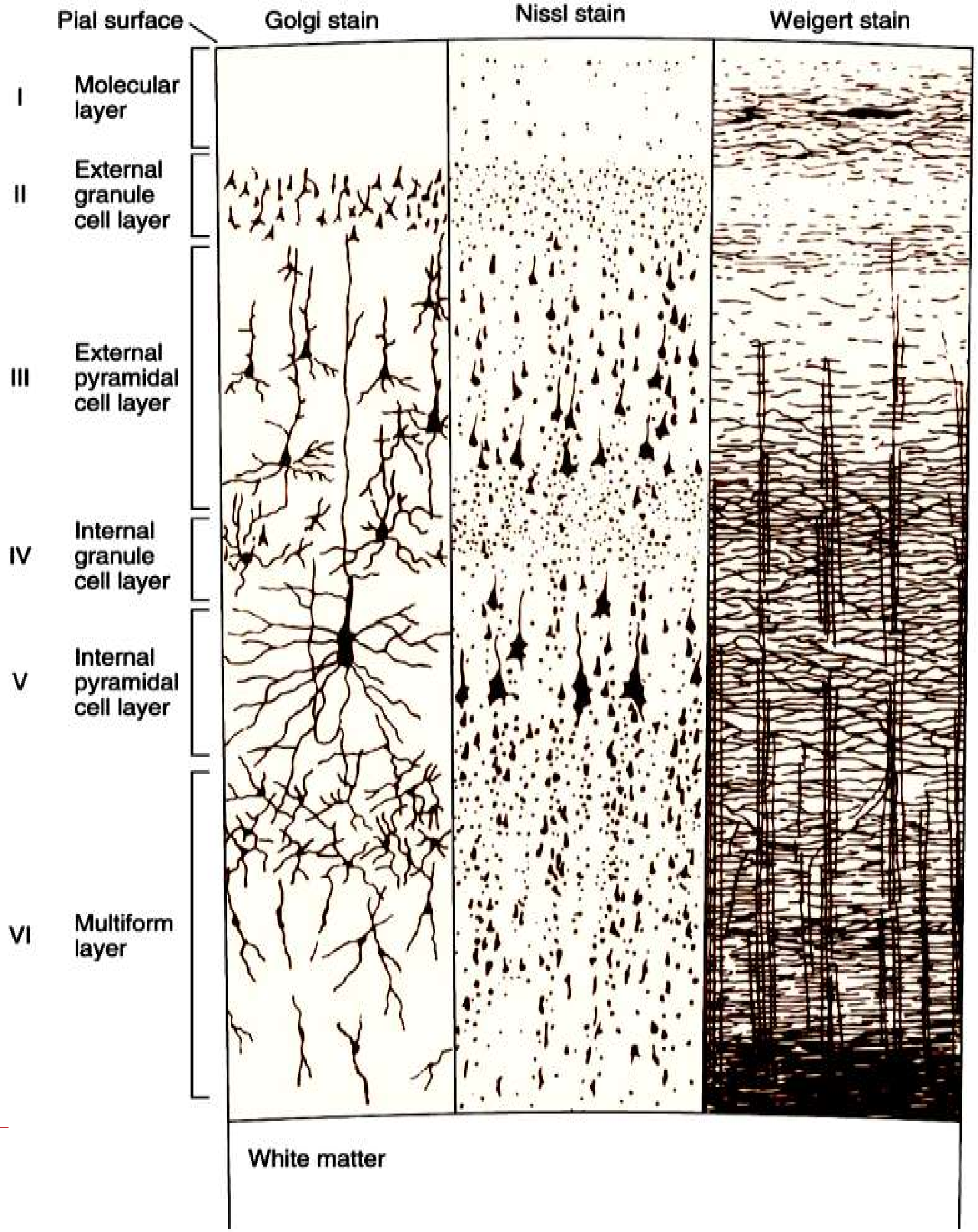
EEG is the record of electrical activity of brain by placing the electrodes on the scalp.

BRAIN ELECTRICAL ACTIVITY

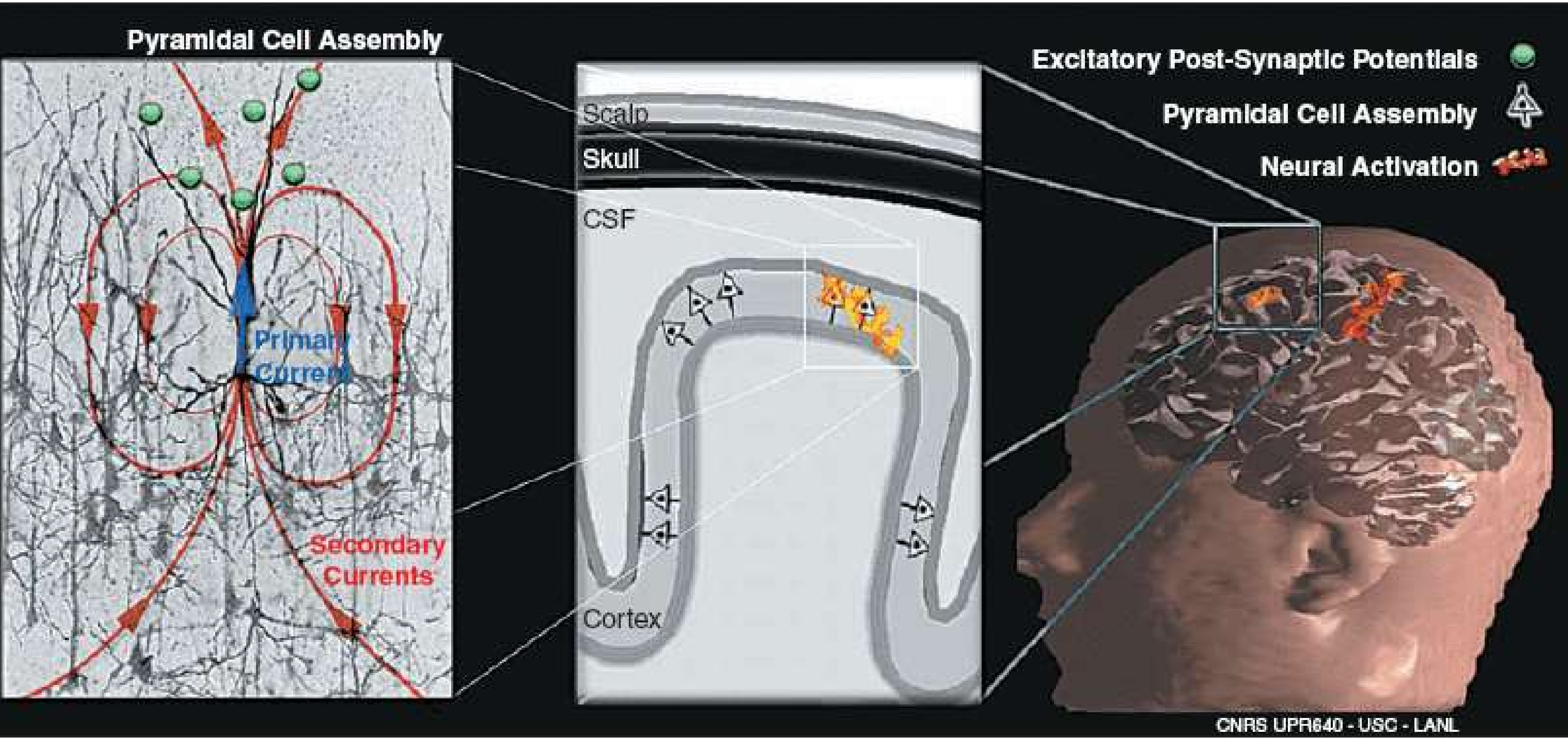
EEG is the record of electrical activity of brain by placing the electrodes on the scalp.

The elctrical brain activity is generated mainly by Cortical Neurons, and it could be considerated as the sum of the following process:

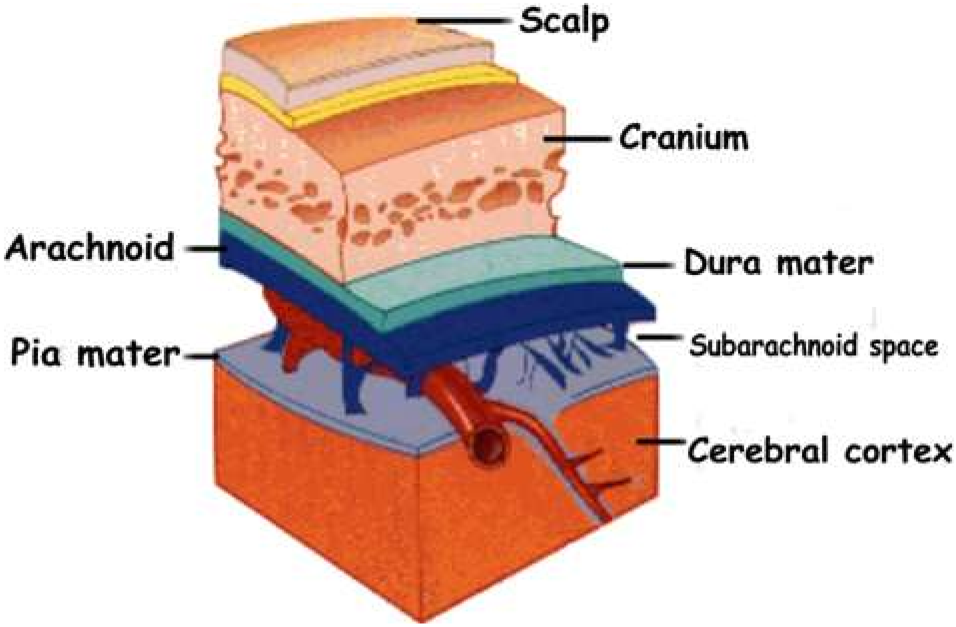
1. Synapsys
2. Denditric Potential
3. Action Potentials
4. Neuroglia Potentials



Genesis of EEG activity

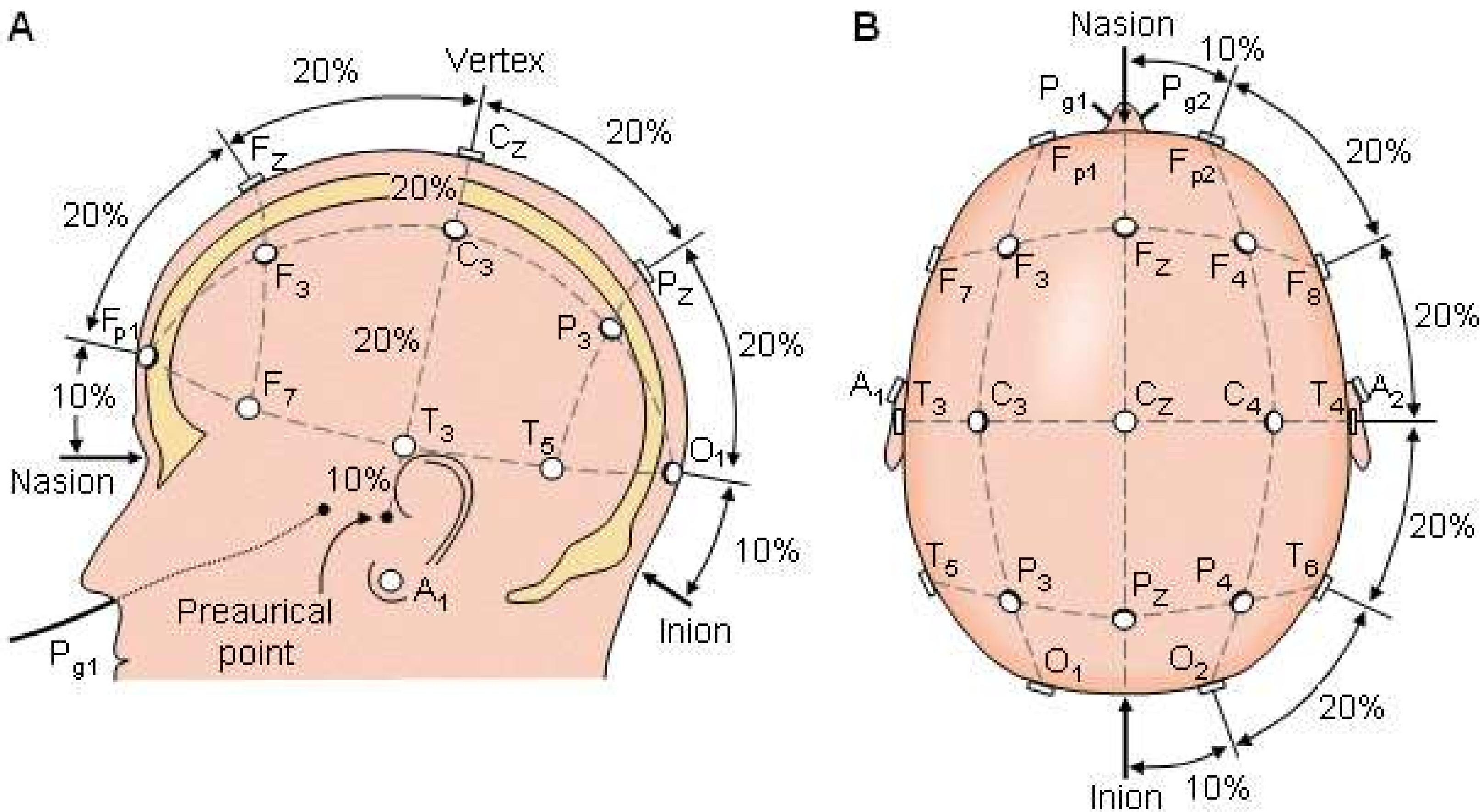


Genesis of EEG activity



EEG RECORDING

International (10-20) Electrode Placement



•Each electrode site is labeled with a letter and a number.

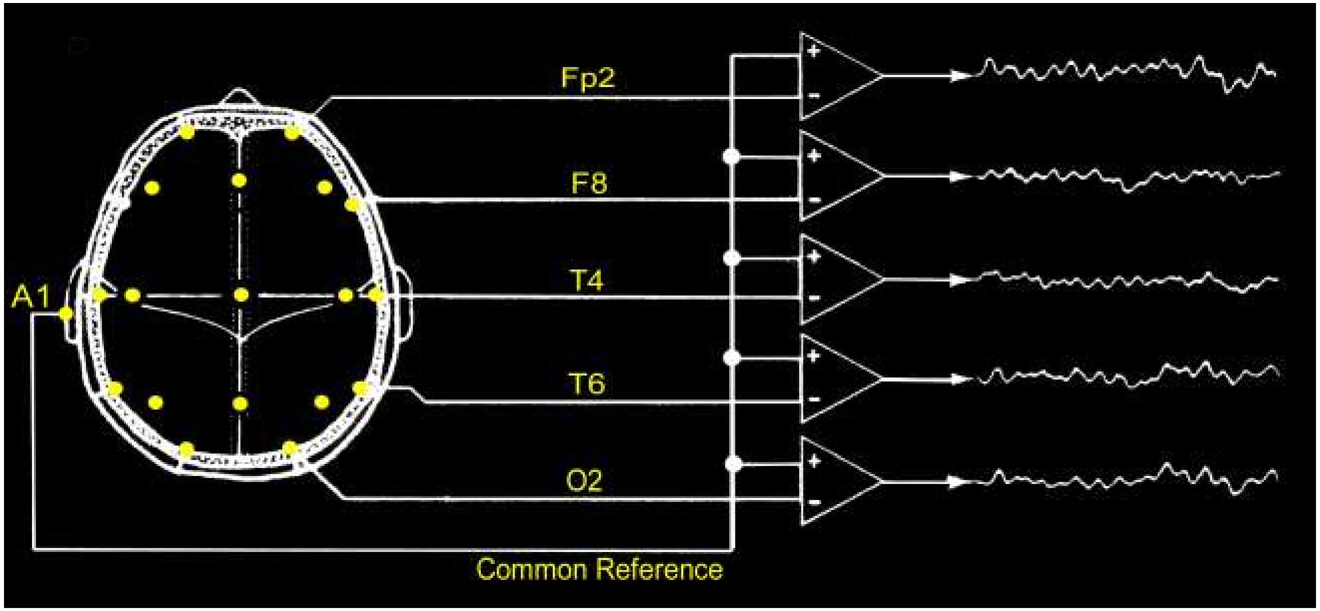
•The letter refers to the area of brain underlying the electrode

•Even numbers denote the right side of the head and

•Odd numbers the left side of the head.

EEG acquisition: practical hints.

EEG is a difference in potential between two electrodes. The acquired signal is conveniently amplified and conditioned, and successively digitalized.



- If the two electrodes are "active", the recording is called "bipolar".
- If one electrode is "silent", the recording is called "monopolar". Possible reference sites are: ear lobe, mastoid, nose.

EEG SIGNALs FEATURES

- **AMPLITUDE RANGE**:
  - Wake EEG:: Vpp = 100µV
  - Sleep EEG: Vpp = 300µV
- **FREQUENCY RANGE**:
  - From 0.01 to 100 Hz
- **Zero Mean**
- **COMMON EEG ARTIFACTs**:
  - Eye blinking (eye movement)
  - Muscular activity (EMG)
  - ambient (50Hz-60Hz) Noise
  - Head Shake
  - Electrodes Movement

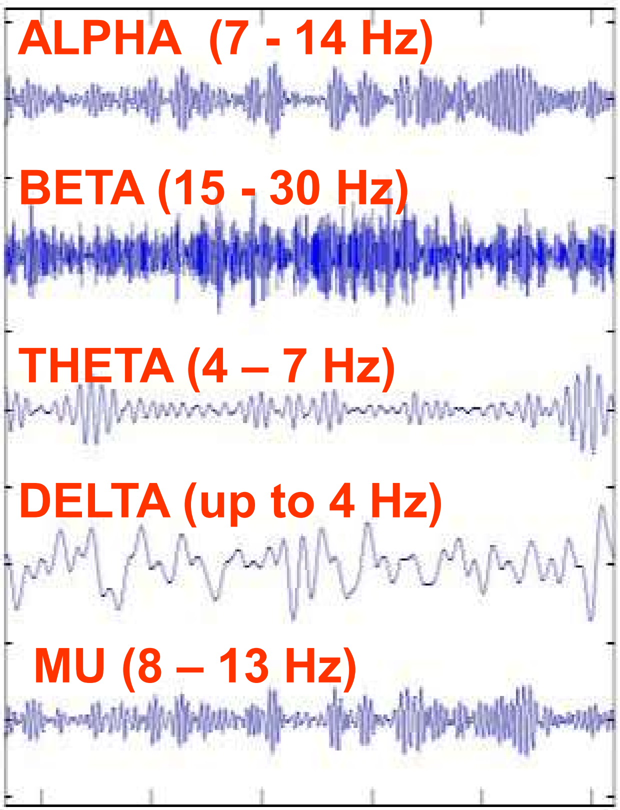
REMINDER : Caratteristiche EMG

AMPIEZZA: 10uV – 2mV

Frequenza: 20Hz - 500Hz

EEG rhythmic activity

I ritmi di fondo del segnale EEG
Si distinguono per frequenza



Band	Location	Normally
Alpha	posterior regions of head, both sides, higher in amplitude on non-dominant side.	• closing the eyes • Also associated with inhibition control,
Beta	both sides, symmetrical distribution, most evident frontally;	• alert • active, busy, or anxious thinking, active concentration
Theta	Found in locations not related to task at hand	• Associated with inhibition of elicited responses
Delta	frontally in adults, posteriorly in children; high-amplitude waves	• Has been found during some continuous-attention tasks
Mu	Sensorimotor cortex	• Shows rest-state motor neurons.[42]

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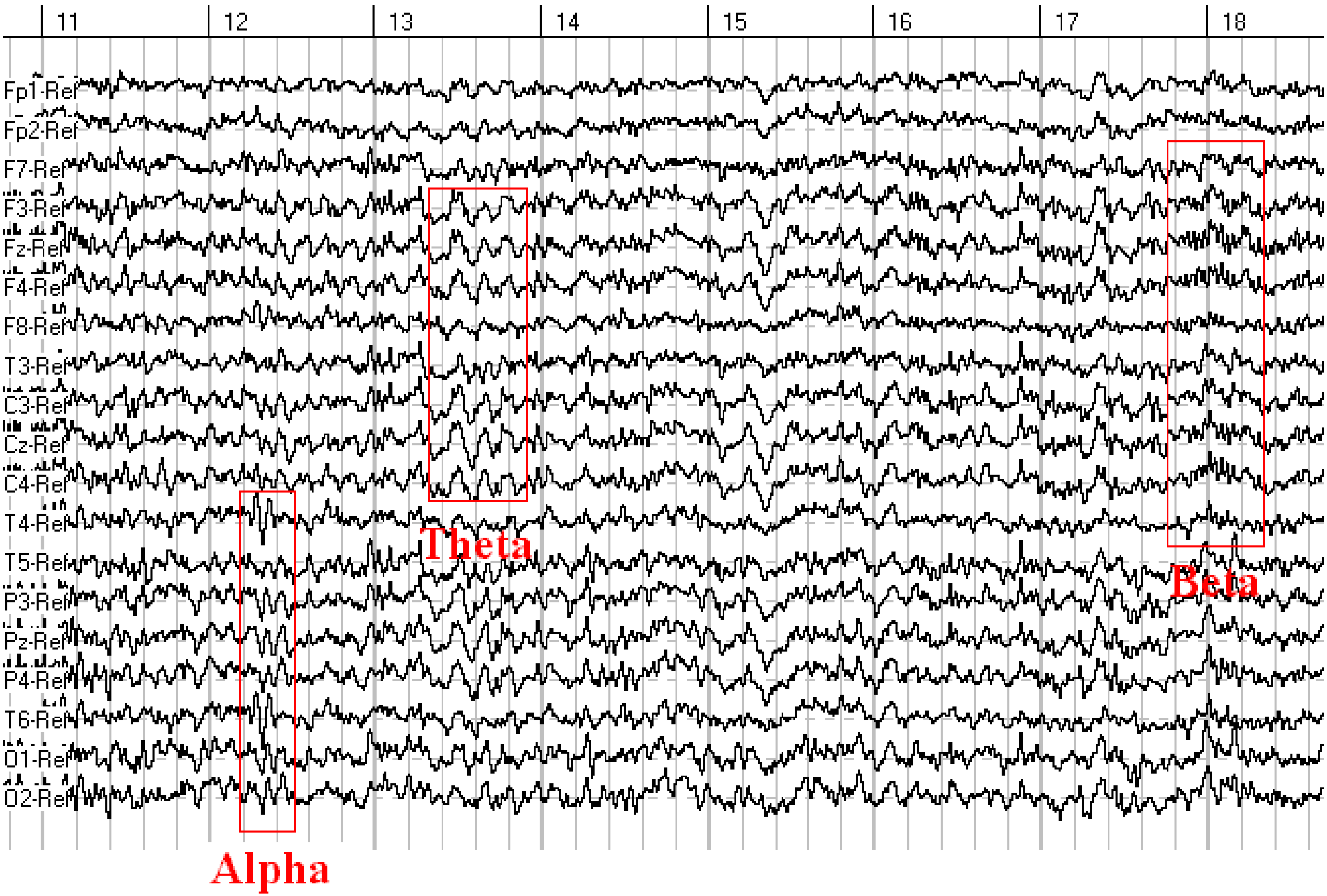
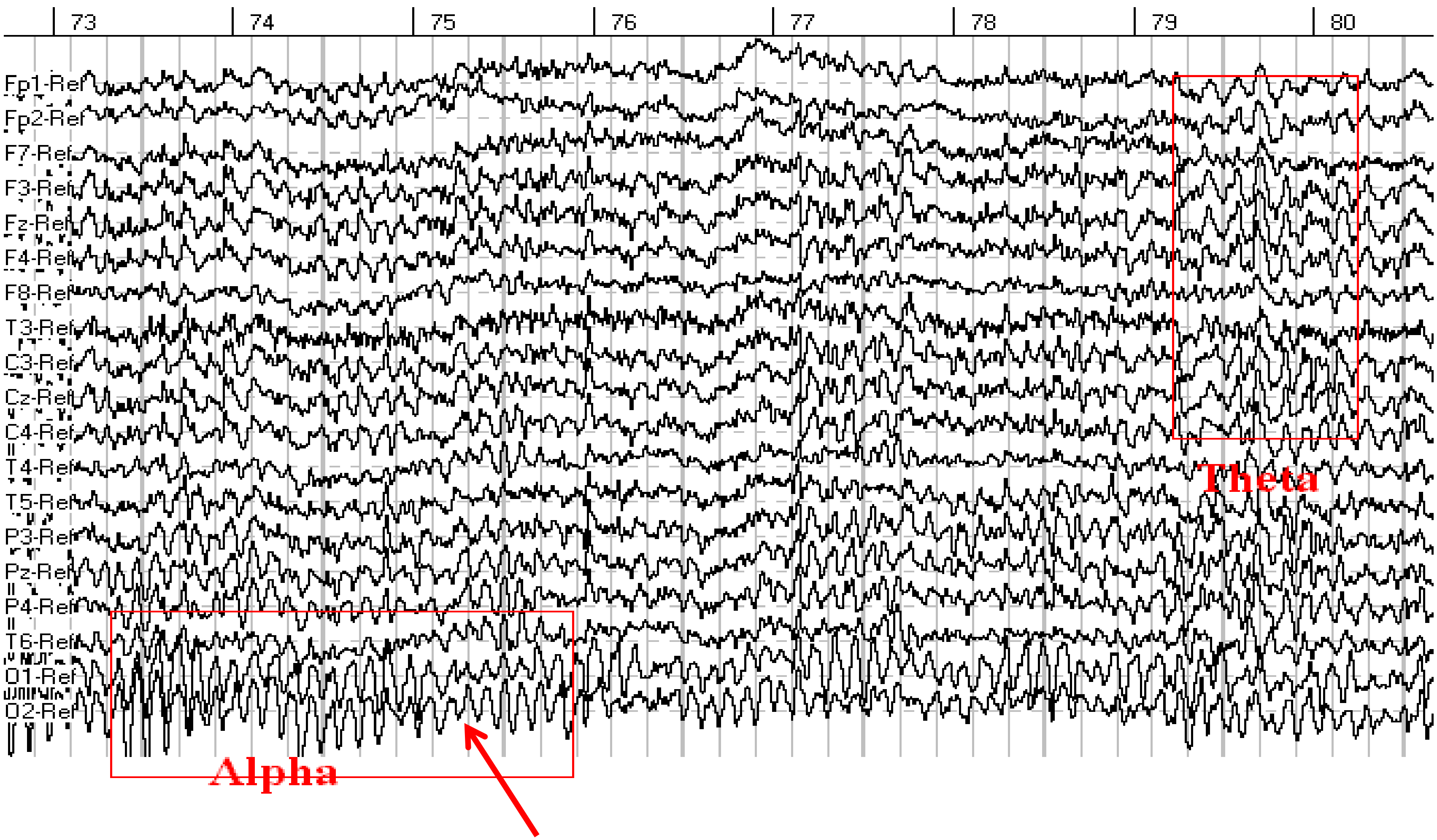
EEG recording during wake, eyes open

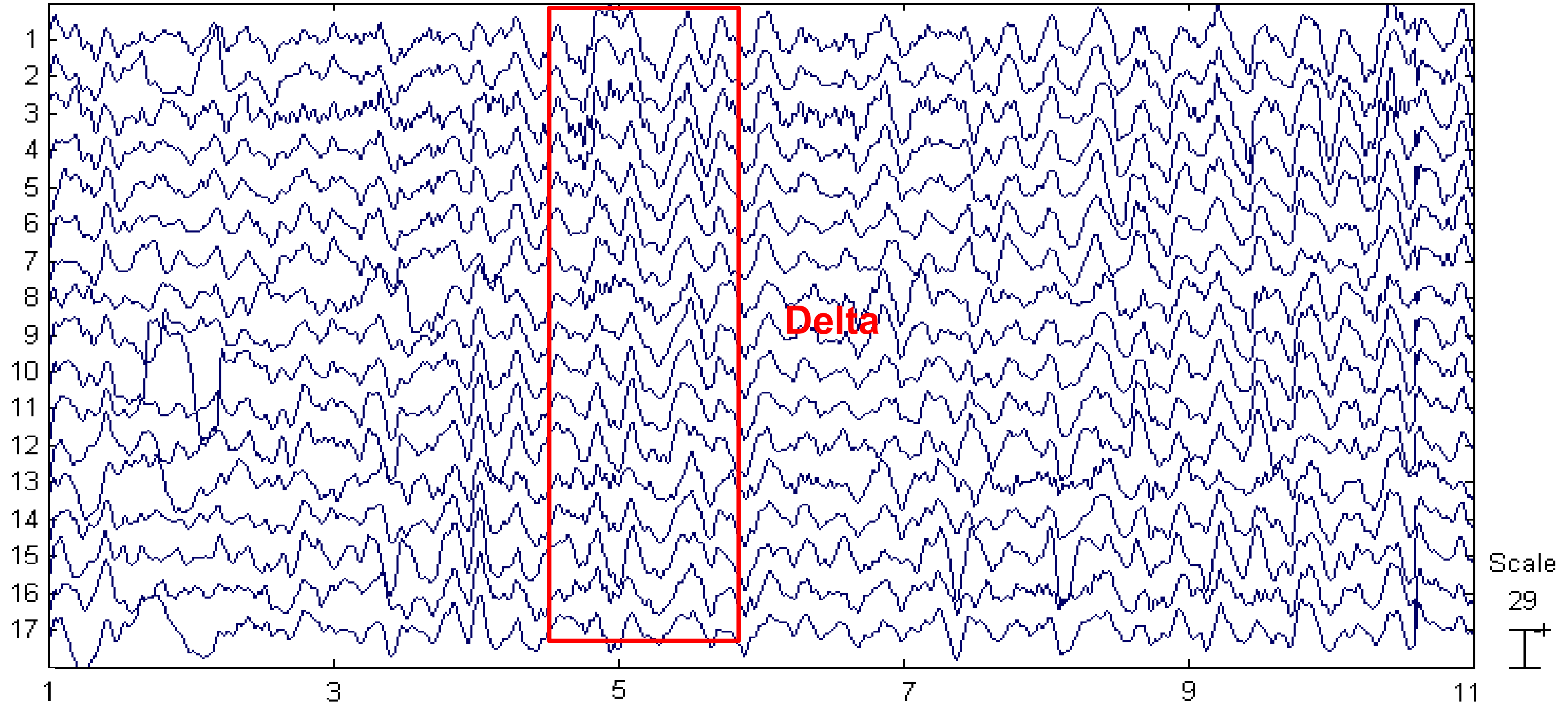


EEG recording during wake, eyes closed



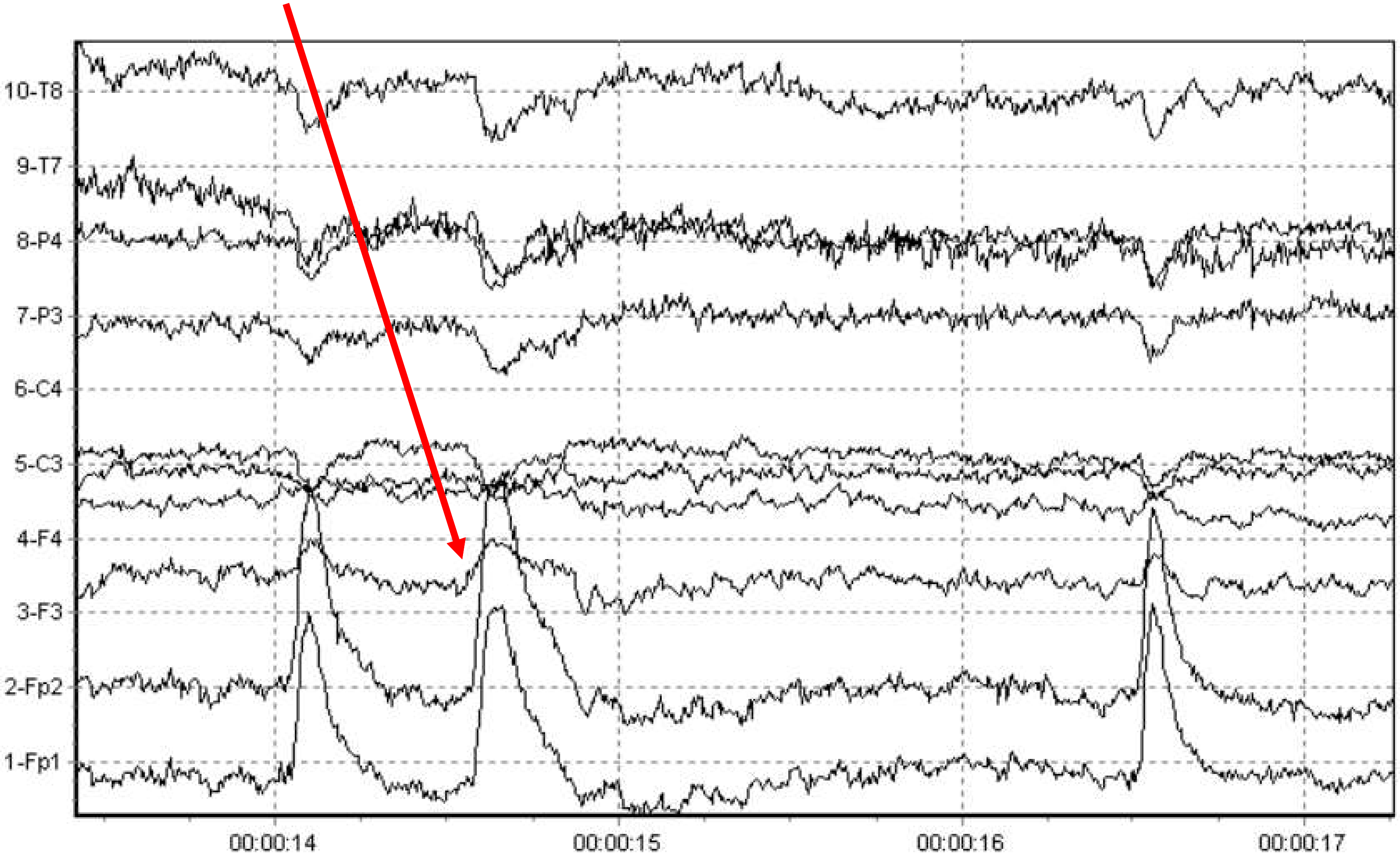
Enhancement of alpha waves during eyes-closed condition

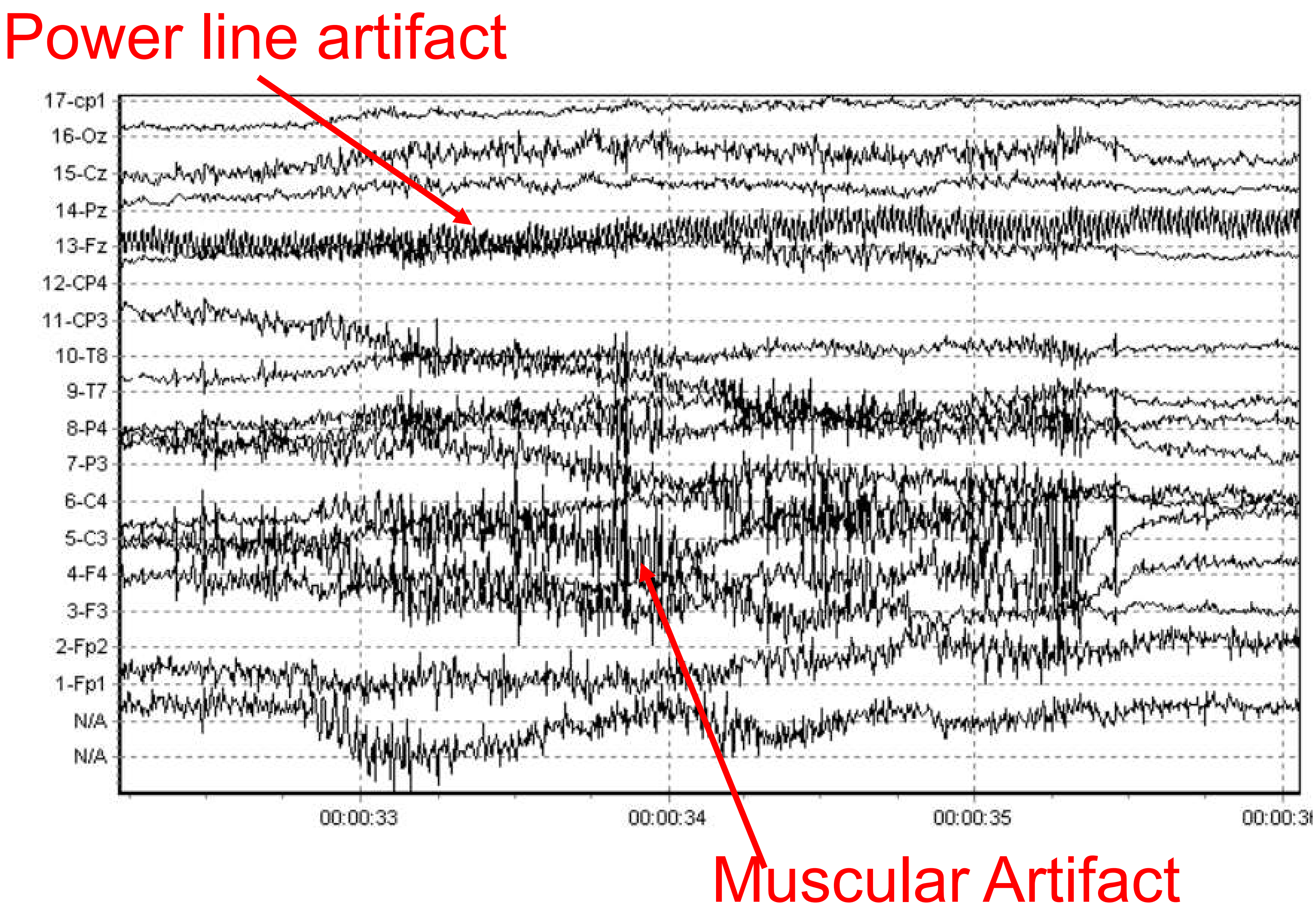
EEG recording during NREM sleep

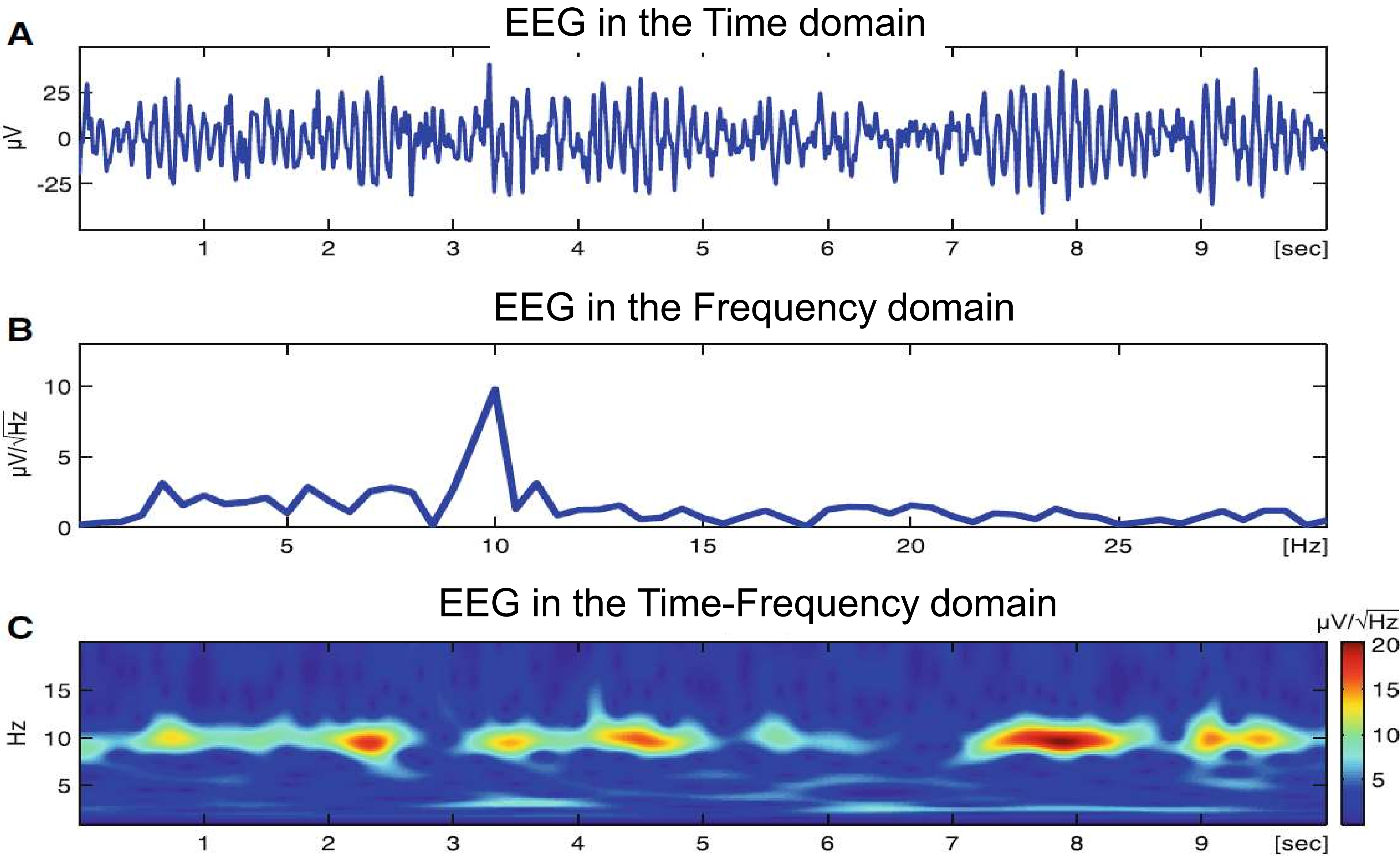


EEG activity during non-REM sleep (high amplitude and highly synchronous delta waves).

Eye blink artifact

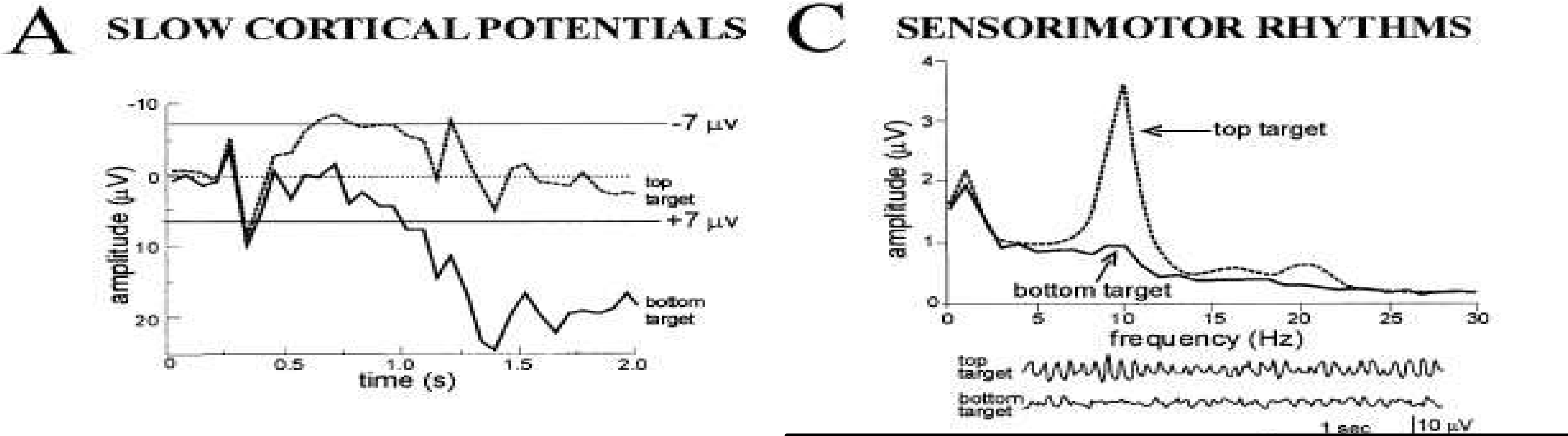


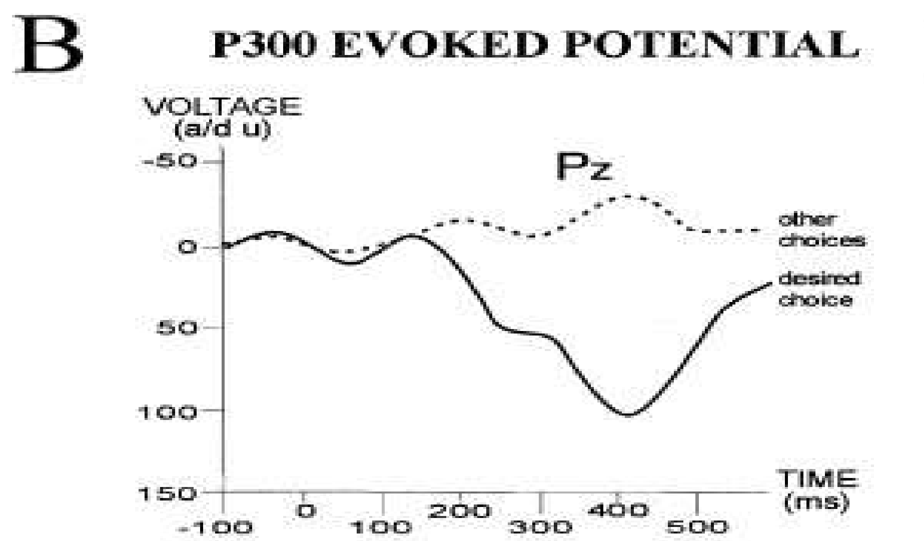

Power line artifact
17-cp1
16-Oz
15-Cz
14-Pz
13-Fz
12-CP4
11-CP3
10-T8
9-T7
8-P4
7-P3
6-C4
5-C3
4-F4
3-F3
2-Fp2
1-Fp1
N/A
N/A
00:00:33
00:00:34
00:00:35
Muscular Artifact



Herrmann, Christoph S., et al. "Time–Frequency Analysis of Event-Related Potentials: A Brief Tutorial." *Brain topography* (2013): 1-13.

EEG PHENOMENAL USABLE FOR BCI





A : Potenziali Oscillatori Lenti

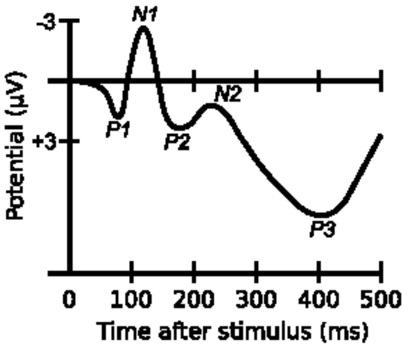
B: Potenziale Evento-correlati

C: ritmi sensitivo-motori

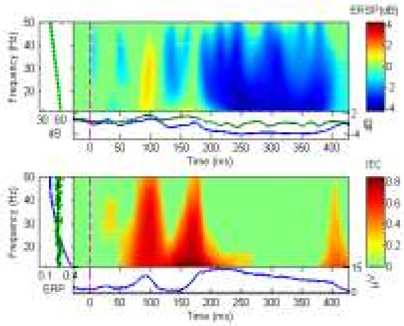
J R Wolpaw, N Birbaumer, D J McFarland, G Pfurtscheller, and T M Vaughan. Brain-computer interfaces for communication and control. Clin Neurophysiol, 113(6):767–791, Jun 2002.

EEG PHENOMENAL USABLE FOR BCI

- **Event Related Potential (ERP)**:
  - An event-related potential (ERP) is the measured brain response that is the direct result of a specific sensory, cognitive, or motor event.
    - Repeatedly present discrete stimulus, average raw EEG responses across presentations.



- **Event Related Spectral Perturbation (ERSP)**:
  - The ERSPs are similar to the ERP but they take into account also frequency information
    - Average *spectral features* across presentation.
    - Characteristic suppression/increase in power (ERD/ERS: Event Related De-Synchronization).



EVENT RELATED POTENTIAL (ERP)

- The ERPs recorded on the scalp represent the neural activity inside the brain.
- This activity is correlated to :
  - sensory information
    - Evoked brain activity related to a physical stimulus
  - motor processes
    - Brain activity that reflects motor preparation
  - cognitive processes
    - Related to the mental task the user is performing (mental object rotation, computational tasks, etc…)

ERP AND EVOKED POTENTIAL (EP)

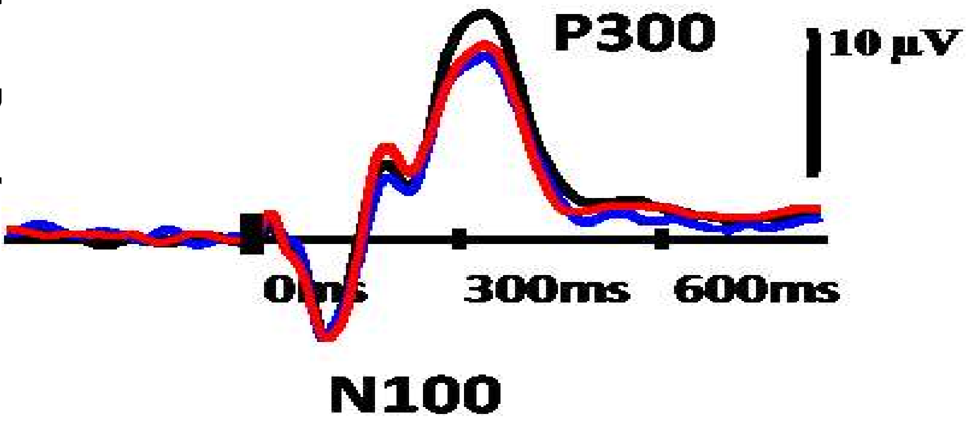
- The ERP reflects the synchronous activity of those neurons that are involved in the stimulus information processing.

- Thus ERPs are changes in the EEG signal that result from a stimulus (eg, visual, auditory or somesthetic).

- When the stimulus is an event defined experimentally, the resulting ERP is called EVOKED POTENTIAL

ERP AND EVOKED POTENTIAL (EP)

❑ The naming sch
identify the Positiv
their latency (defir
stimulus onset).



EXAMPLES:

❑ N100 → A negative peak that occurs 100ms after the stimulus onset (is usually associated with visual and auditory sentence comprehension tasks.)

❑ P300 → Would identify the positive peak occurred 300ms post stimulus onset (Attention to stimuli, low probability of targets)

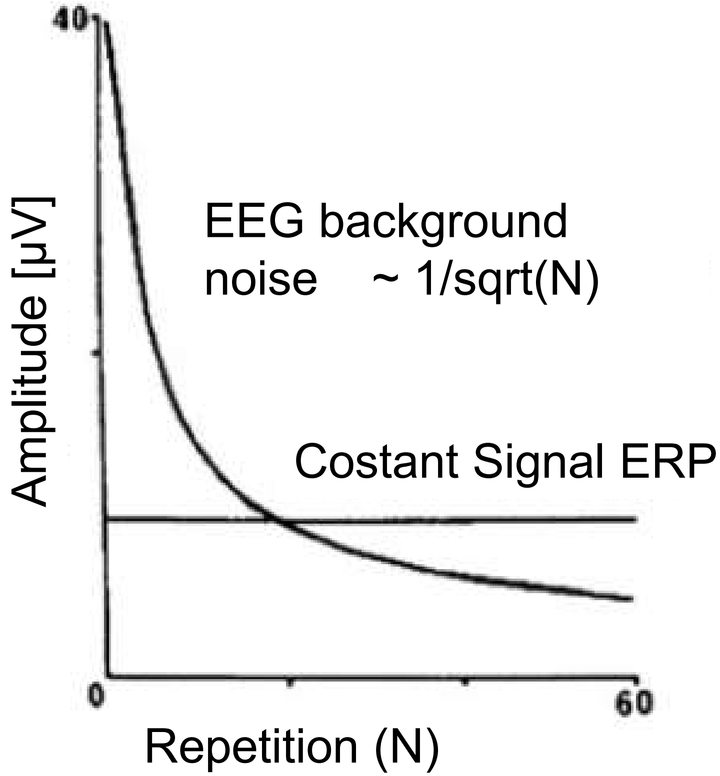
AVERAGING

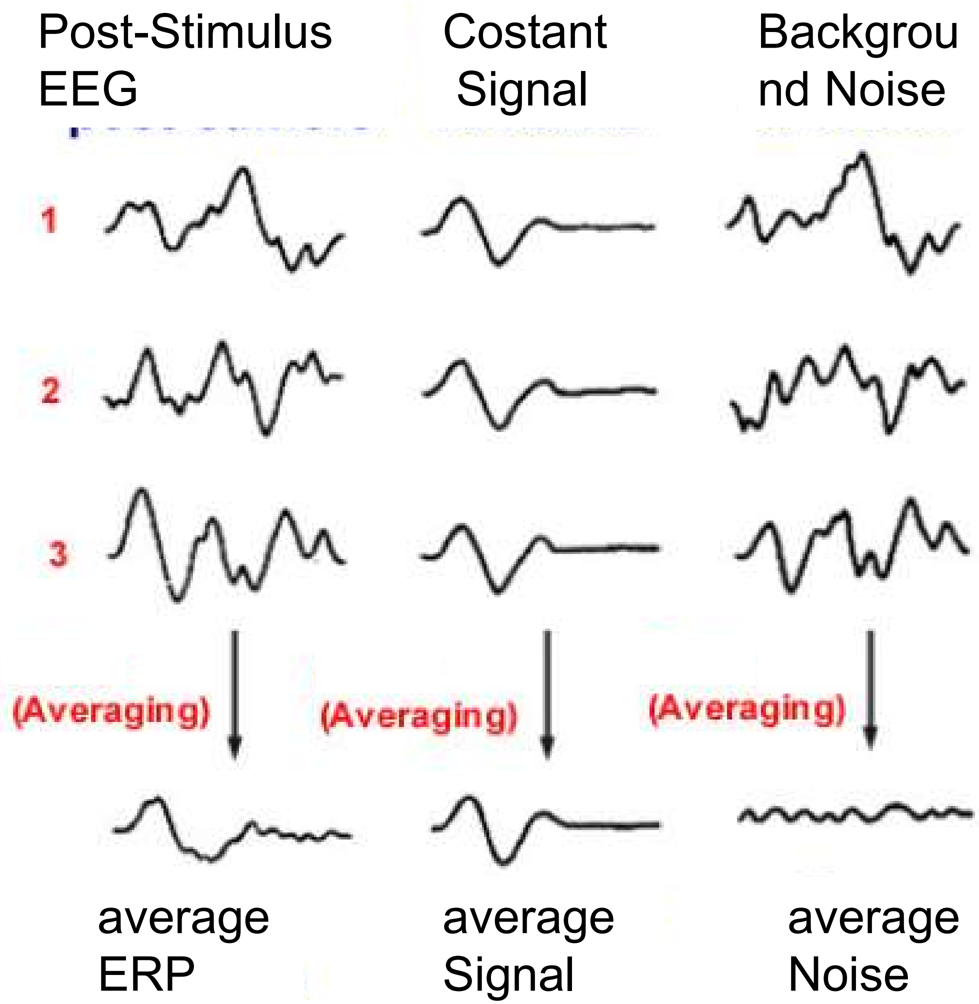
- ERPs have a very small size compared to the ongoing EEG

- The ERPs are then extracted from the background noise mediating many recordings (Epochs)

- Segment length: at least 100 ms should precede the stimulus onset (for baseline correction).

AVERAGING THEORY

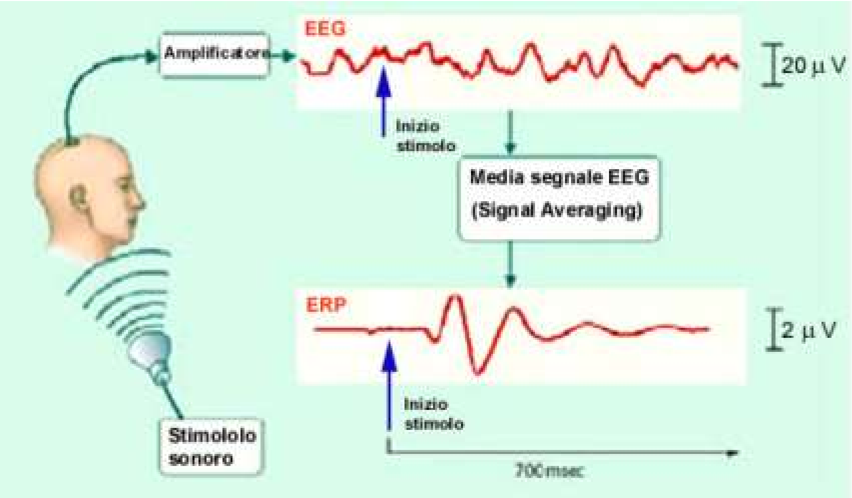


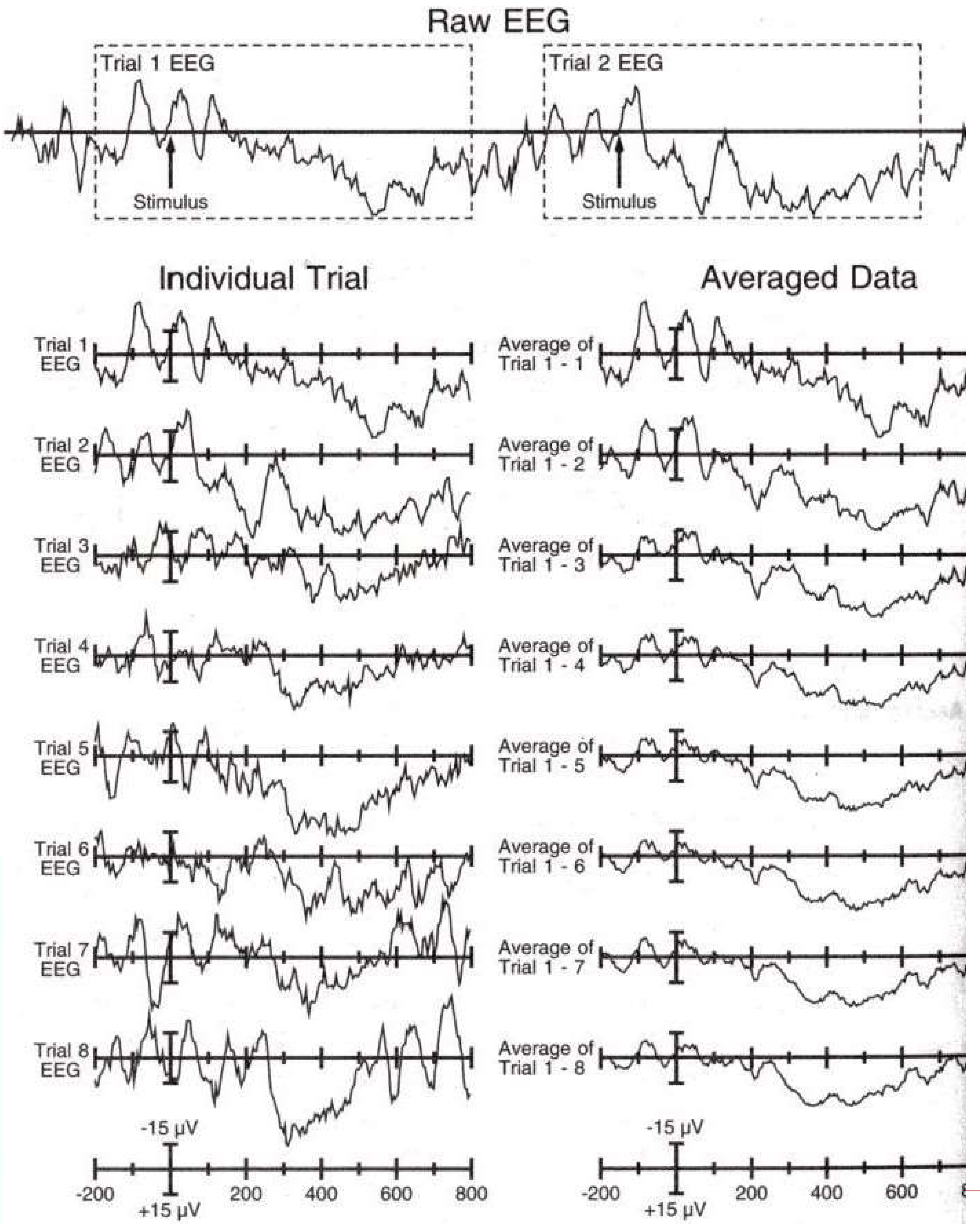


AVERAGING

S/N ratio increases as a function of the square root of the number of trials.

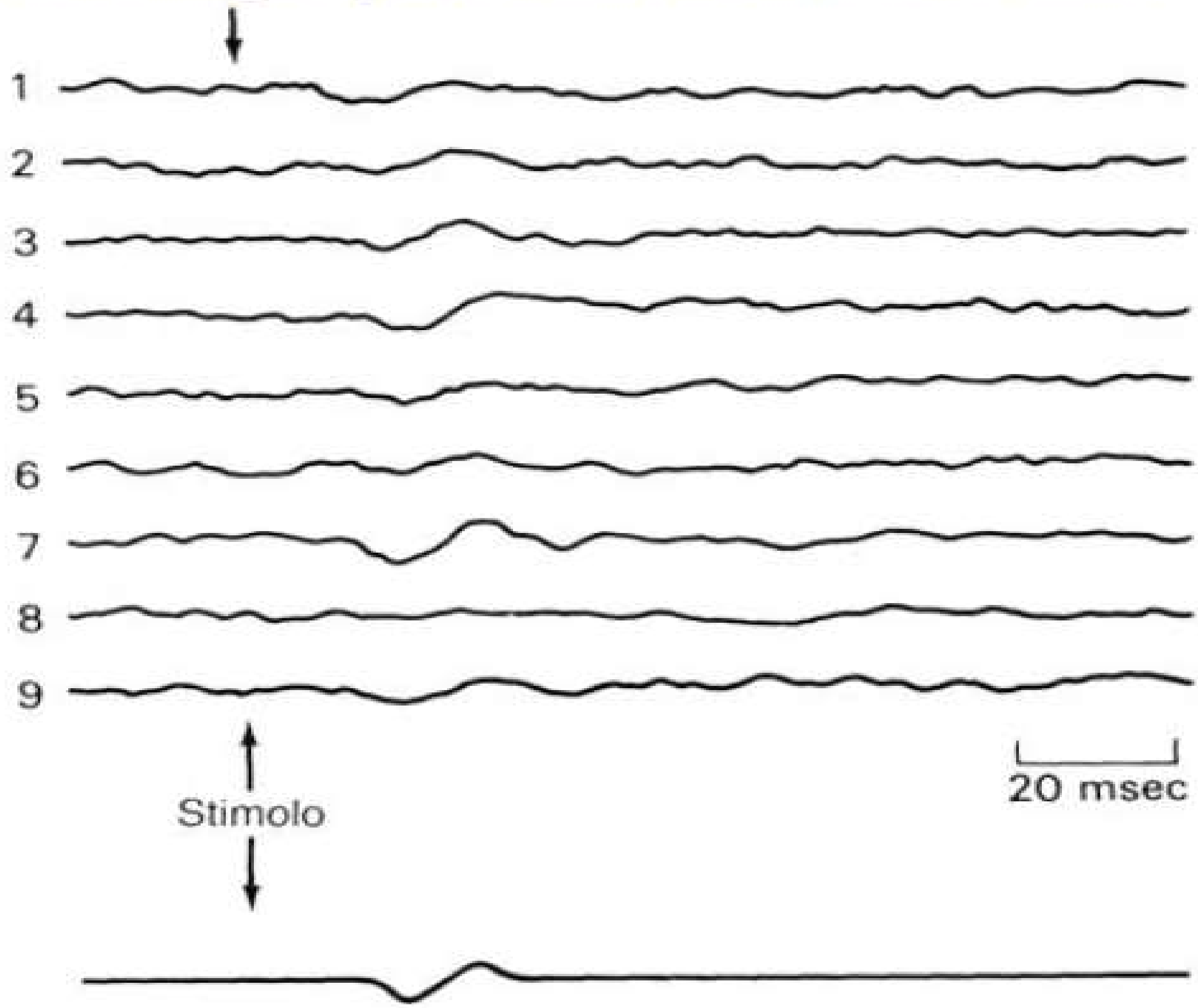
As a general rule, it's always better to try to decrease sources of noise than to increase the number of trials.





AVERAGING: EXAMPLE

Number of trials

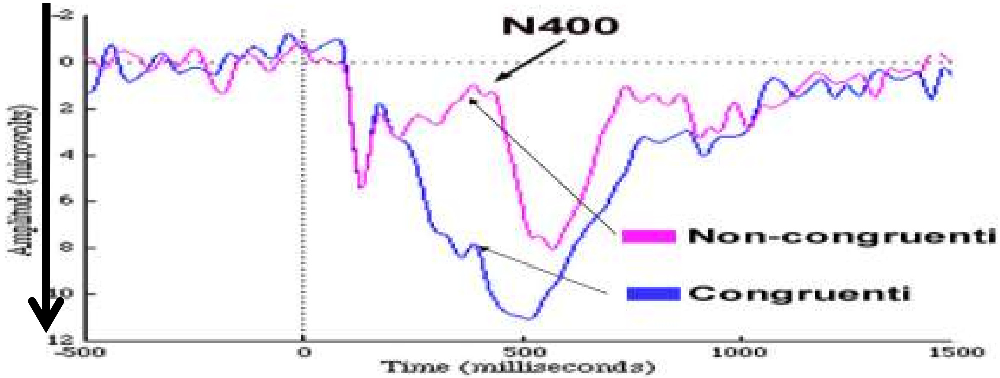


Average response

N400

• The **N400** is a negative-going deflection that peaks around 400 milliseconds post-stimulus onset

• The **N400** is part of the normal brain response to words and other meaningful (or potentially meaningful) stimuli, including visual and auditory words, sign language signs, pictures, faces, environmental sounds, and smells



MOST WIDELY USED ERP FOR BCI: P300

- The **p300** wave is an ERP elicited in the process of decision making.

- The **p300** appears only if the stimulus is relevant for the user.

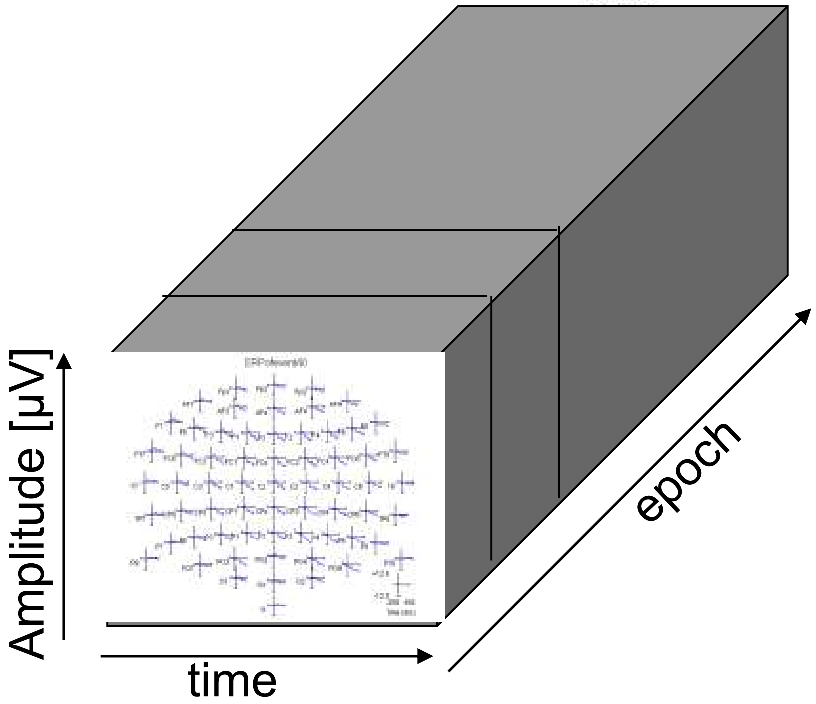
- It is usually elicited using the “oddball paradigm”, in which low-probability target items are mixed with high-probability non-target (or "standard") items.

- The signal is typically measured most strongly by the electrodes covering the parietal lobe.

ERP, ERSP AND EVOKED POTENTIAL

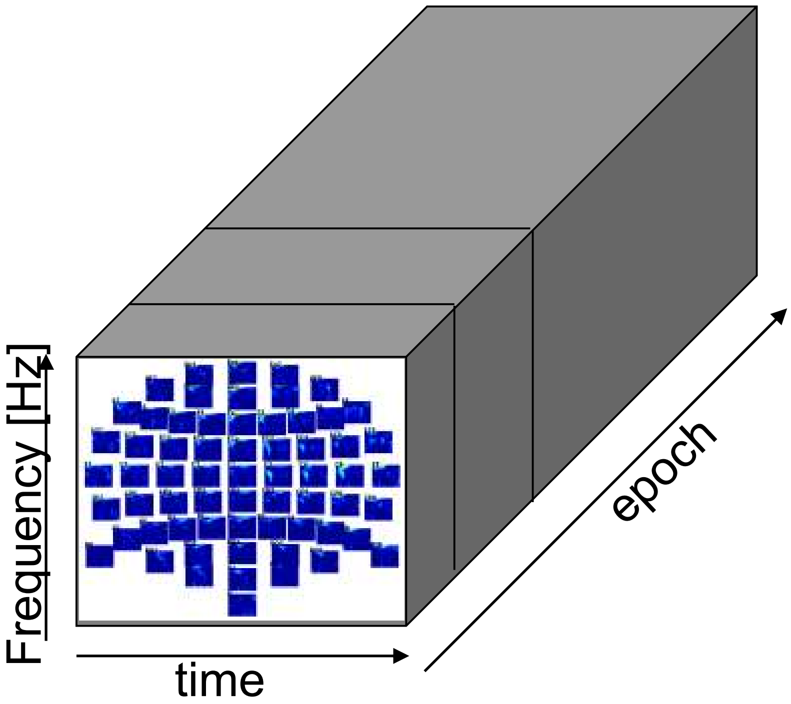
ERP

$$x^{channel \times time \times epoch}$$

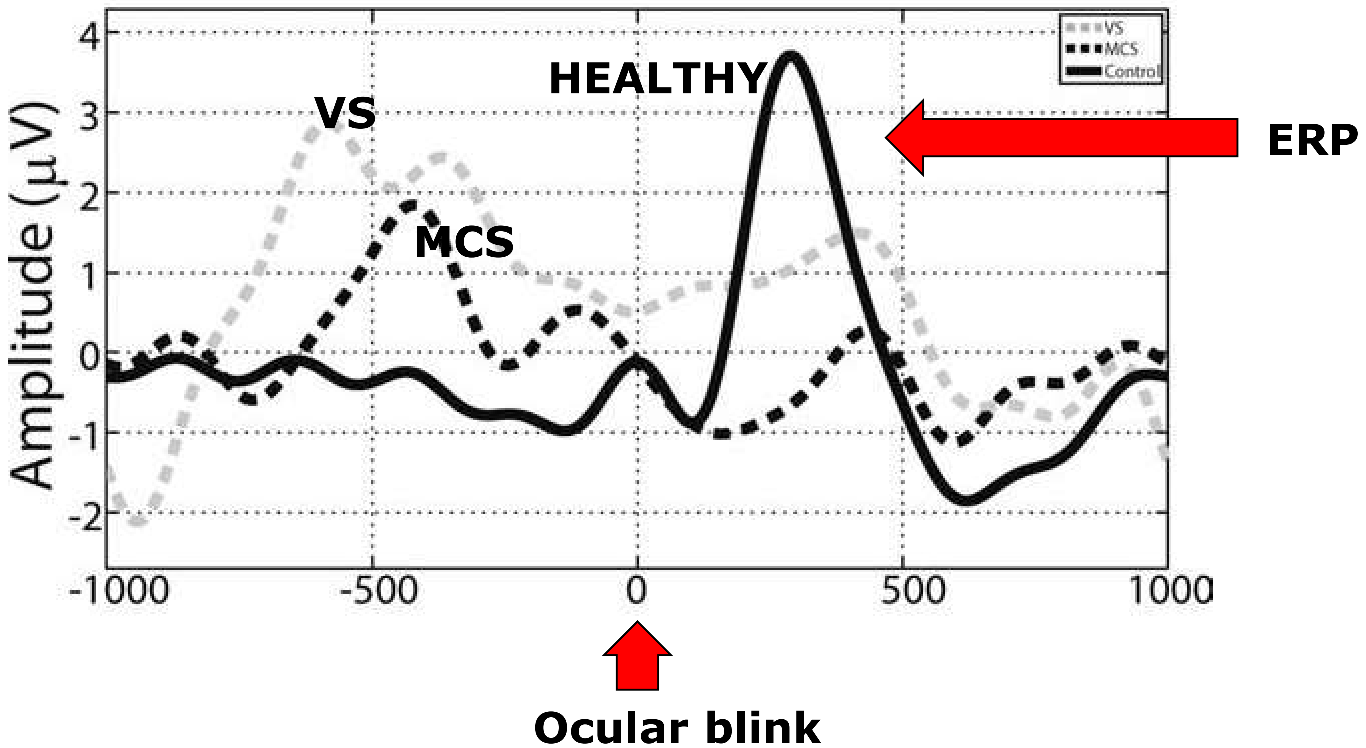


ERSP

$$x^{channel \times time - frequency \times epoch}$$

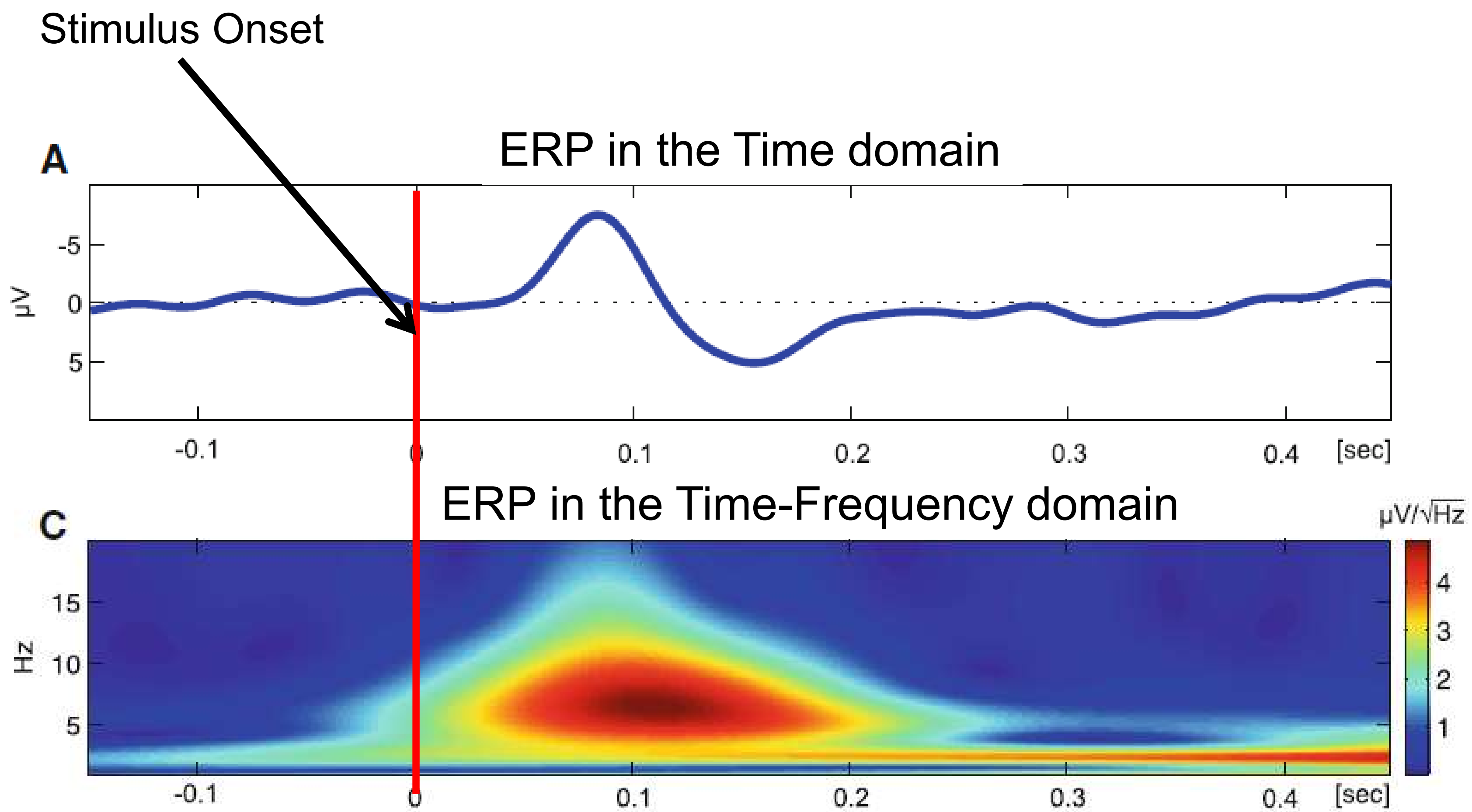


Time-domain: ERP morphology

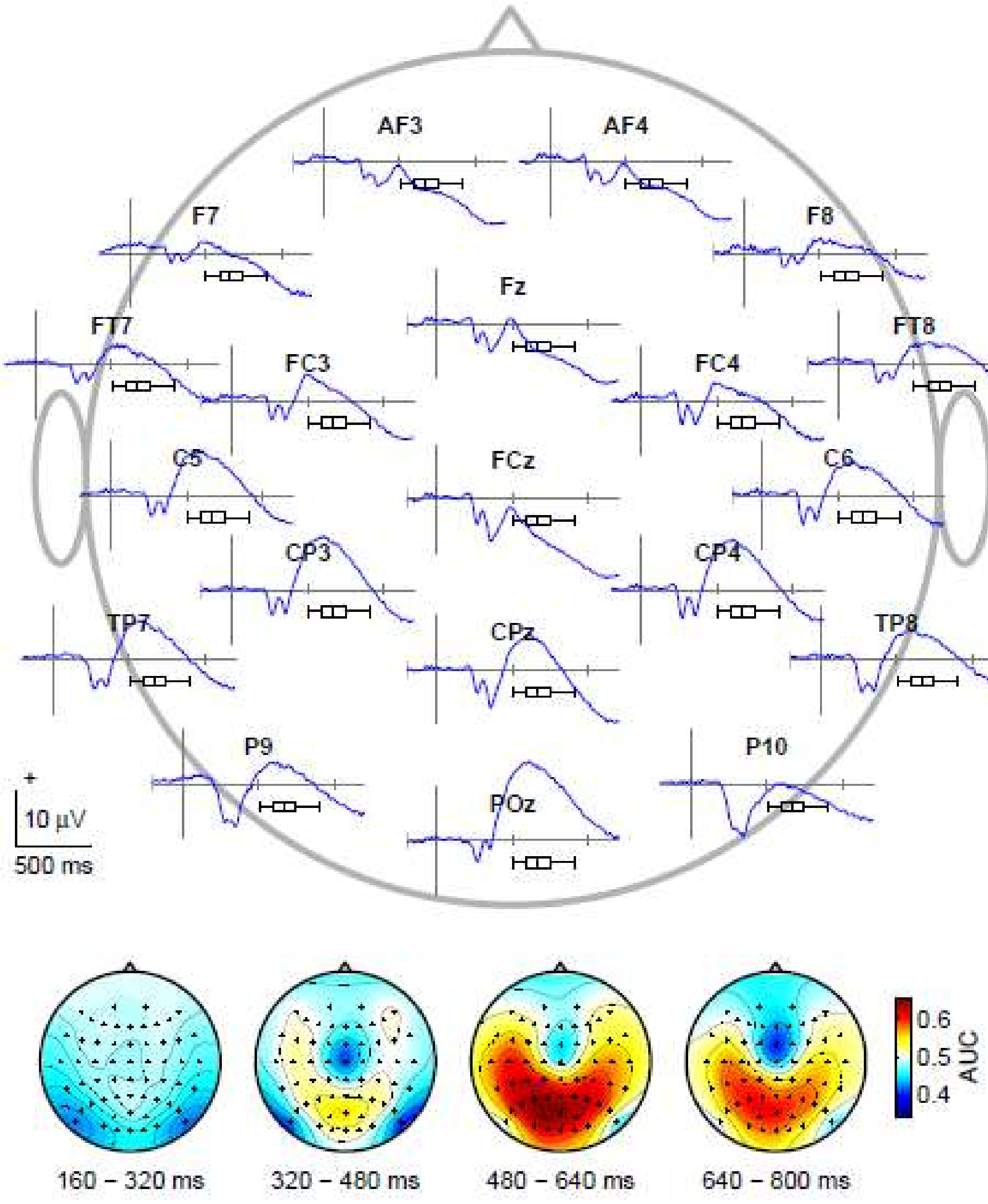


Blink related potential differentiate normal controls from Minimum Conscience and Vegetative states. A large positive deflection (see black continuous trace) is the cortical response associated with the ocular blink. No significant deflection is apparent either for Vegetative or Minimum Conscience patients (dotted lines).

Frequency-domain: Time-frequency analysis of ERPs



Topology: spatial distribution of a specific activity



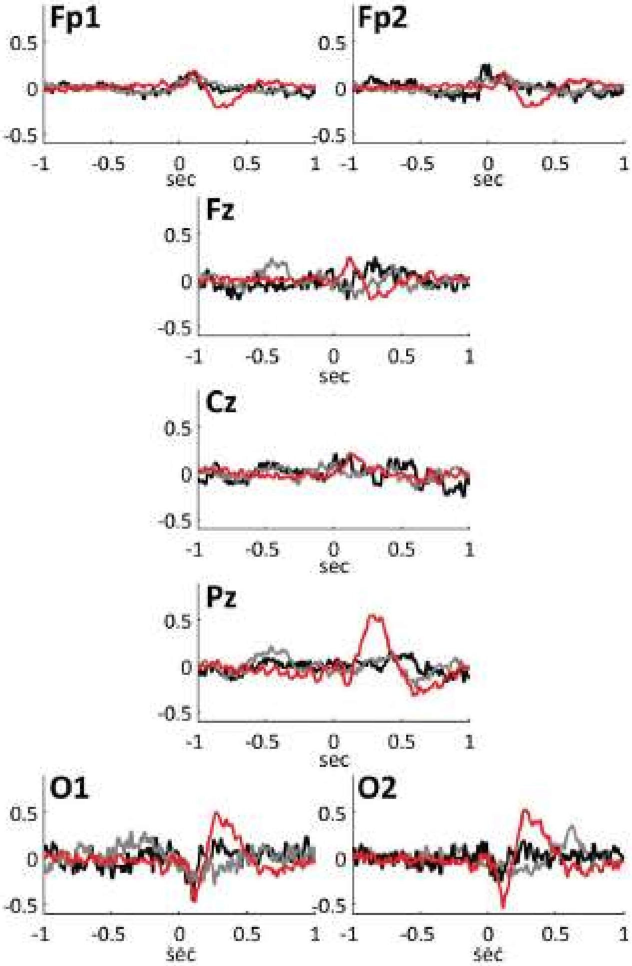
OPEN ACCESS Freely available online

PLOS ONE

Spectral Parameters Modulation and Source Localization of Blink-Related Alpha and Low-Beta Oscillations Differentiate Minimally Conscious State from Vegetative State/Unresponsive Wakefulness Syndrome

Luca Bonfiglio[1]*, Andrea Piarulli[2], Umberto Olcese[3], Paolo Andre[4], Pieranna Arrighi[1], Antonio Frisoli[2], Bruno Rossi[1], Massimo Bergamasco[2], Maria Chiara Carboncini[1]

1 Department of Translational Research on New Technologies in Medicine and Surgery, School of Physical Medicine and Rehabilitation, University of Pisa, Pisa, Italy, 2 TeCIP Institute, PERCRO Laboratory, Scuola Superiore Sant'Anna, Pisa, Italy, 3 Department of Neuroscience and Brain Technologies, Italian Institute of Technology, Genova, Italy, 4 Department of Medical and Surgical Sciences and Neuroscience, University of Siena, Siena, Italy


Fp1
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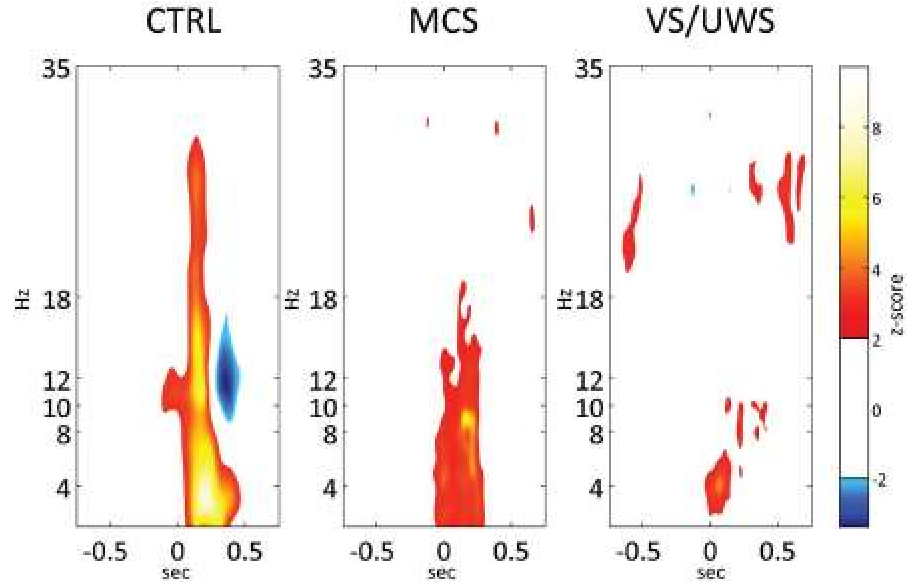
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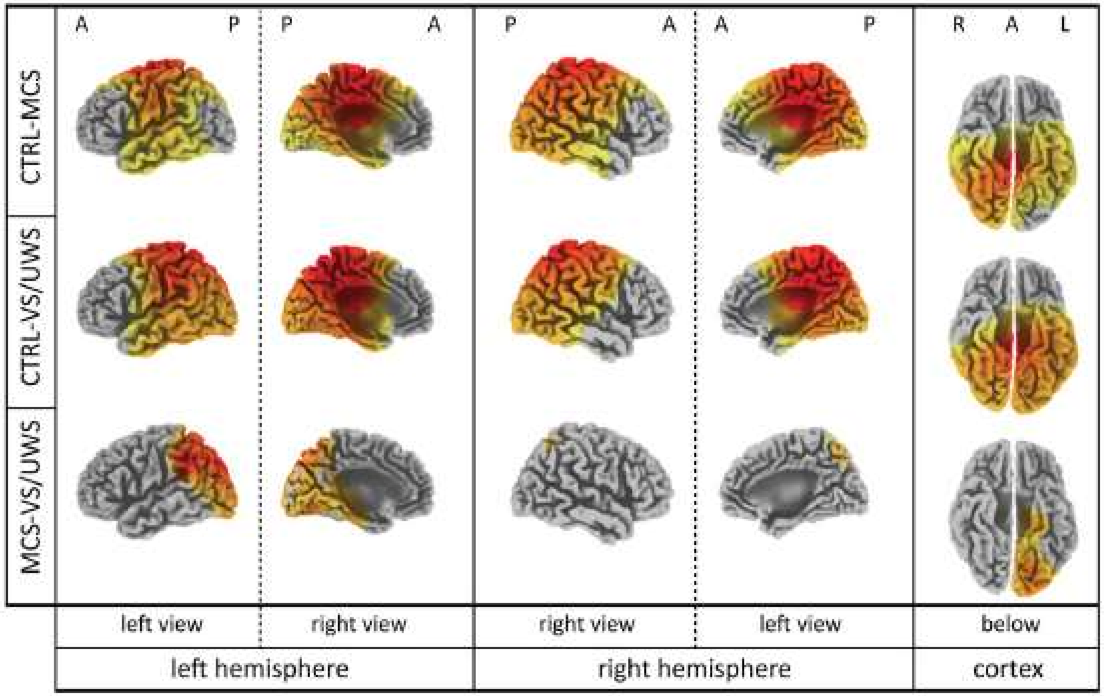
CTRL-MCS
CTRL-VS/UWS
MCS-VS/UWS
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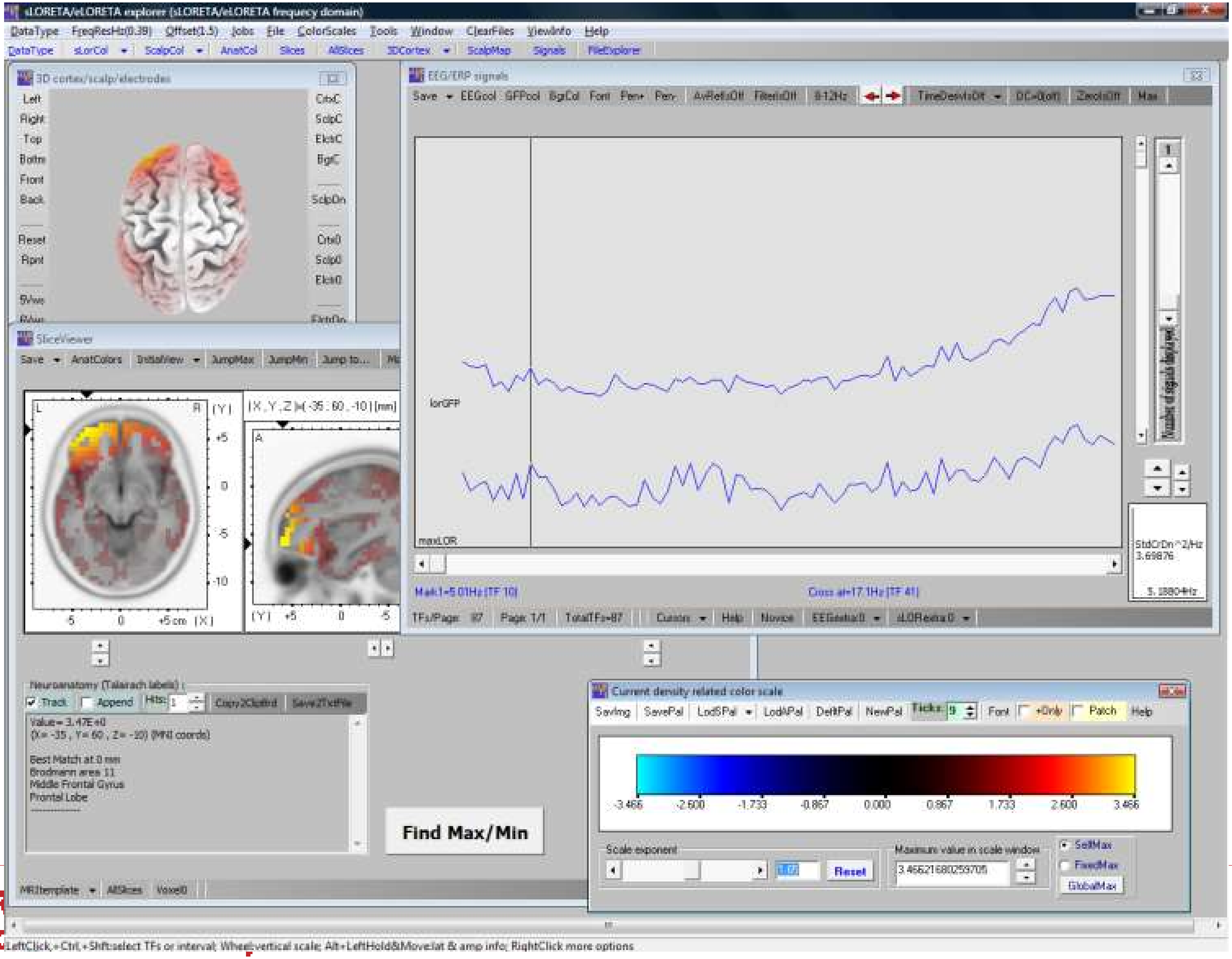
L
left view
right view
below
left hemisphere
right hemisphere
cortex

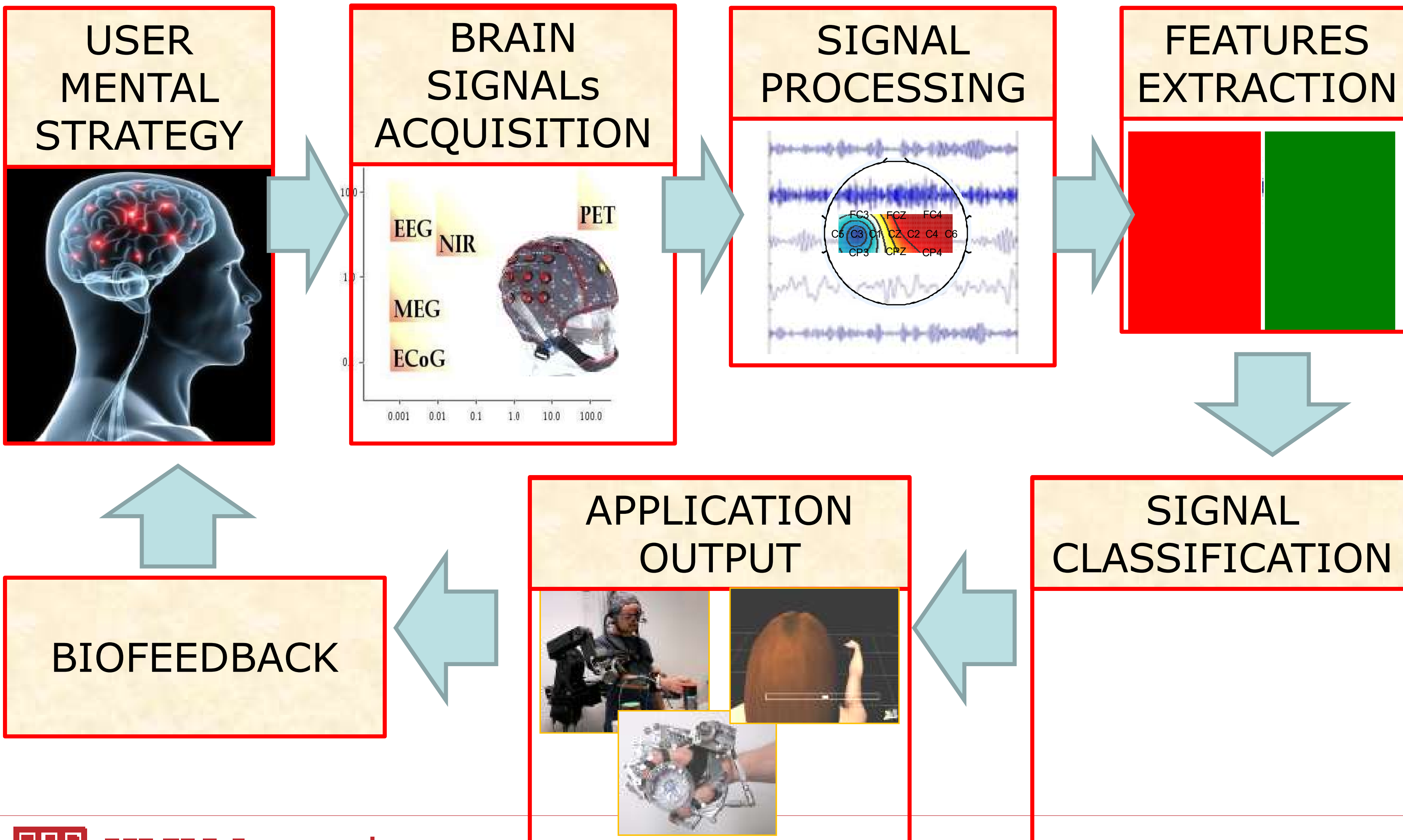
LORETA :
LOw REsolution Tomography Analysis



BCI SYSTEM

- What is a Brain Computer Interface?
- Classification of BCI system
- Application of BCI
  - Assistive Technologies
  - Rehabilitation Purposes
- BCI paradigms:
  - P300 (Face Speller)
  - Motor Imagery
  - SSVEP

GENERAL BCI FRAMEWORK



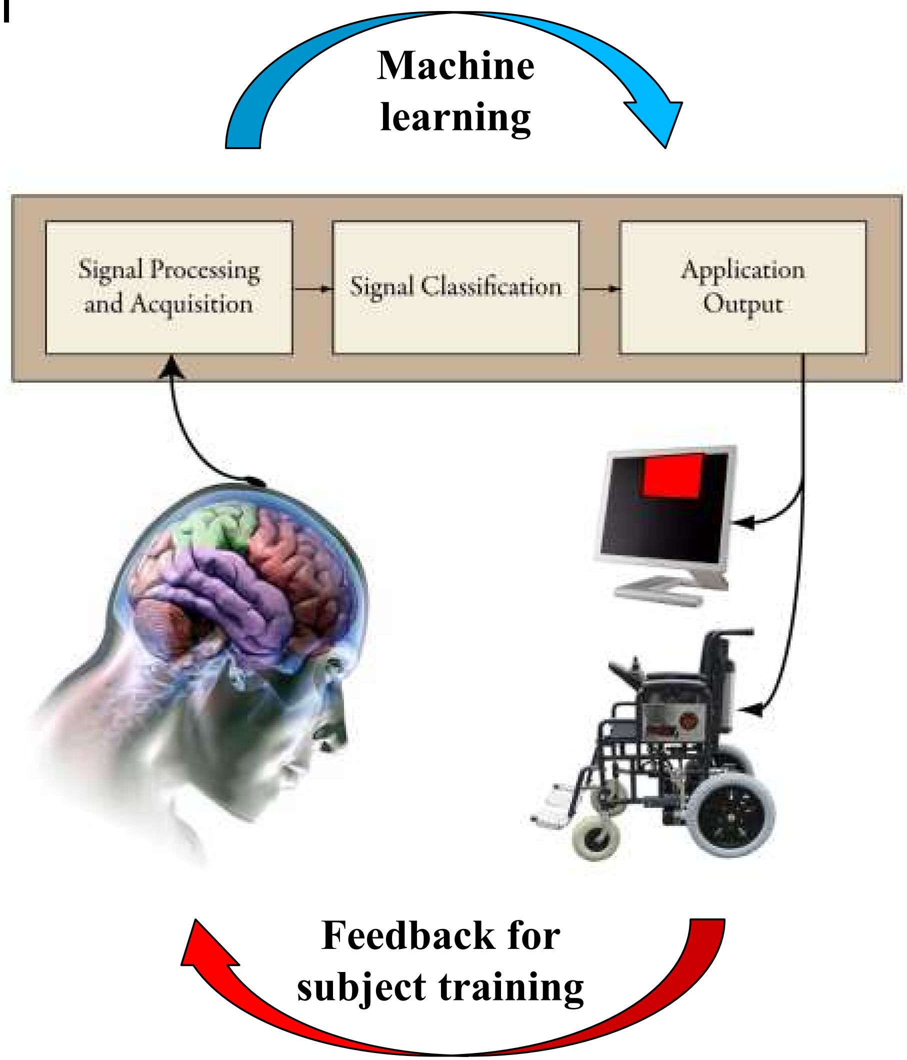
GENERAL BCI FRAMEWORK

- BCIs represent a set of techniques to allow direct control of a software or device via brain activity – without the need of a motor output

- The most common BCI approach exploits voluntary modulation of EEG activity, although more invasive approaches have been explored

- These techniques have successfully been employed to aid disabled patients

- Recently BCIs have also been investigated as a rehabilitation tool



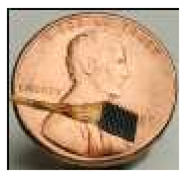
BCI CATEGORIES

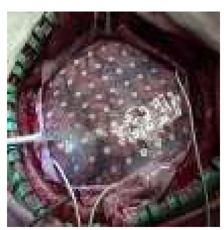
DEPENDING ON THE ACQUISITION SYSTEM

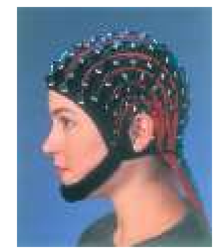
INVASIVE	NON-INVASIVE
Implanted sensors (electrode array, needle electrodes, electrocorticogram **ECoG**)	Without penetrating the skalp, mostly **EEG**, rarely magnetoencephalogram (**MEG**)

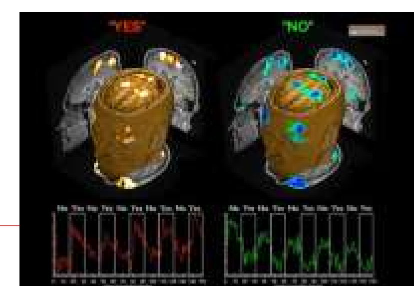
Classification: signal acquisition

- BCI
  - Invasive
    - Single recording site
    - Multiple recording sites
    - ECoG
  - Non invasive
    - EEG
    - MEG
    - fMRI



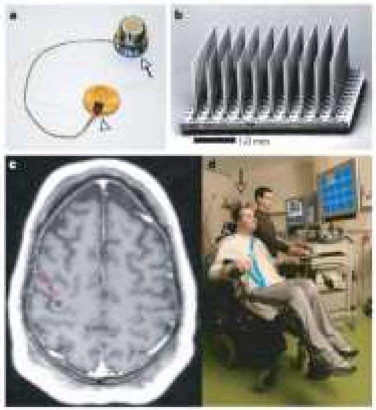






Invasive vs. non-invasive BCI

- Invasive BCI



Hochberg et al., Nature, 2006

- Insertion of arrays of microelectrodes in cortical tissue
- Control of 2-3 DoF, with good accuracy.
- Implants have only been tested for months after surgery
- Highly expensive

- Non-invasive BCI

- EEG systems range from low to high density (2 to 256 eletrodes)
- Several portable, cheap systems exist
- Motion artifacts and interferences can be greatly reduced by employing active electrodes

BCI CATEGORIES

DEPENDING ON THE MENTAL STRATEGY

ENDOGENOUS

Unstimulated Brain Signals:
Users can voluntarily produce the required signals
(**Motor Imagery**, **Computational Task**)

EXOGENOUS

Evoked Potentials:
Users modulate brain responses to external stimuli
SSVEP
p300

BCI CATEGORIES

DEPENDING ON THE COMMAND-TIMING

ASYNCHRONOUS

The system detects when the user wants to emit a command

Subjects are asked to perform visual imagery tasks and the local changes in EEG power spectra are recorded

SYNCHRONOUS

Commands can only be emitted synchronously with external pace.

The differences in EEG response following different stimuli are used to discriminate what subjects want

BCI CATEGORIES - SUMMARY

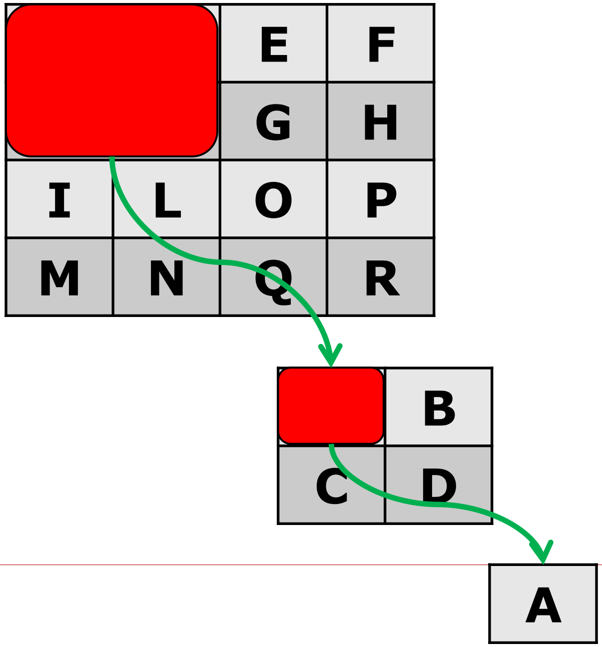
	ENDOGENOUS	EXOGENOUS
DEPENDENT		▪ **SSVEP** ▪ **VEP**
INDEPENDENT	▪ **MOTOR IMAGERY**	▪ **ERP (i.e.P300)**

BCI: communication strategies

Sistema di BCI usato per la scrittura mentale basato su P300

Communication

- Selection among many possibilities
- Sequential selection



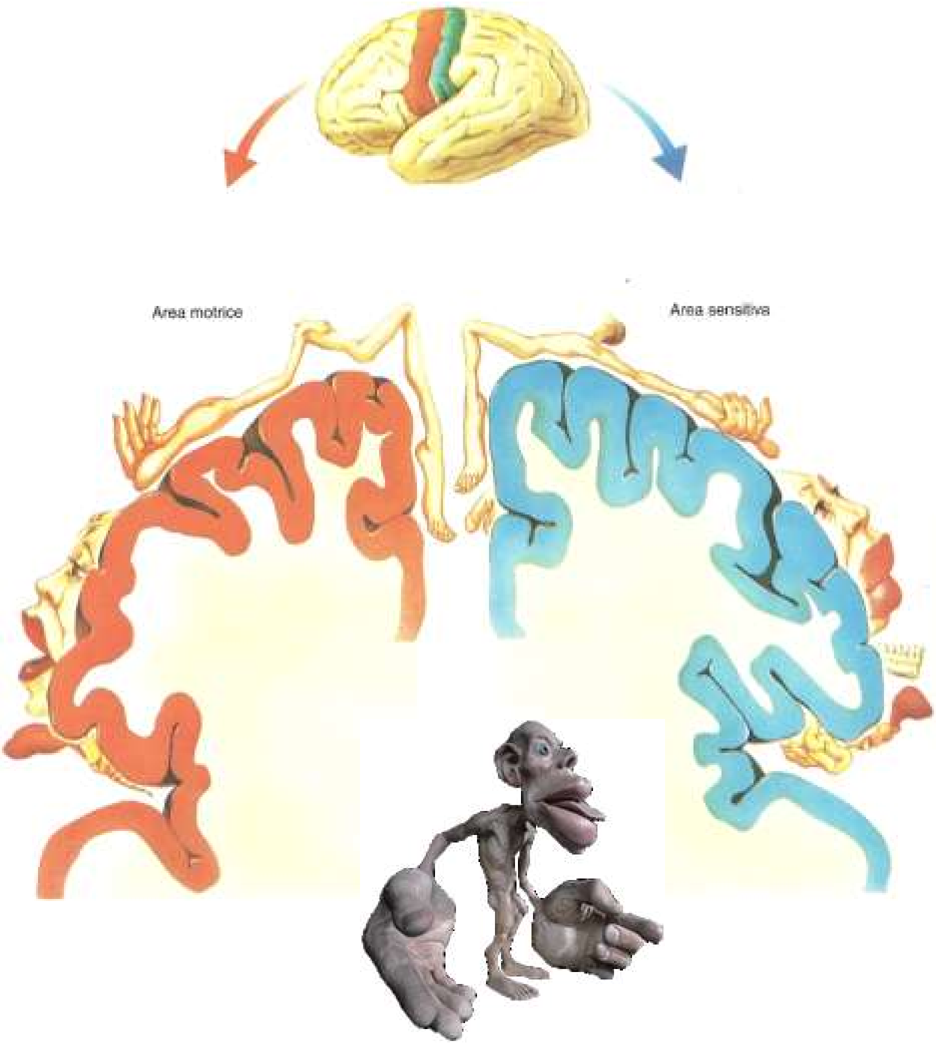
BCI: device control strategies

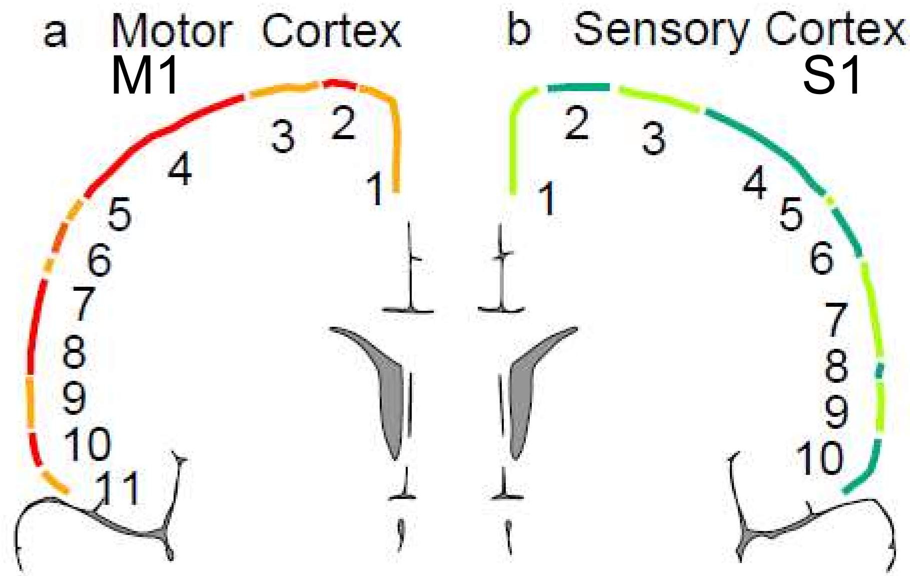
Device control

- Manual control
- Shared control
- Autonomous control

BRAIN ANATOMY & EEG MOVEMENTS CORRELATES

BRAIN ANATOMY: THE CEREBRAL CORTEX





1 Foot, Leg
2 Trunk, Head
3 Arm
4 Hand, Fingers
5 Eye
6 Face
7 Lips
8 Jaw, Teeth
9 Tongue
10 Pharynx
11 Intra – abdominal

The Primary Somatic Sensory Cortex (Parietal Lobe) and the Primary Motor Cortex (Temporal Lobe) are the most important regions for BCI research.

TYPES OF MOVEMENT

Three types of movements may occur in respect of to ascending and descending signals via different pathways and at different levels:

When a voluntary movement is started, neurons in the M1 send commands to upper and lower motor neurons.

The M1 needs to be stimulated by neurons from the premotor cortex and the supplementary motor area (SMA), which support and coordinate the M1, in order to initiate a voluntary movement

- **Voluntary movement**: usually goal directed and therefore fully conscious. It arises in the motor cortex and is executed by the spinal cord.

MOTOR IMAGERY

Motor imagery is a mental process by which an individual rehearses or simulates a given action.

Performing motor imagery or attempting a movement (i.e. for patients) influences the brain activity as the voluntary movements do.

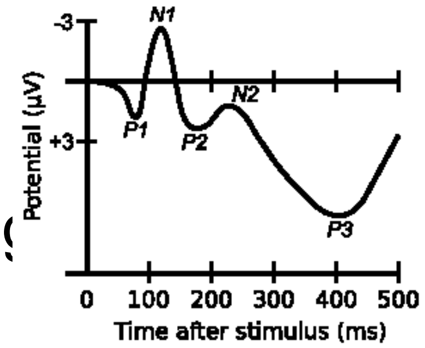
Why MOTOR IMAGERY is suitable for BCI?

- No need of external stimulus (it could be asynchronous)
- Not depend in any way on the brain's normal output/input pathways (independent)
- Possibility to provide different commands depending on which body part is evolved in the simulated action
- Mental practice of motor actions via BCI training affect neuro-rehabilitation in a positive way.
- the power in μ (8-12 Hz) and β (12-24Hz) EEG rhythms are affected by motor imagery: Event Related Spectral Perturbation (ERSP)
- Users learn to perform motor imagery tasks
- Can be employed even if the motor areas are impaired
- Works mostly for digital control, has a fast response

DECODING MOVEMENT INTENTIONS BY ANALIZING EEG

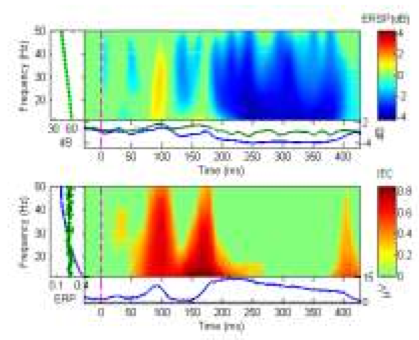
EEG PHENOMENAL USABLE FOR BCI

- Event Related Spectral Perturbation (ERSP) and Event Related Potential ERP are the measured brain response that are the direct result of a specific sensory, cognitive, or motor event.



- **Event Related Potential (ERP)**:
    - \- Repeatedly present discrete stimulus, averag raw EEG responses across presentations. Characteristic feature (eg. P300)

- **Event Related Spectral Perturbation (ERSP)**:
    - Frequency band changes
    - \- Average *spectral features* across presentation.
    - \- Characteristic suppression/increase in power (**ERD**/**ERS**: **E**vent **R**elated **De**-**S**ynchronization).

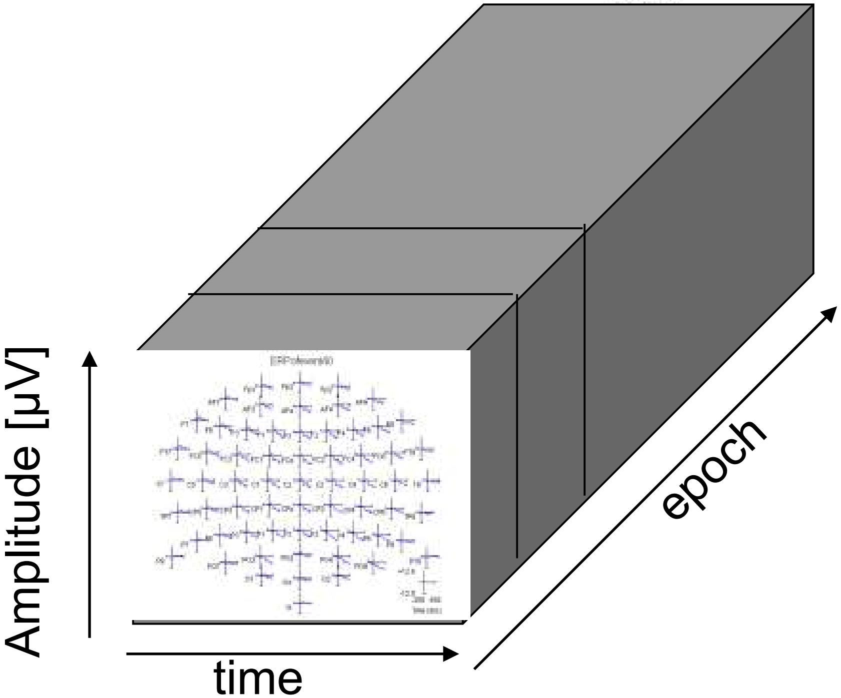


AVERAGING

- The ERPs and ERSP should be extracted from the background noise mediating many recordings (Epochs or Trials)

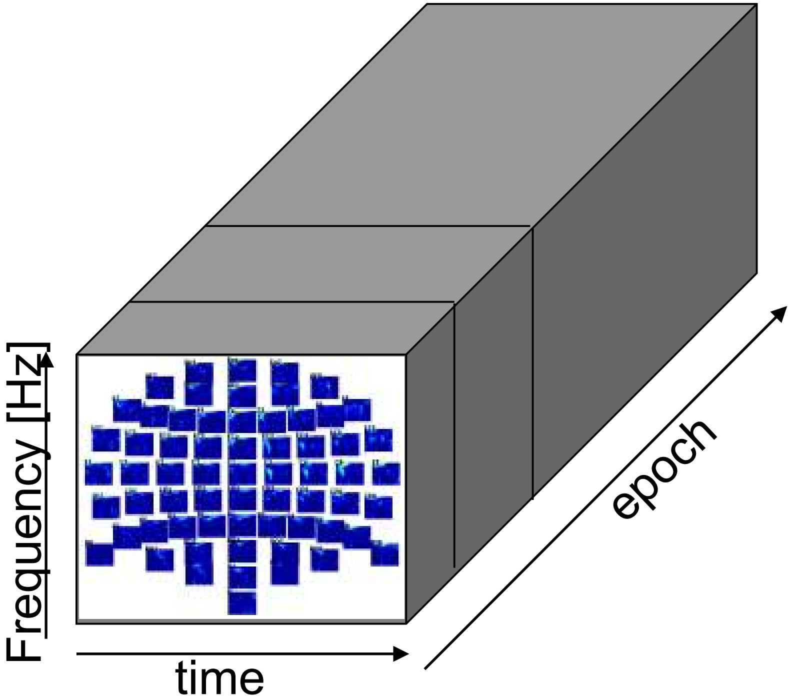
ERP

$$x^{channel \times time \times epoch}$$



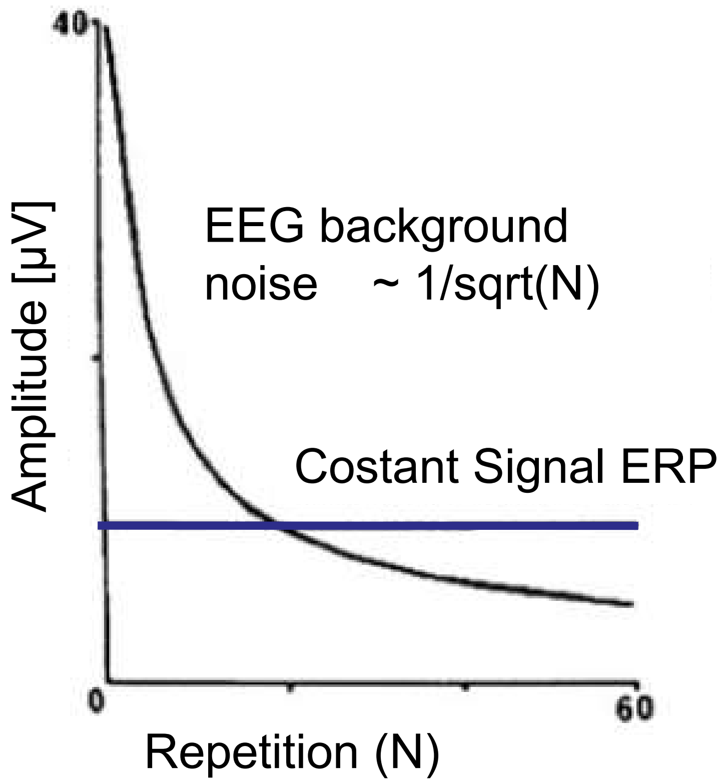
ERSP

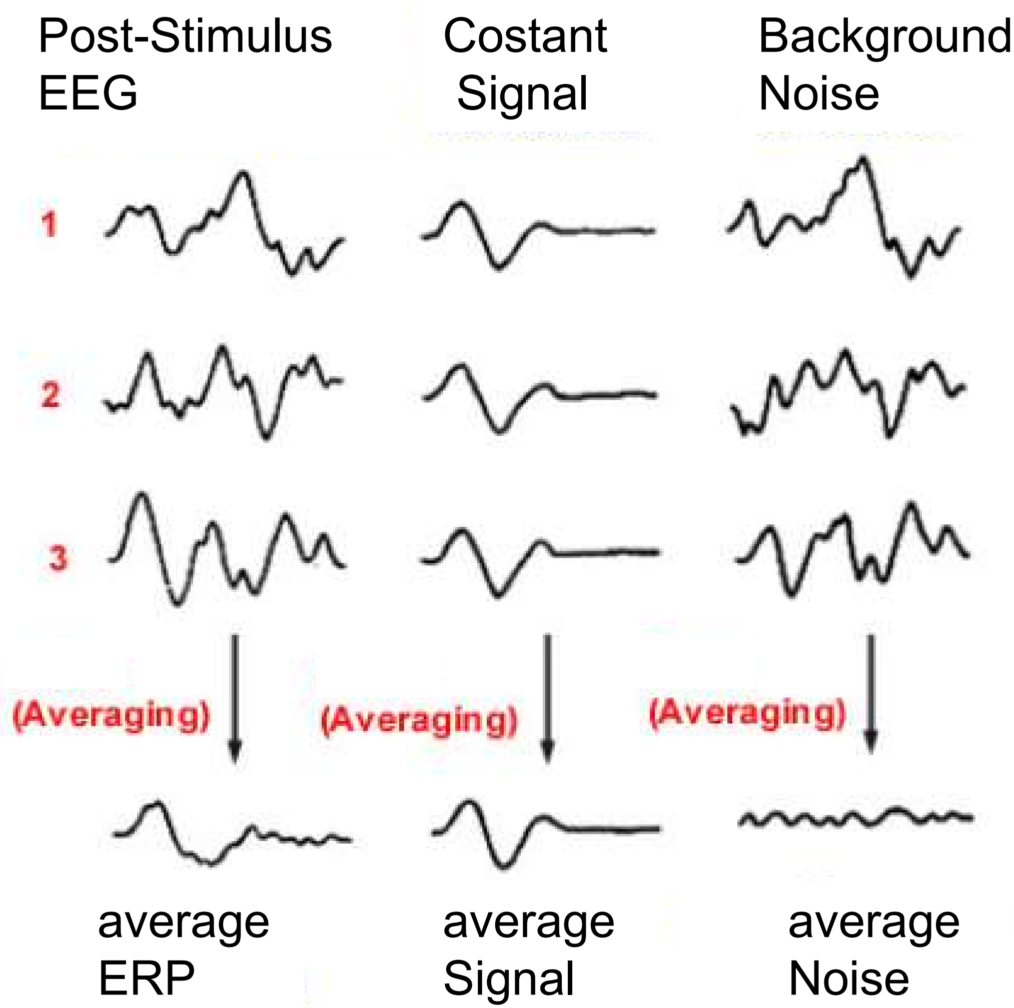
$$x^{channel \times time-frequency \times epoch}$$



AVERAGING THEORY

S/N ratio increases as a function of the square root of the number of trials.



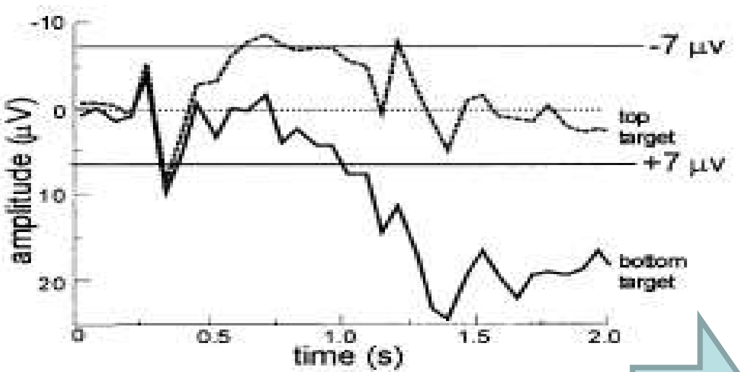


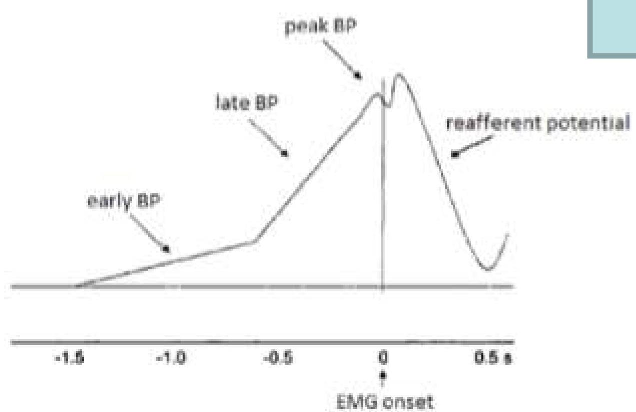
MOTOR IMAGERY CORRELATES IN EEG

Performing (or imagining) a motor action influences the EEG with two main phenomena:

MOTOR IMAGERY CORRELATES IN EEG

SLOW CORTICAL POTENTIALS [Kornhuber and Deecke (1965)]



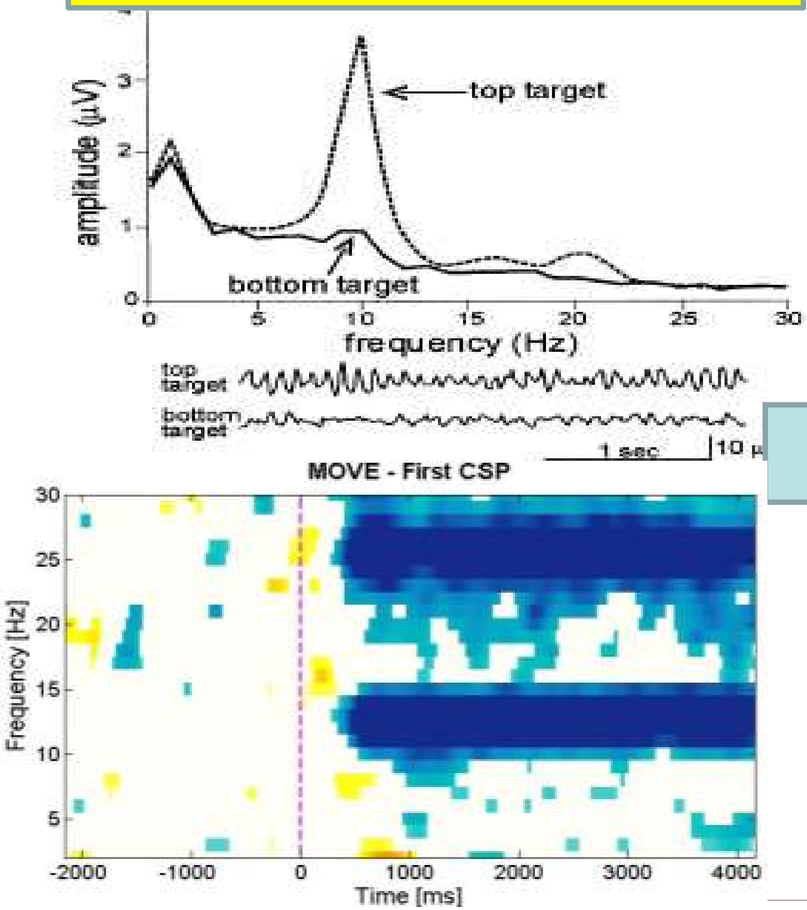


- Know as BereitschaftPotential (readiness potential) or Movement Related Cortical Potentials (MRCPs).
- Slow oscillations preceding the movement
- Localized over the supplementary motor area (SMA)
- Steps for MRCP detection
  - Spatial filter,
  - LP frequency filter
  - Template extraction from the training data
  - matching with the ongoing eeg

•Frequency close to the DC -> very challenging to detect in single trial

MOTOR IMAGERY CORRELATES IN EEG

SENSORIMOTOR RHYTHMS [Pfurtscheller and Lopes da Silva, (1999)]



- the power in μ (8-12 Hz) and β (12-24 Hz) EEG rhythms are affected by motor imagery.
- Know also as Event Related De/Synchronization (ERD,ERS)

- Steps for ERD detection
  - Spatial filter,
  - Band Pass frequency filter
  - Feature extraction
  - LDA classifier

- High average classification accuracy (>80%)

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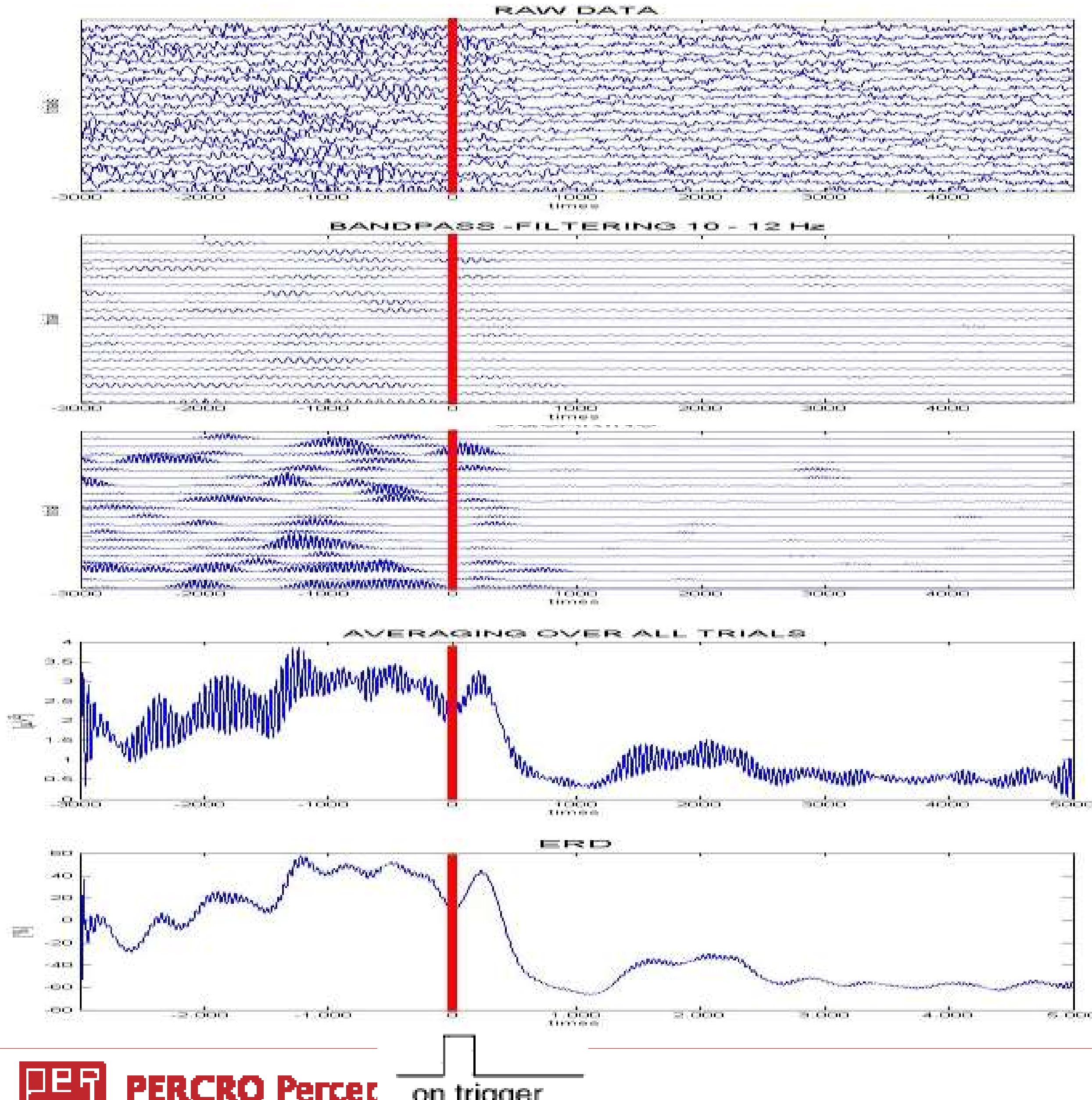
ERD extraction: example with motor imagery



Collecting Trials from a specific electrode

↓

Bandpass on the specific frequency

↓

Squaring Signals

↓

Averaging over Trials

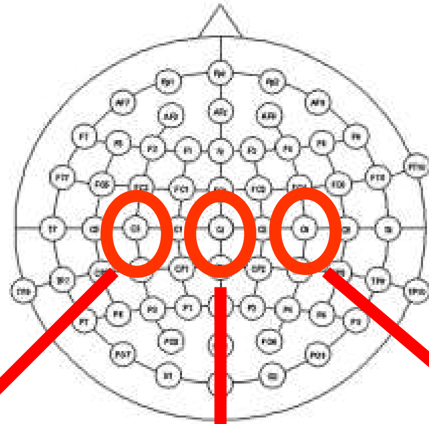
↓

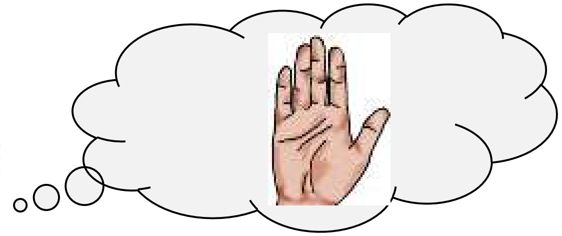
Smoothing

[Pfurtscheller and Lopes da Silva, (1999)]

SENSORIMOTOR RHYTHMS
EVENT RELATED SPECTRAL PERTURBATION

Event Related
De\Synchronization
ERD

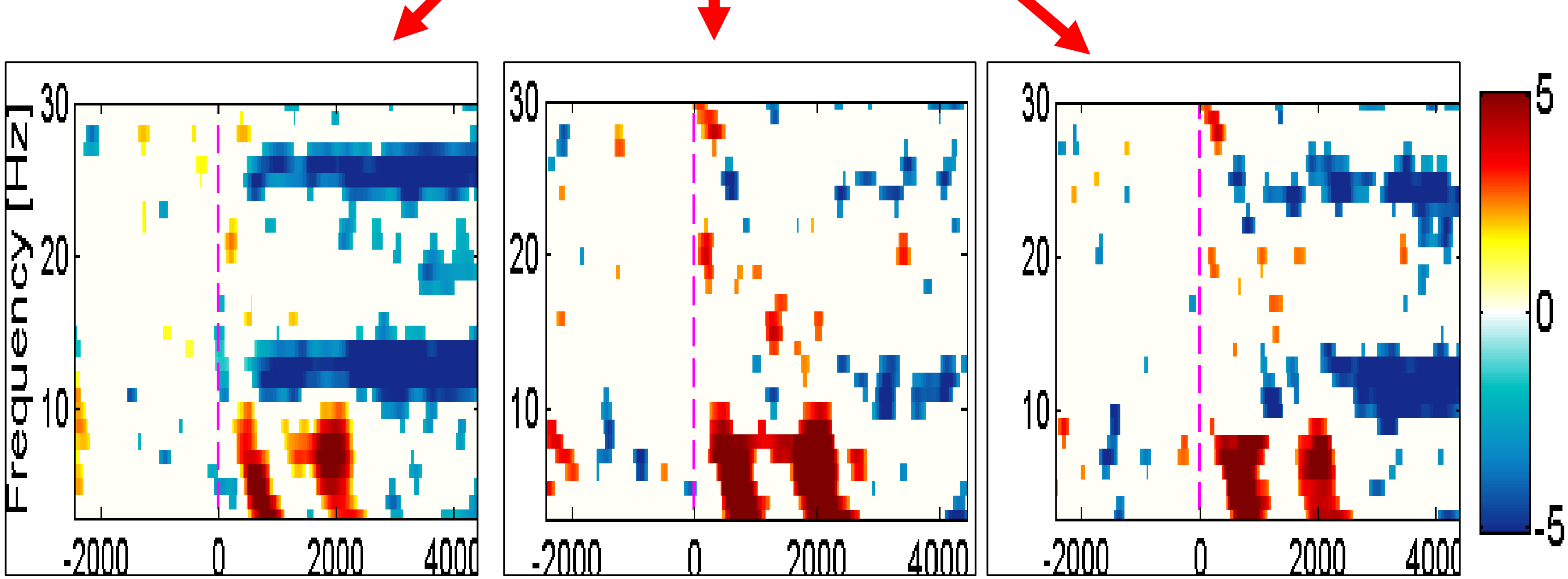




Motor Imagery of right hand movement

β ERD
13-30 Hz

μ ERD
8-12 Hz



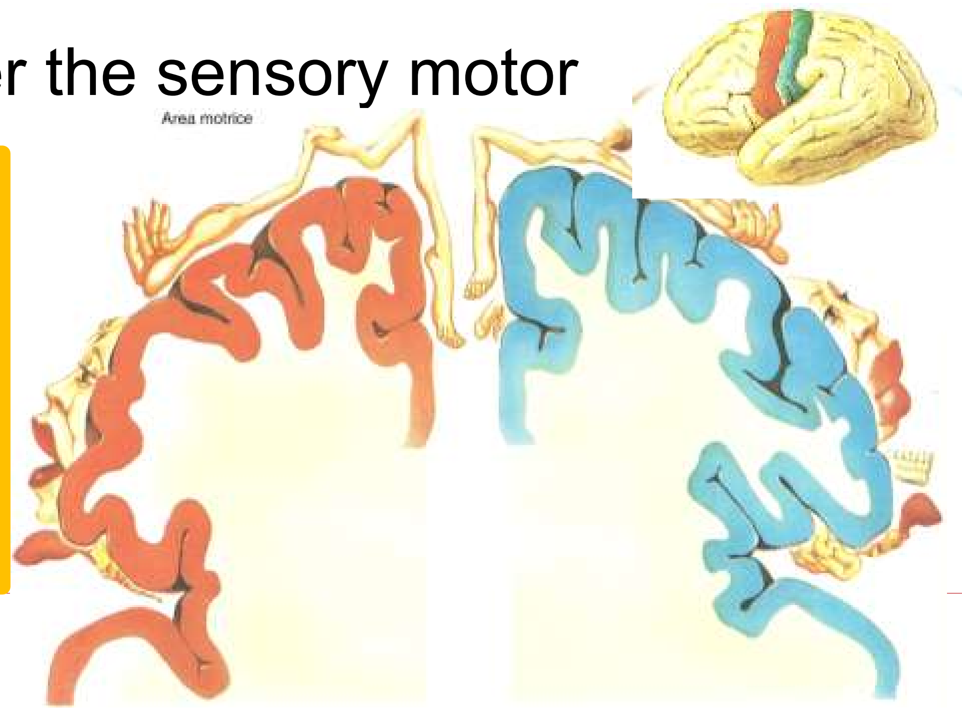
MOTOR IMAGERY: SIGLE TRIAL DETECTION

The important features of the motor imagery are:

- ❑ The <u>frequency</u> band.
- ❑ The <u>spatial</u> localization

A priori knowledgment:

- ❑ The frequency band are **mu** (8 -13Hz) and **beta** (15-30 Hz).
- ❑ The spatial localization is over the sensory motor

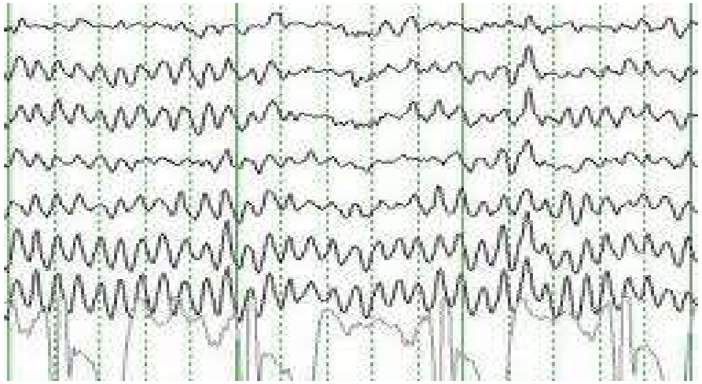


Very high intersubject variability!
Need of optimized spatial filters

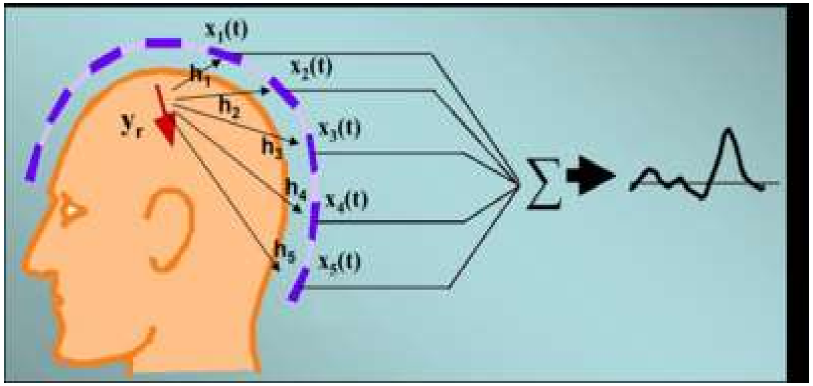
SPATIAL FILTERING

The aim of spatial filtering is to improve the signal-to-noise ratio by creating a virtual channel which is a (linear, in the following cases) combination of the input channels of the filter.

y(t) = a*ch1(t) + b*ch2(t) ....

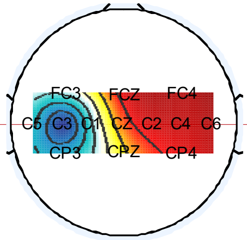


N-channel input (ex. 16 ch)



1-optimized channel output

A spatial filters can optimize the data extracted from an high number of electrodes reducing the dimension of the features'space to only few significant dimensions.



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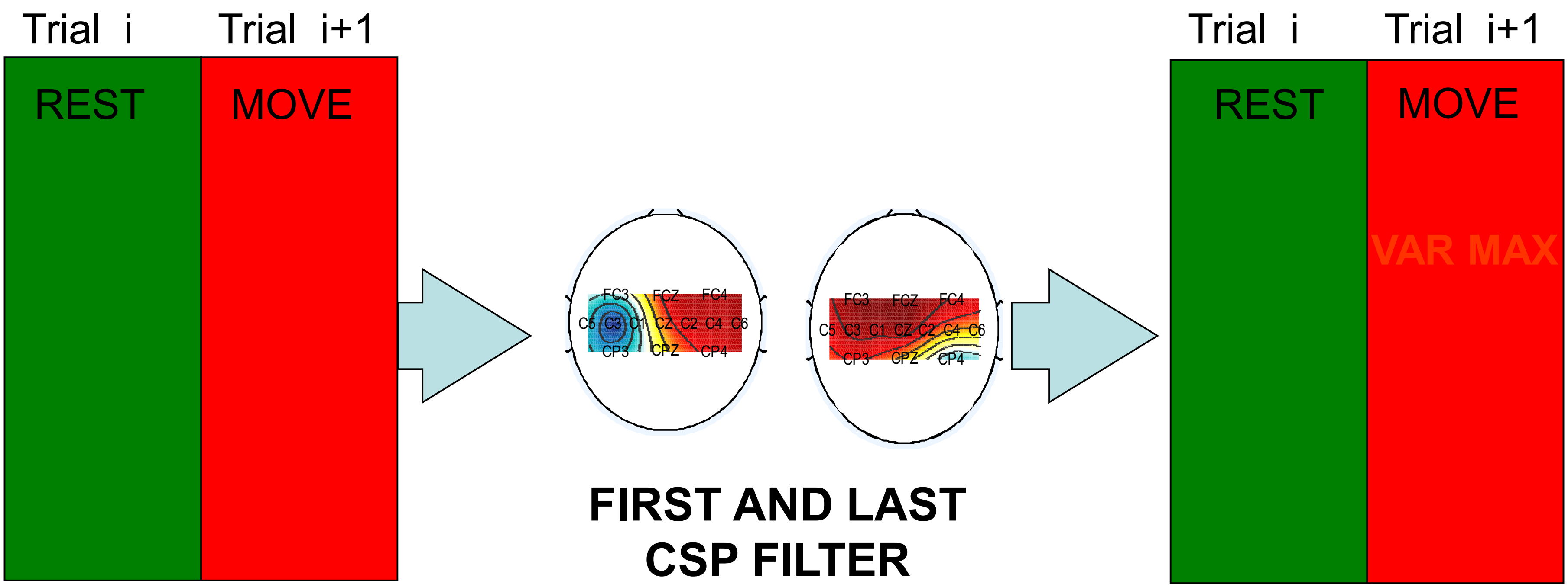
Optimized Spatial filter: **C**ommon **S**patial **P**attern – **CSP**

[Pfurtscheller 1999]



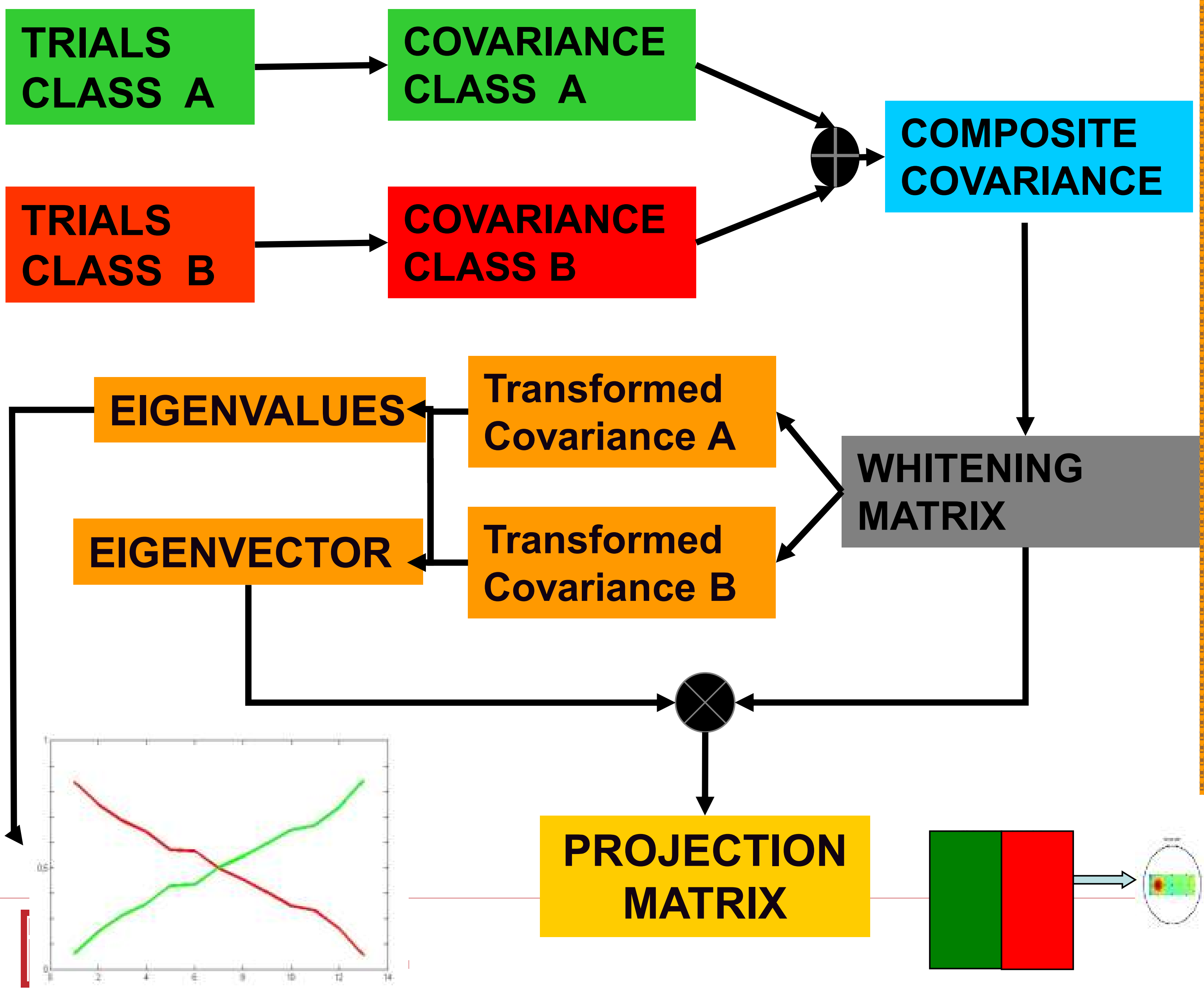
RAW CHANNELS

FIRST AND LAST CSP FILTER

PROJECTED DATA

Common Spatial Pattern (CSP) is a supervised spatial filtering method for two-class discrimination problems, which finds directions that maximize variance for one class and at the same time minimize variance for the other class.

Common **Spatial** Pattern – **Algorithms**



$$R_A = \left\langle \frac{X_A^i X_A^{i\,T}}{trace(X_A^i X_A^{i\,T})} \right\rangle_i$$

$$R_B = \left\langle \frac{X_B^i X_B^{i\,T}}{trace(X_B^i X_B^{i\,T})} \right\rangle_i$$

$$R_c = R_A + R_B$$

$$R_C = U_C \Lambda_C U_C^T$$

$$W = \sqrt{\Lambda_C}^{-1} U_C^T$$

$$S_A = W R_A W^T$$

$$S_B = W R_B W^T$$

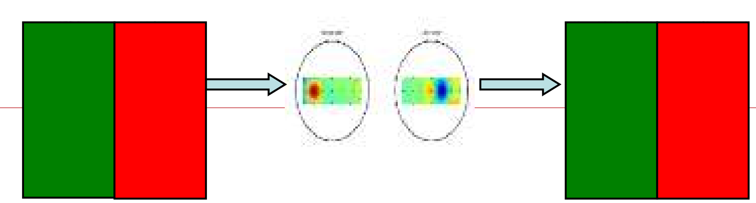
$$S_A = U \Lambda_A U^T$$

$$S_B = U \Lambda_B U^T$$

$$\Lambda_A + \Lambda_B = I$$

$$P = U^T W$$

$$Z = PX$$



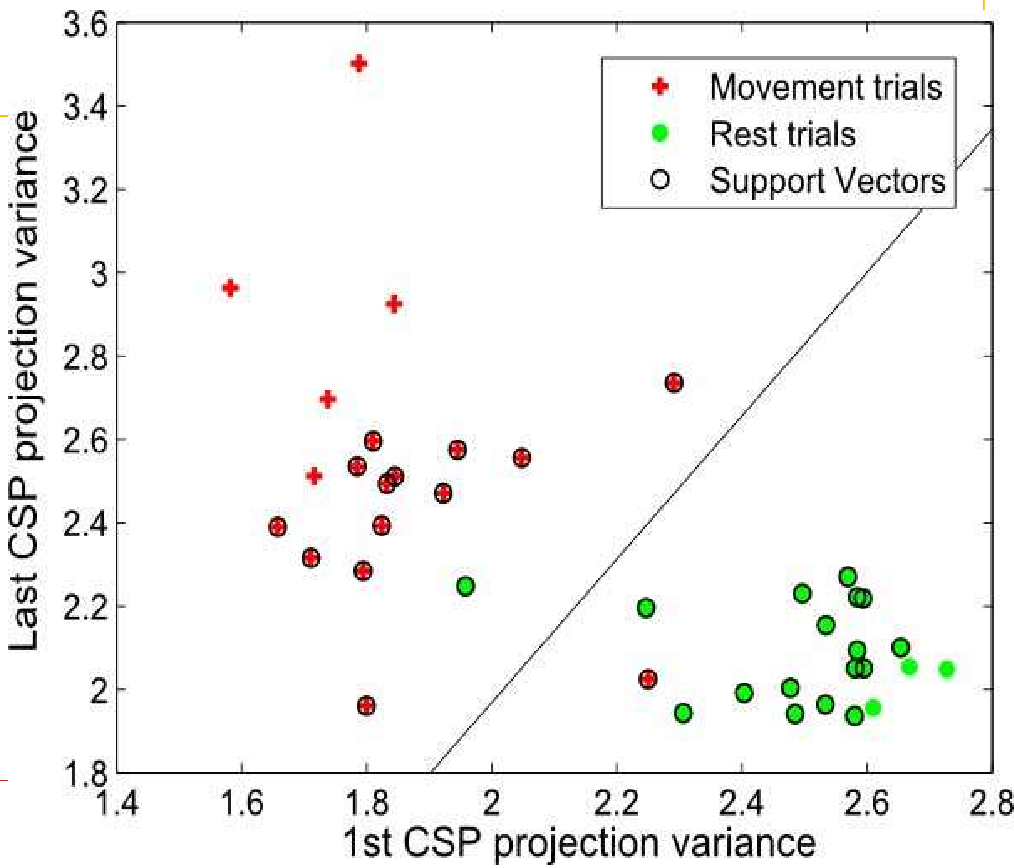
Common Spatial Pattern: advantages

- The scalp-plot of the Common Spatial Pattern can be also used to give a physiological interpretation of the data

- Since variance of band-pass filtered signals is equal to band-power, CSP filters are well suited to discriminate mental states characterized by spectral perturbations (ERD and motor imagery based BCIs).

CLASSIFICATION

The log-scaled band-power values in the *mu* and *beta* band of the resulting two projected channels, can be used as a two-dimensional feature of the brain activity. Classification is performed using a linear discriminant classifier (LDA) or a support vector machine (SVM)



- BCI FOR REHAB USING F.E.S.
  - https://www.youtube.com/watch?v=Mr-Azo3Wvfs
- BCI FOR COMMUNICATION
  - https://www.youtube.com/watch?time_continue=1&v=O6Qw3EDBPhg
- BCI CONTROL OF THE SMART HOME
  - https://www.youtube.com/watch?time_continue=33&v=bFwNi_M32cE

FEEDBACKs for motor imagery - BCI

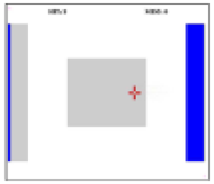
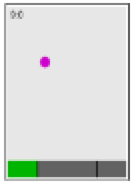
FEEDBACK FOR MOTOR IMAGERY

The biofeedback provided as a response to the mental activity can improves the usability of motor imagery BCI.

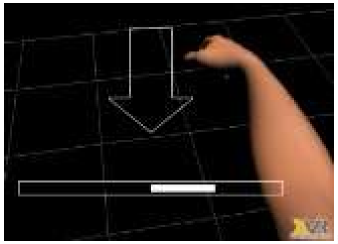
The congruency of the provided feedback with the mental task is expected to ease the performance of motor imagery.

VISUAL

- Game

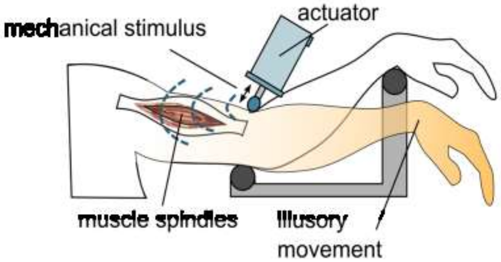



- Virtual reality



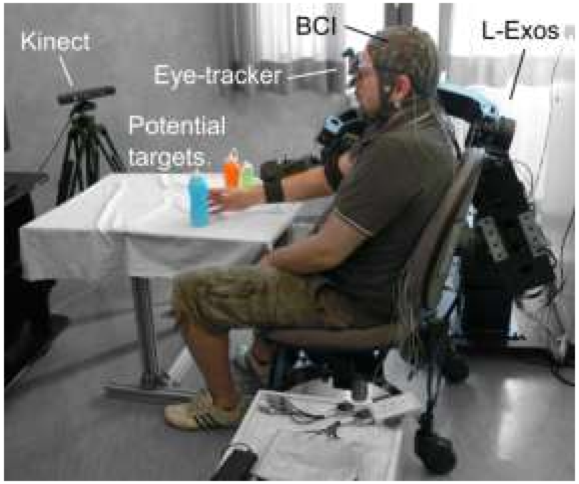
PROPRIOCEPTIVE

- Illusion

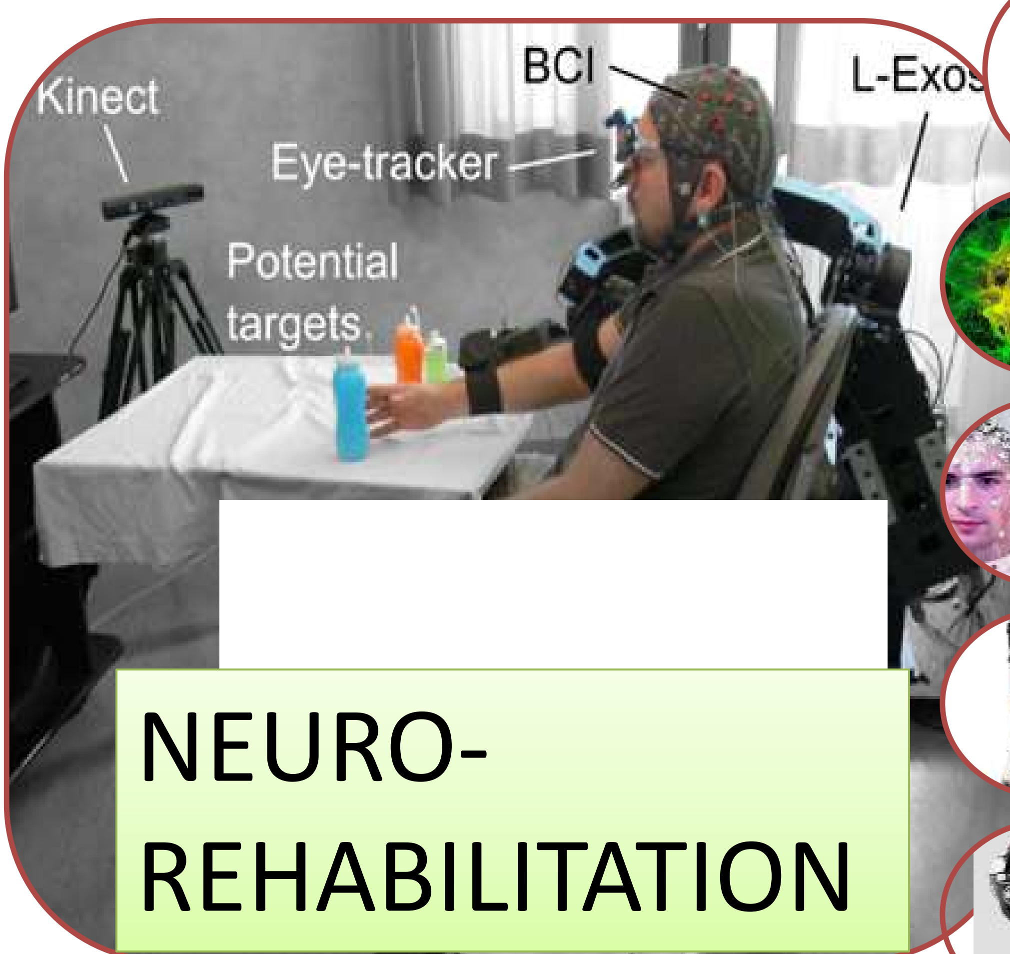


- Exoskeleton

motor imagery – BCI in neurological rehabilitation

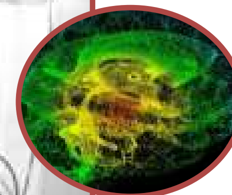


NEUROROBOTICA PER LA RIABILITAZIONE



NEURO-
REHABILITATION

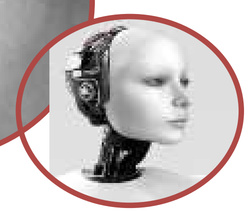
MEDICINE



NEUROSCIENCE

BIO SIGNALS

ROBOTICS



ARTIFICIAL
INTELLIGENCE

CENTRAL NERVOUS SYSTEM INJURIES

SPINAL CORD INJURY

Characterized by a nerve fiber lesion at spinal level.

Restoring movement in patients with SCI would require a **bypass of the spinal** injury.

Once the acute phase is over and the person has been stabilized, he or she enters the **rehabilitation** stage of treatment.

Treatment during this phase has the goal of **returning as much function as possible** to the person.

STROKE

Occurs when blood supply to the brain is blocked or when blood vessels in the brain burst

Structural and metabolic brain imaging and electrophysiological recording of the primary motor cortices have been used to document **reorganization of neural activity** after stroke.

Since stroke does not impair the capacity to perform Motor Imagery, MI provides a substitute for Active Motor Training as a means to activate the motor network in stroke.

Because all patients are different, a **unique** plan designed to help the person function and succeed in everyday life have to be designed.

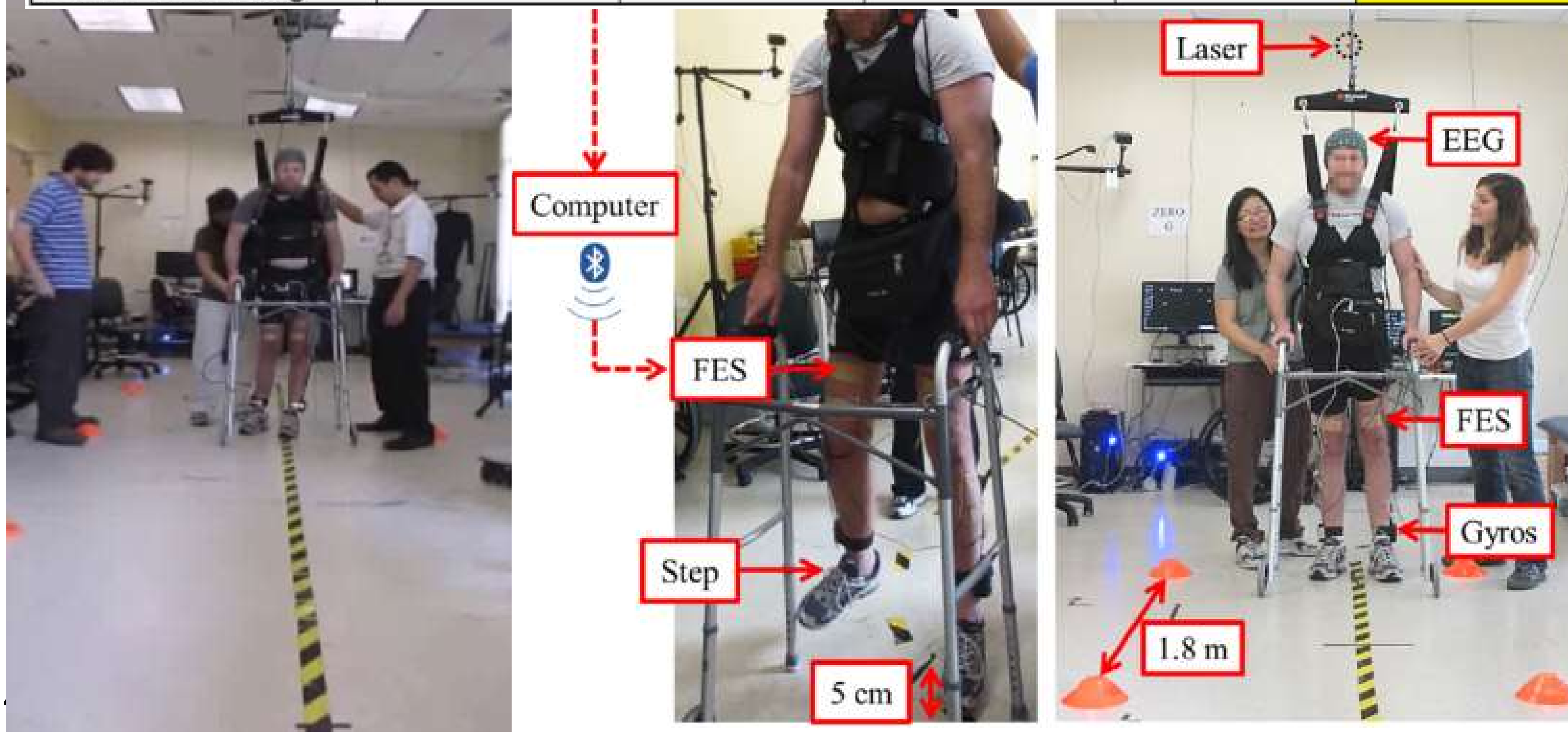
PROTOCOLLO RIABILITATIVO ADATTABILE

King *et al. Journal of NeuroEngineering and Rehabilitation* (2015) 12:80
DOI 10.1186/s12984-015-0068-7

JNER JOURNAL OF NEUROENGINEERING AND REHABILITATION

RESEARCH Open Access

Day Since Start of Study	1 to 17	22 to 38	43 to 59	75 to 117	124 to 208	214 to 256
Visit No.	1 to 4	5 to 9	10 to 14	15 to 19	20 to 24	25 to 30
Screening & Exams						
BCI Screening						
FES Screening						
BCI Training						
FES Training						
BCI-FES Testing						



Medical News TODAY

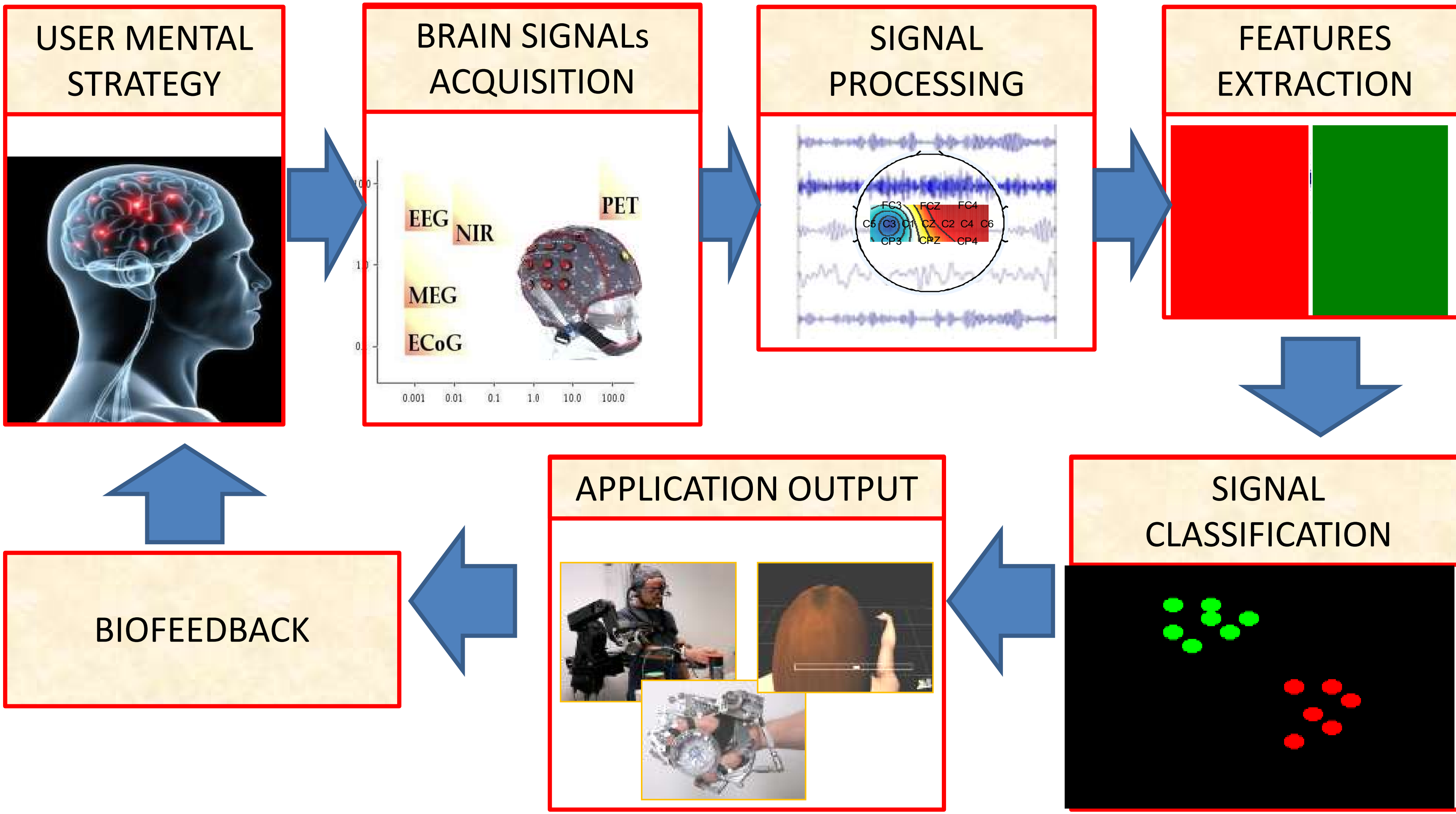
KurzweilAI.net

NewScientist

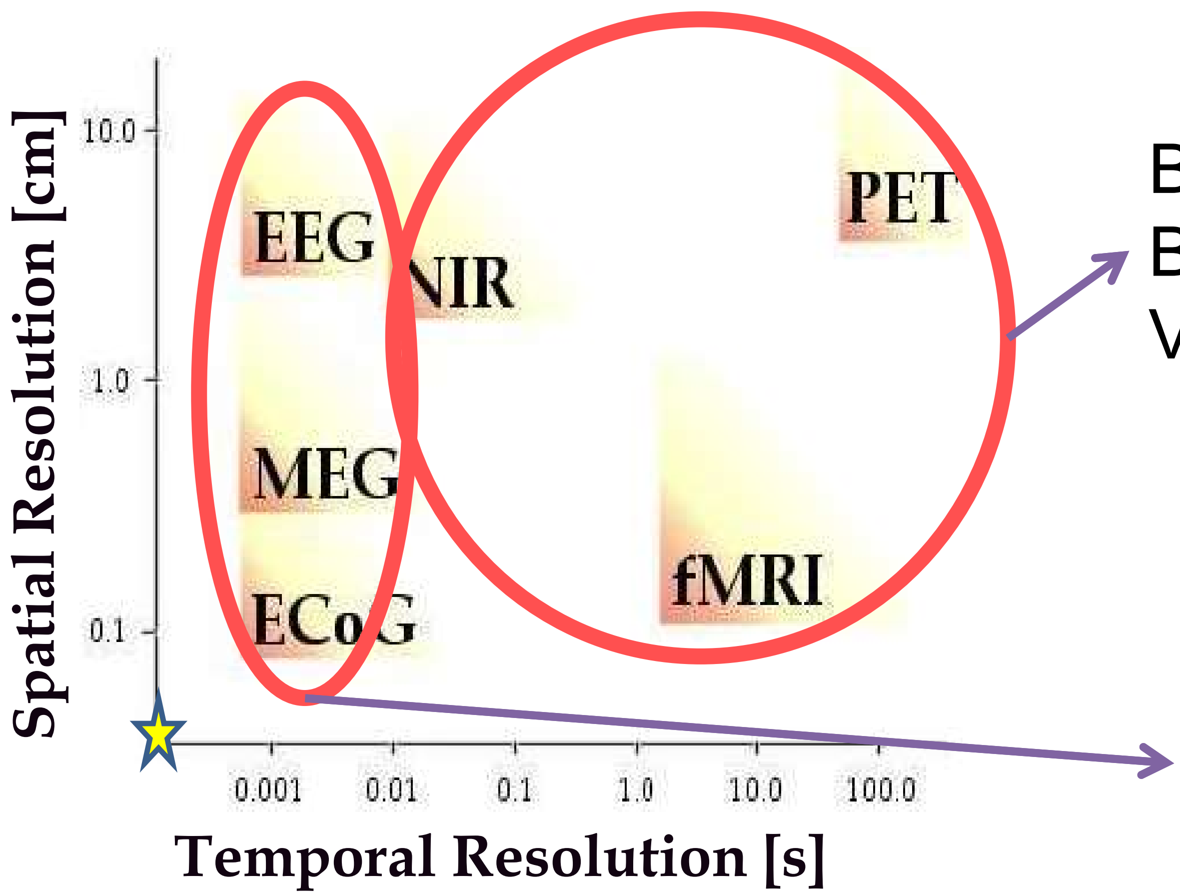
TheCelebrityCafe.com

GENERAL BCI FRAMEWORK

(BCI/BMI) can utilize electric, magnetic, or metabolic brain signals recorded invasively or noninvasively to control, (robotic arm or exoskeleton), allowing to engage in daily life activities.



ACQUIRING BRAIN ACTIVITY



BASED ON THE BLOOD FLOW VARIATION

BASED ON THE MAGNETIC-ELECTRICAL ACTIVITY

NON-INVASIVE BCI BASED ON EEG

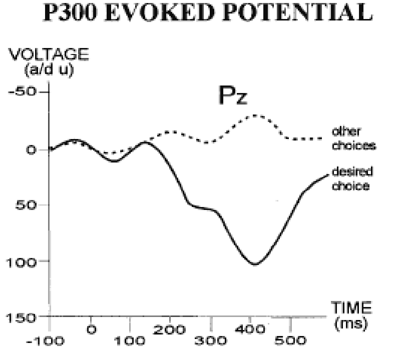
- EEG signals are the most widely used non-invasive strategy for BCI applications
- Several portable, cheap systems exist
- Motion artifacts and interferences can be greatly reduced by employing active electrodes

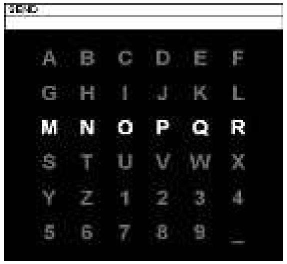
TYPES OF BCI DEPENDING ON MENTAL STRATEGIES

EXOGENOUS POTENTIAL

BCIs based on external cues:

- **ERP (P300)**
- **SSVEP**

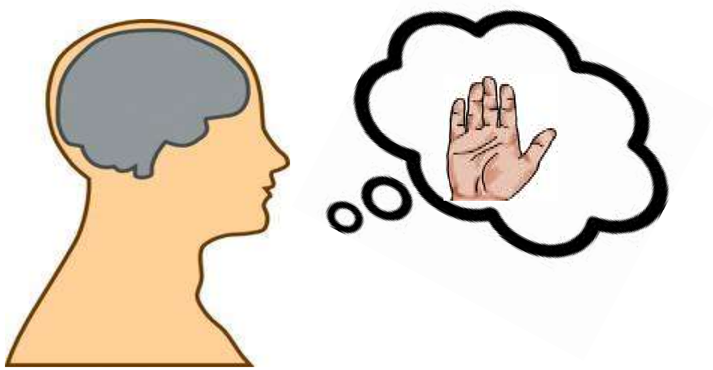




ENDOGENOUS POTENTIAL

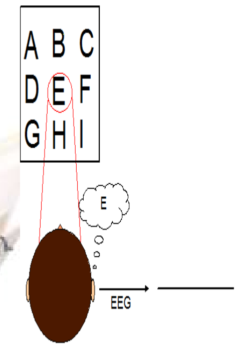
BCIs based on self-paced brain activity:

- **Motor Imagery**



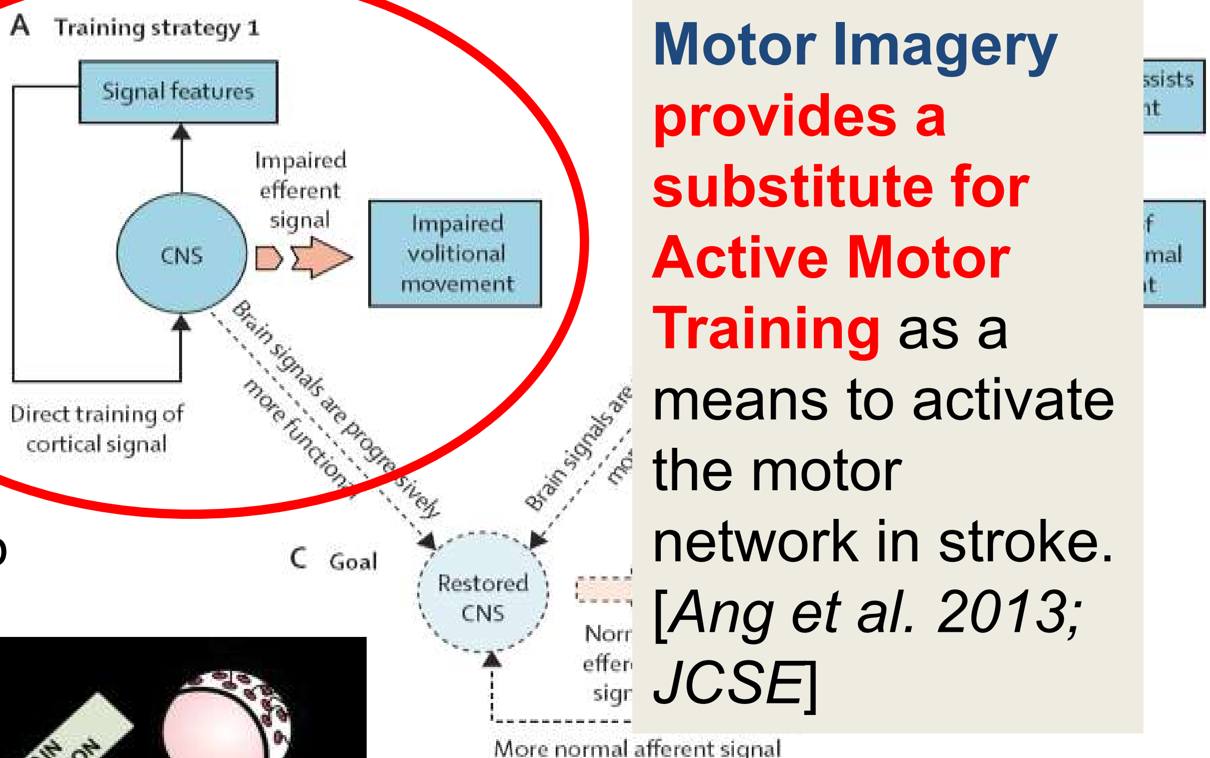
Brain Computer Interface in NEURO-REHABILITAION

- **ASSISTIVE BCI**: continuous high-dimensional brain control of **robotic devices** or functional electric stimulation (**FES**) to assist in performing daily life activities



- **RESTORATIVE BCI**: aiming at augmentation of **neuroplasticity** facilitating recovery of brain function. The development of restorative BCI systems is tightly associated with the development and successes of **neurofeedback** and its use to purposefully up-regulate or down-regulate brain activity

BCI IN NEURO-MOTOR REHABILITATION



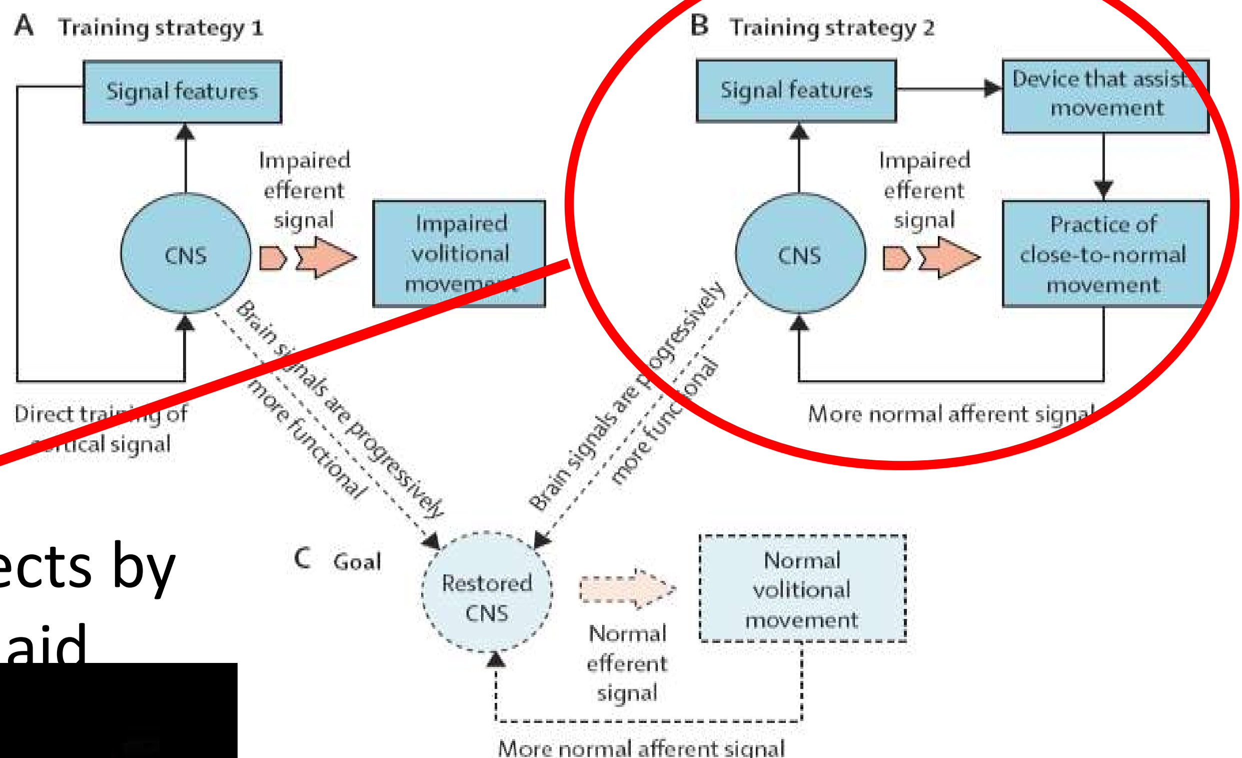
Motor Imagery provides a substitute for Active Motor Training as a means to activate the motor network in stroke. [*Ang et al. 2013; JCSE*]

Daly & Wolpaw, Lancet, 2008

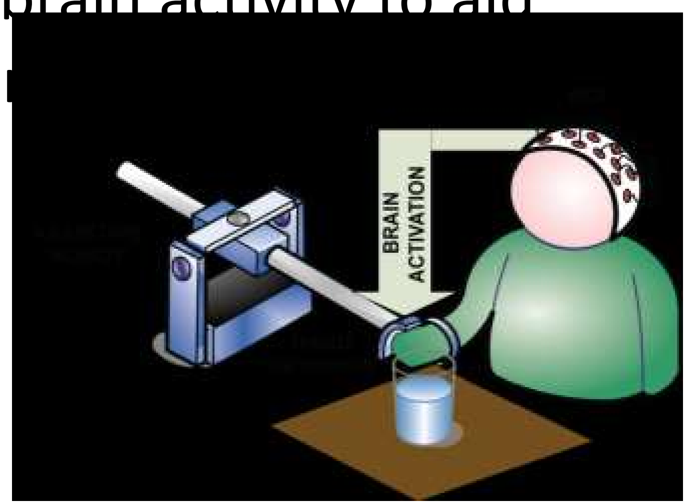
Strategy 1: Train subjects to modulate brain activity via visualization and vol of relevant features

Brain activity promotes brain reorganization

BCI IN NEURO-MOTOR REHABILITATION

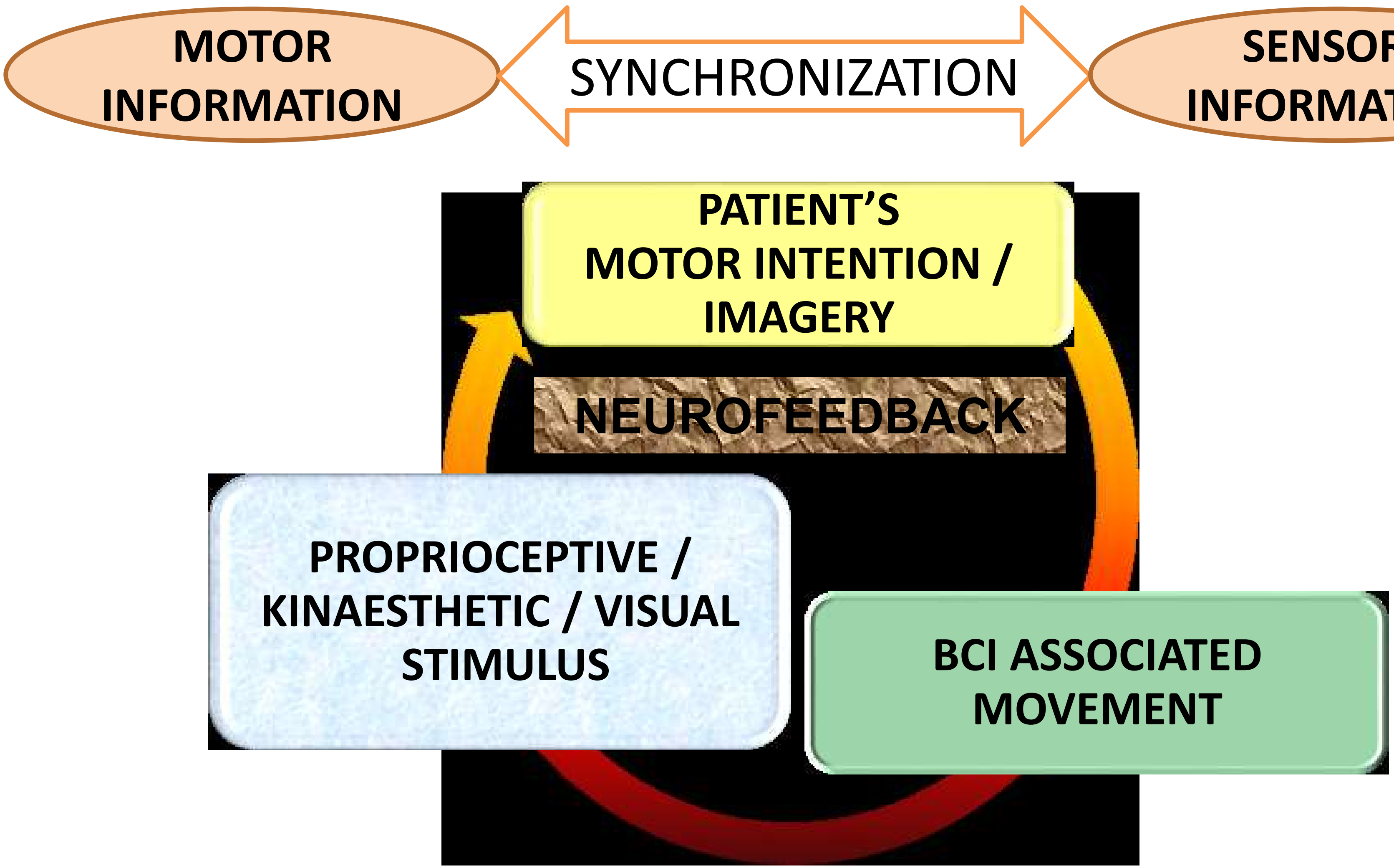


<u>Strategy 2:</u> Train subjects by using brain activity to aid motio



Daly & Wolpaw, Lancet, 2008

BCIs FOR PROMOTING PLASTICITY



[Silvoni et al 2011; Clinical EEG and Neuroscience]

RESULTS

All the three patients enrolled in the study were able to volitionally trigger the task execution through MI within a reasonable amount of time

	Rehabilitation phase Onset Time [s]	
	mean	std
Patient1	4.18	2.30
Patient2	3.83	2.02
Patient3	2.35	0.19
mean	3.45	1.60

- Integration with ALEx exoskeleton
    - Wide range of motion
    - Recording of a task-oriented trajectory
    - Assistance as needed paradigm
    - tasks performed in Virtual Reality

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WORK IN PROGRESS

A new gaze-BCI driven control of an upper limb exoskeleton for rehabilitation in real world tasks

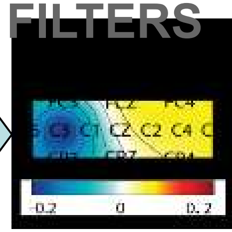
Antonio Frisoli*, Claudio Loconsole*, Daniele Leonardis*, Filippo Bannò*, Michele Barsotti*, Carmelo Chisari**, Massimo Bergamasco*

TRAINING PHASE

ORIGINAL CHANNELS

MOVE REST

CSP FILTERS

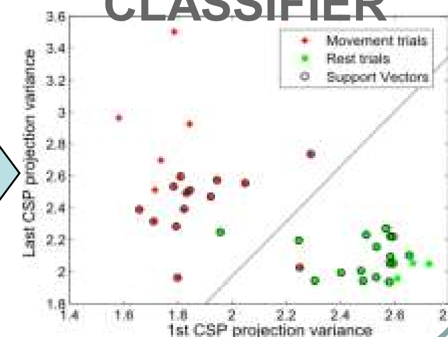


OPTIMAL CHANNELS

MOVE REST

VAR MAX

SVM CLASSIFIER



VISUAL CONDITION

❖ Involving the BCI module only and the visual feedback of a virtual arm controlled through motor

ROBOT CONDITION

❖ The subject performed a test session with the complete system:
Kinect – EyeTracker – BCI – ArmExos

BCI-REHABILITATION PROTOCOL

SESSION STRUCTURE:

- *TRAINING PHASE*: visual and proprioceptive feedback are provided accordingly to the task
- *EXERCISE PHASE*: the real-time classification output of the BCI was used for driving the proprioceptive and visual feedback

TASKs REQUIRED:

- *MOVEMENT*: the patient have to perform motor imagery of his impaired arm
- *REST*: the patient have to hold a resting mental state

MONITOR
visual feedback

BCI
EEG acquisition
& processing

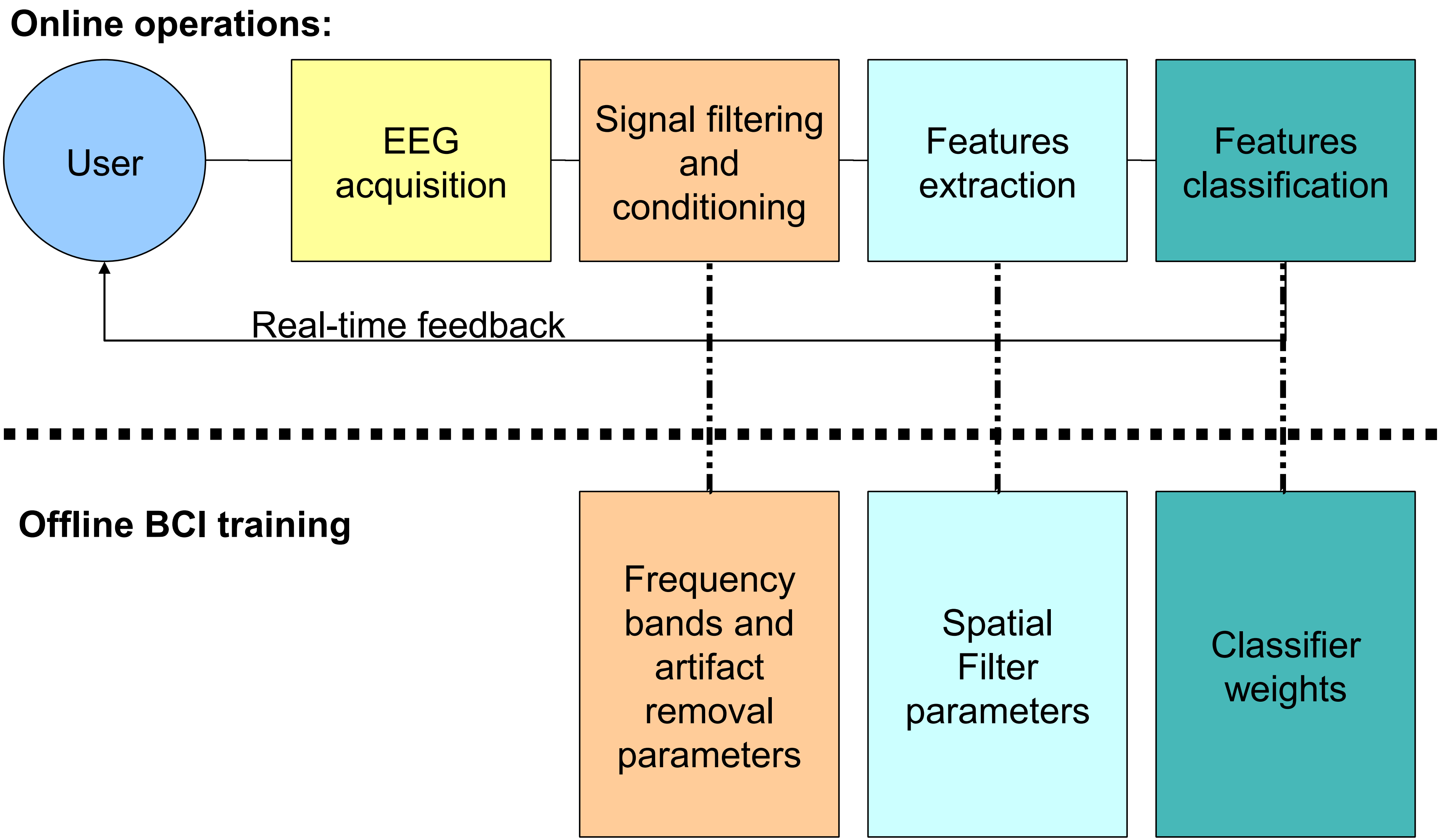
L-EXOS
proprioceptive
feedback

5 right hemiparetic stroke patients enrolled

ALL PATIENTS WERE ABLE TO CONTROL THE BCI SYSTEM AFTER THE FIRST TWO SESSION

BCI paradigm based on Motor Imagery

MOTOR IMAGERY BCI: WORKFLOW



EEG CONFIGURATION

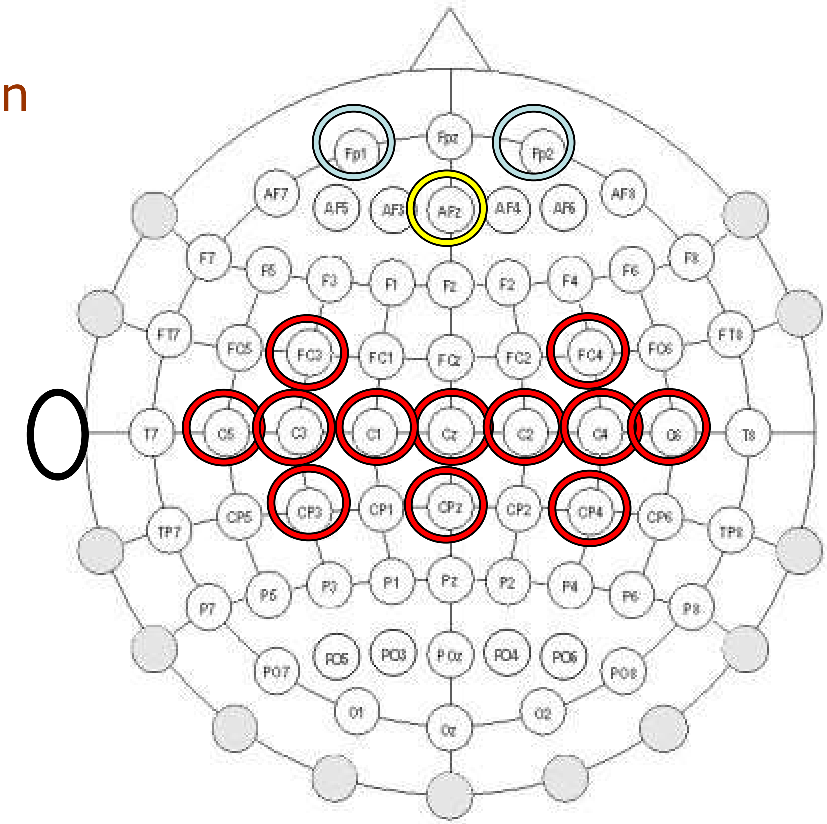
- EEG channels: minimal configuration

Frontal ground electrode

Reference ear lobe electrode

Electrodes covering the motor cortex

Electrode for eye-blink detection and removal



- Feature extraction

The power in the mu (8-12 Hz) and beta (16-24 Hz) bands is computed over 500 ms windows.

TRAINING PHASE

- **Training paradigm**

  Subjects are asked to perform several motor imagery trials.

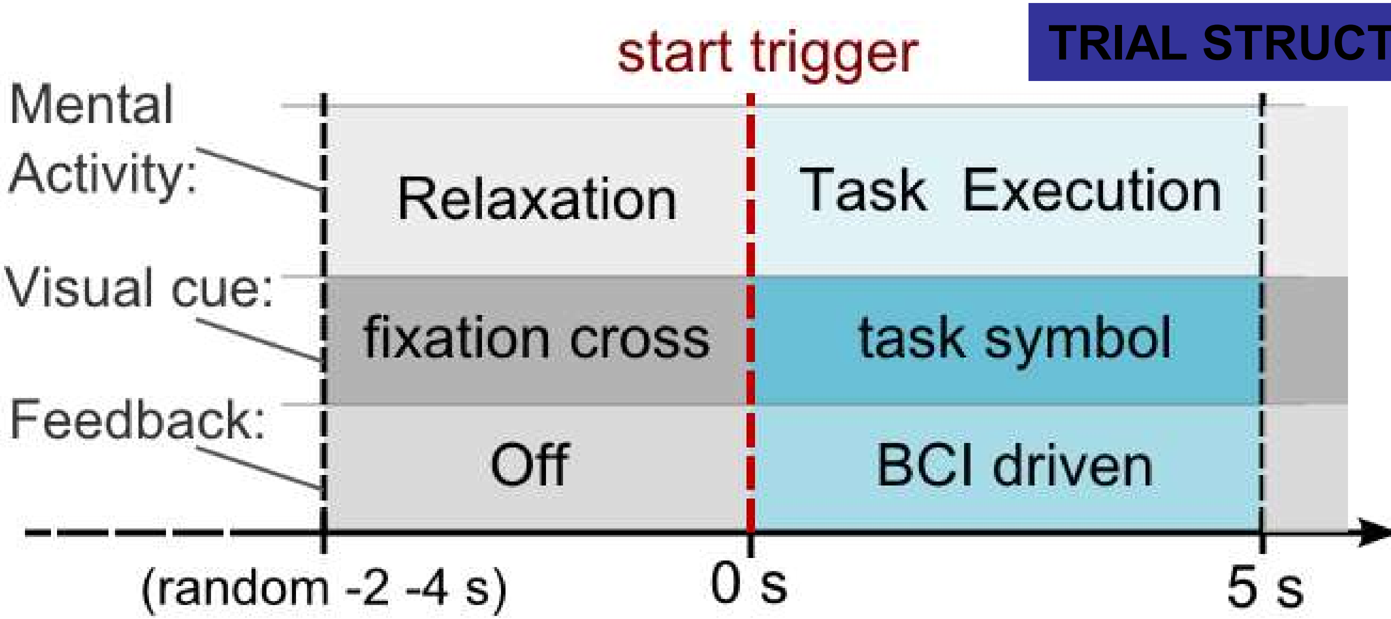
  1. **Feature classification**

     Acquired data is classified into two or more classes via machine learning techniques, to optimize feature classification

  2. **Subject training**

     The subject is trained again with the output of the feature classifier as a feedback signal, in order to optimize its motion imagery

TRIAL STRUCTURE

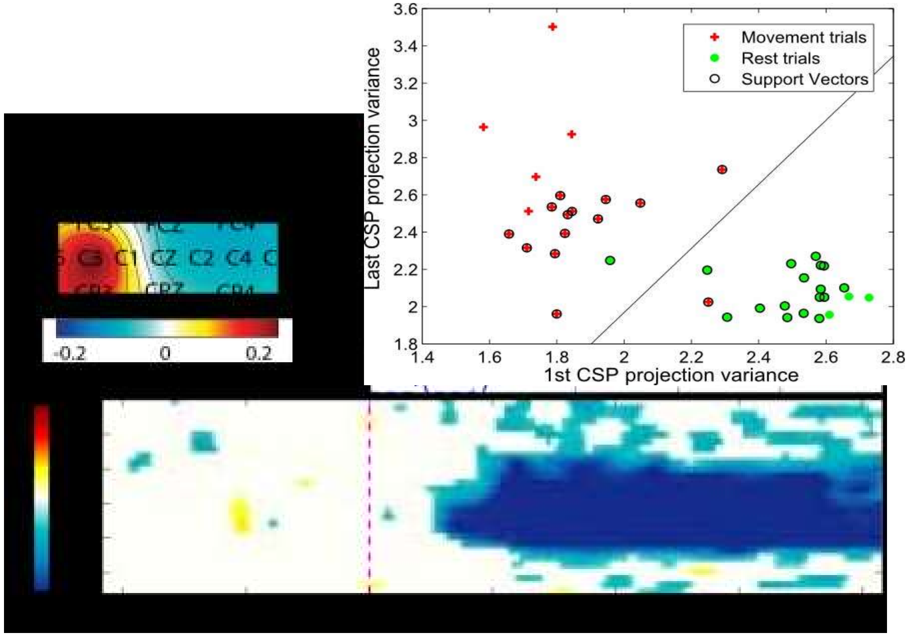


DATA PROCESSING

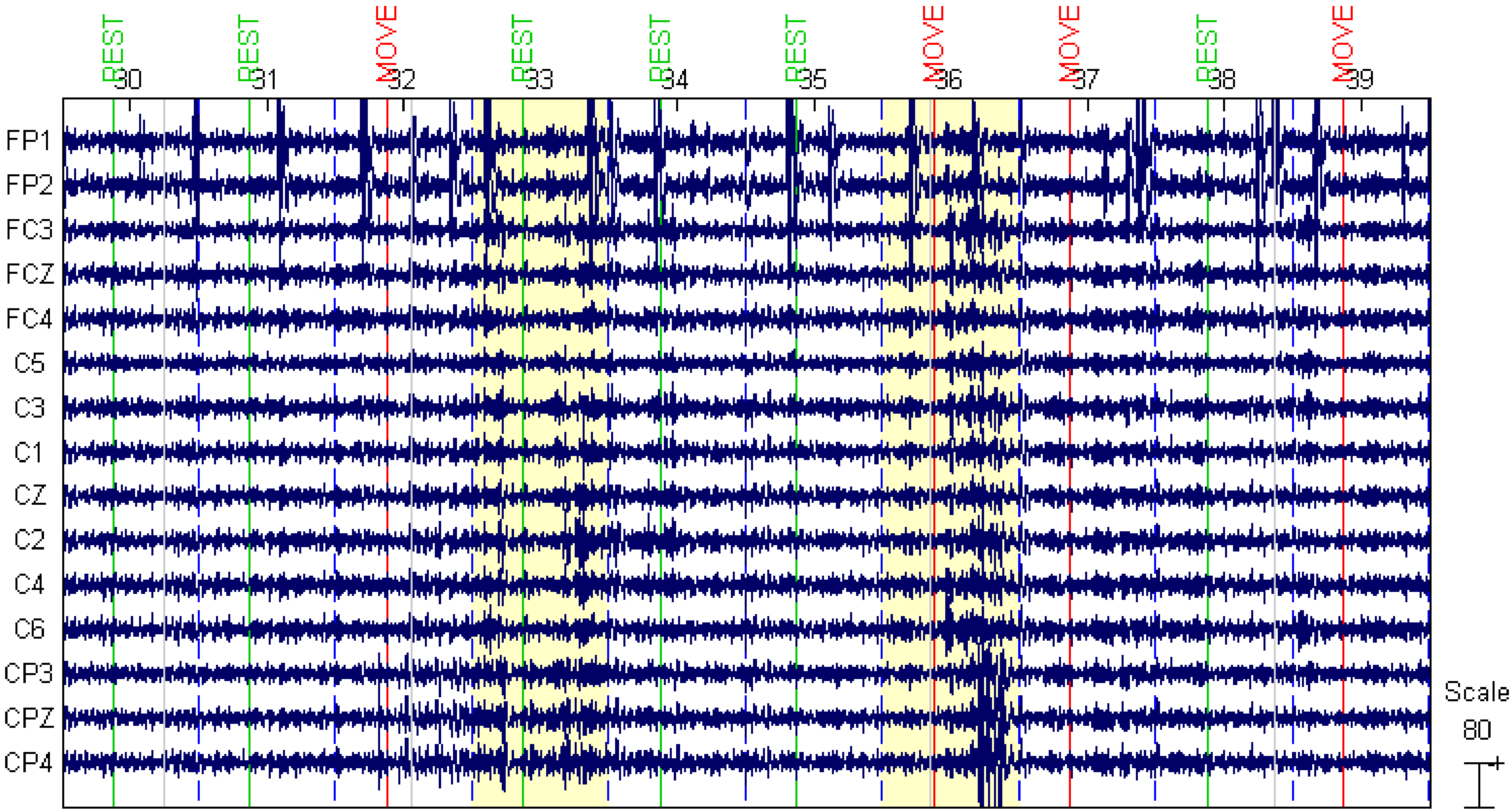
TRAINING

- Import data with the channel location
- Subdivide data into epochs for the two classes
- Remove artifactuated epochs
- Train the Common Spatial filter
- Extract Features
- Train the classifier

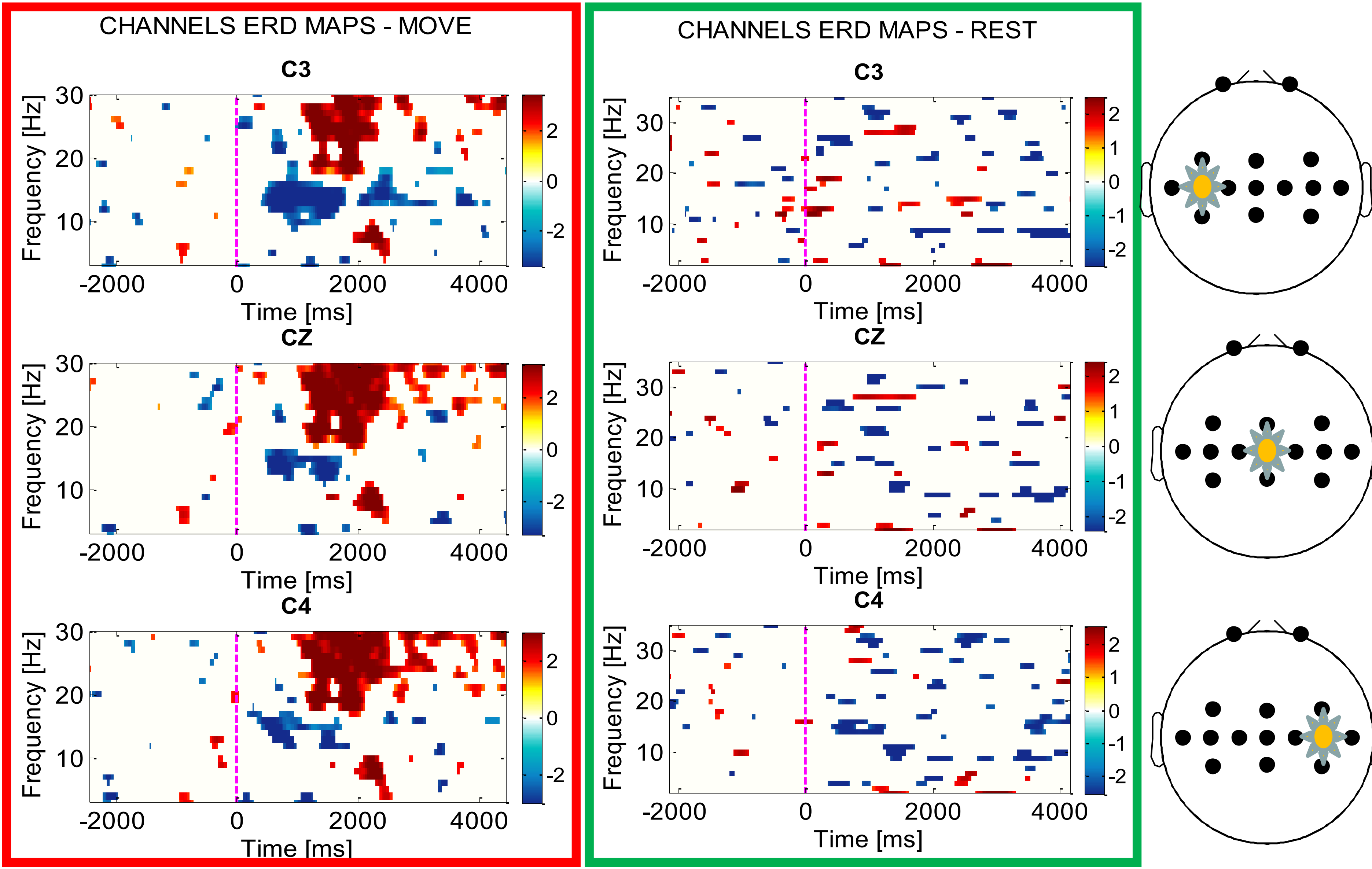
it is possible to predict the BCI performance by a visual inspection of both the time-frequency plot of the CSP-projected channels and the features plot



DATA PROCESSING: Visual Inspection



Time Frequency plot raw channels



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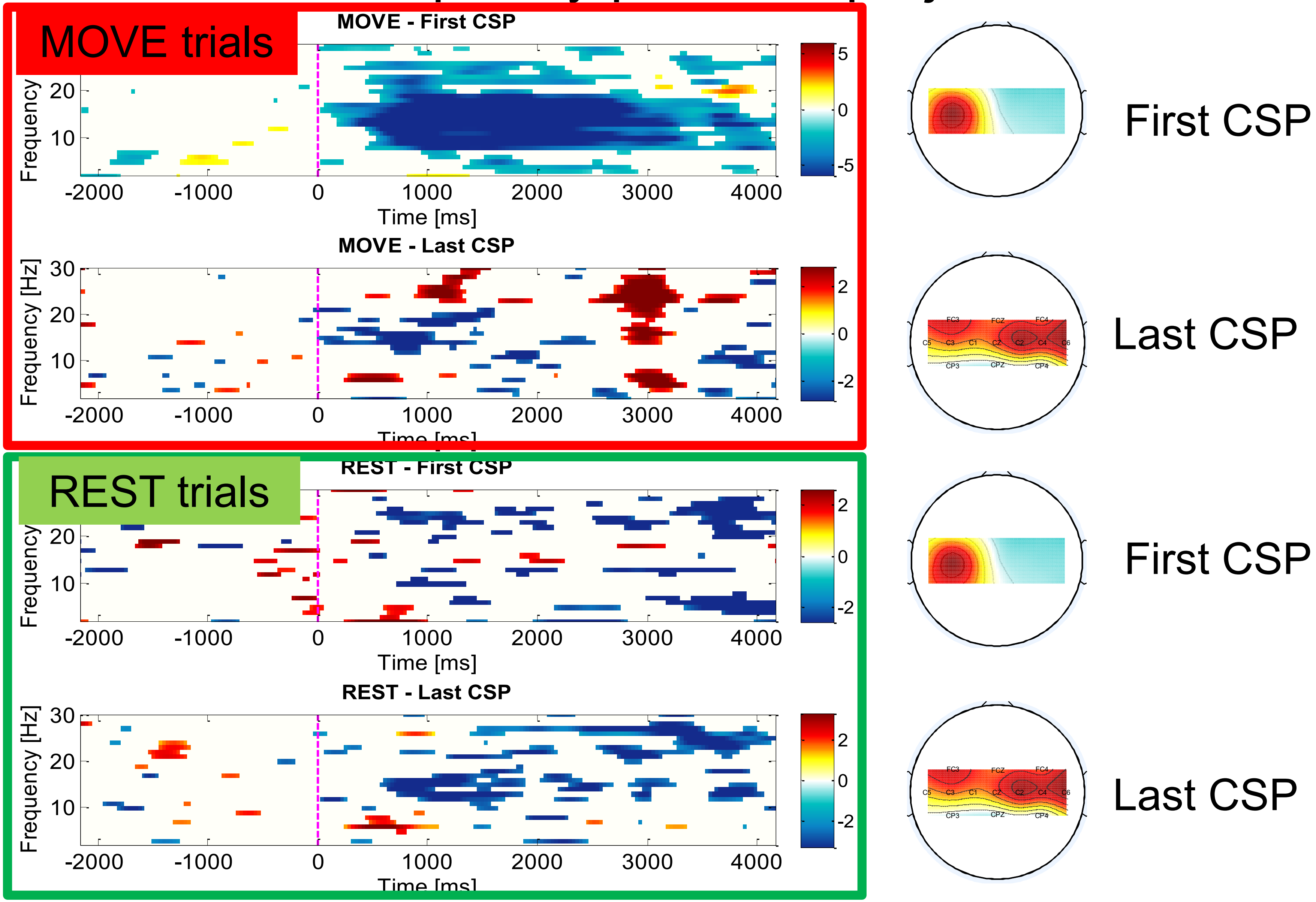
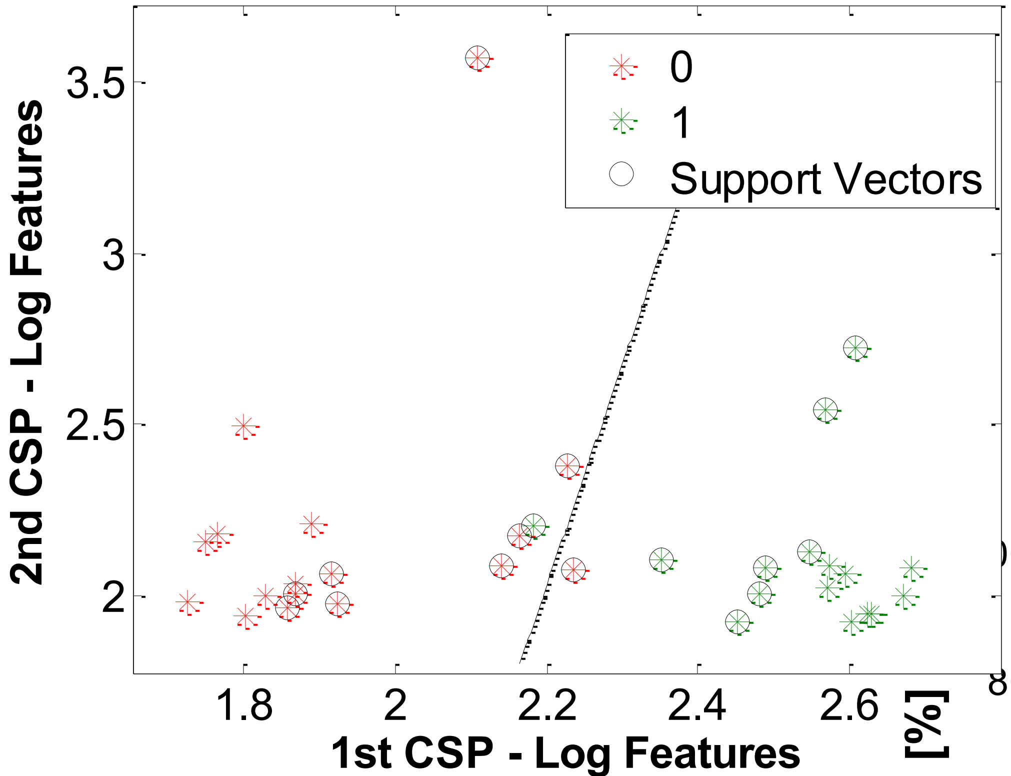
Time Frequency plot CSP projected channels

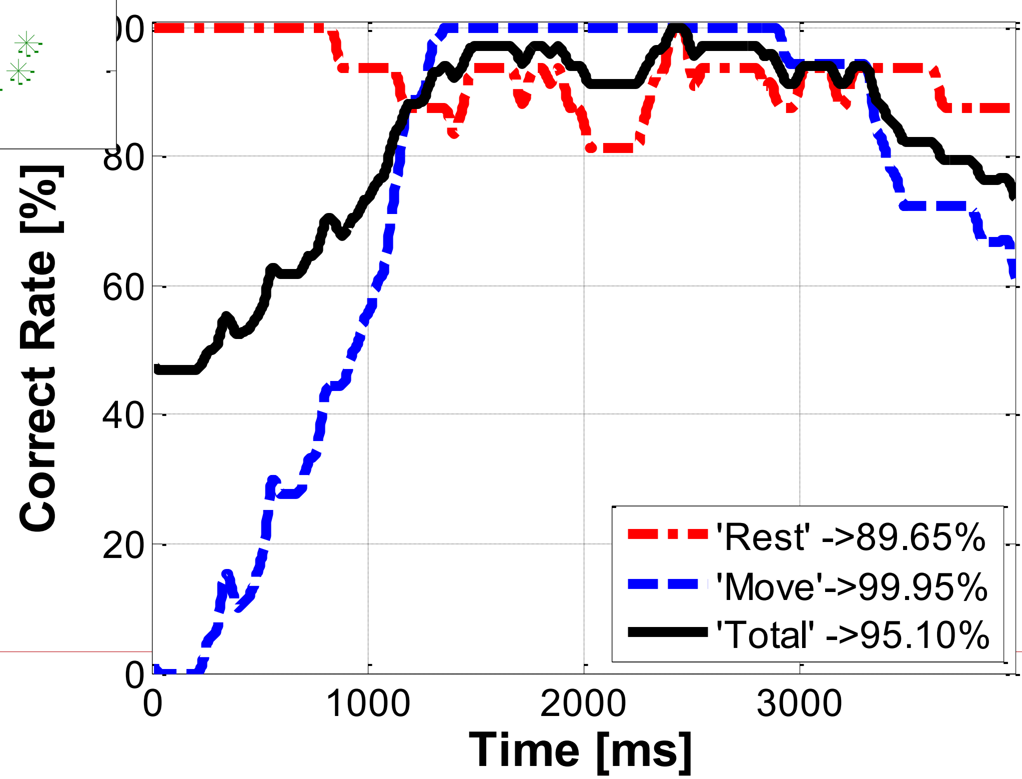


PREDICTING RESULTS



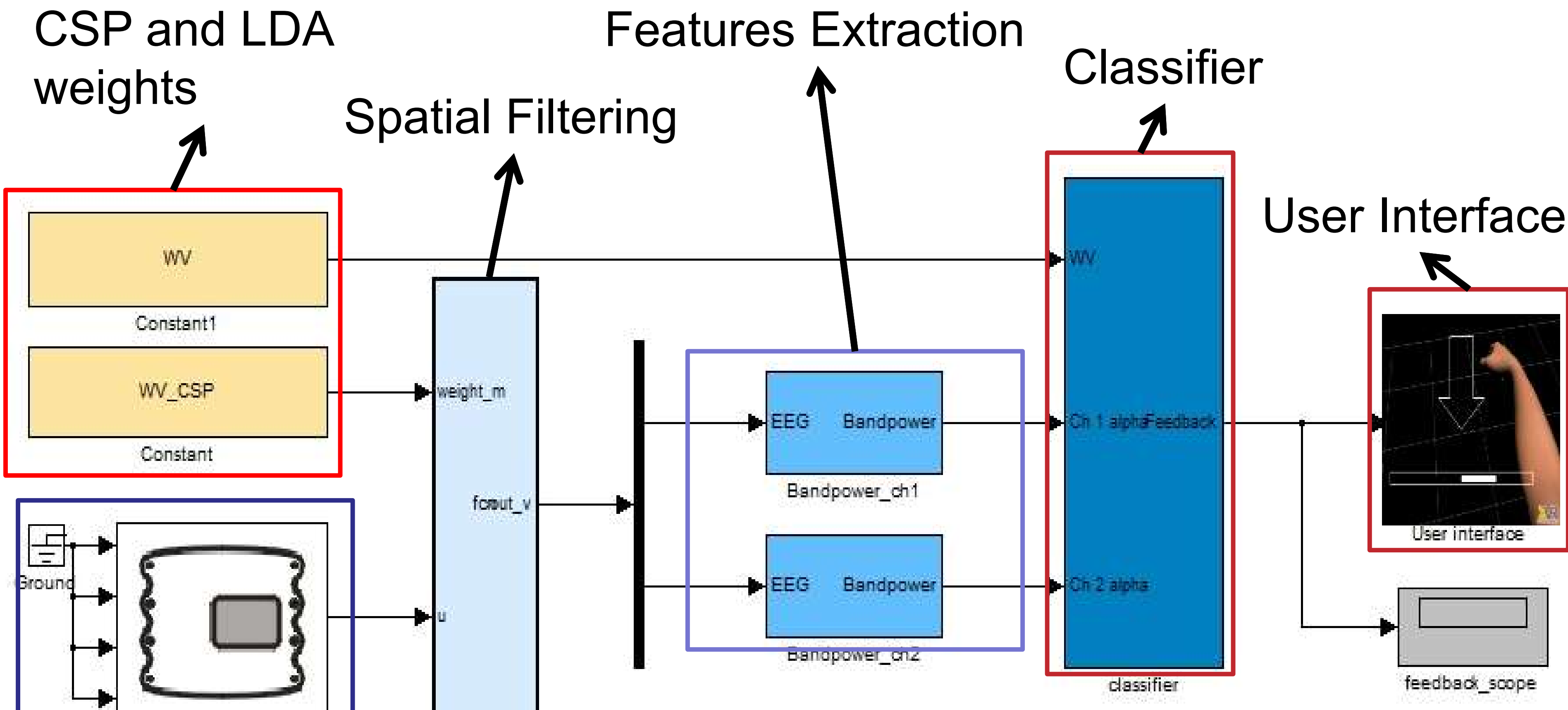
Plot of each trial in the features space

CLASSIFIER PERFORMANCE

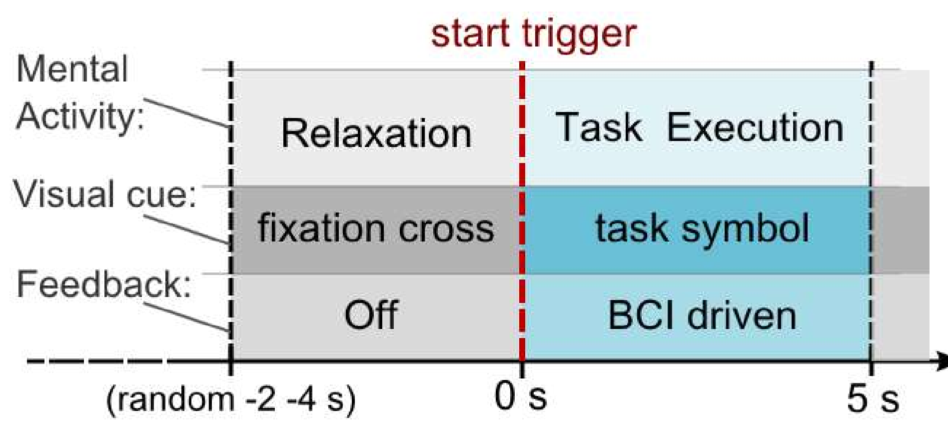


Analysis of the BCI output calculated with parameters extracted from the same dataset

MODEL



CSP and LDA weights
Spatial Filtering
Features Extraction
Classifier
User Interface
WV
Constant1
WV_CSP
Constant
Ground
g.USBamp UB-2010.06.20
EEG amp
weight_m
fcout_v
u
spatial filter
EEG
Bandpower
Bandpower_ch1
EEG
Bandpower
Bandpower_ch2
WV
Ch 1 alpha
Feedback
Ch 2 alpha
classifier
User interface
feedback_scope



start trigger
Mental Activity:
Relaxation
Task Execution
Visual cue:
fixation cross
task symbol
Feedback:
Off
BCI driven
(random -2 -4 s)
0 s
5 s

SHOWING RESULTs

[Frisoli et al. 2012]

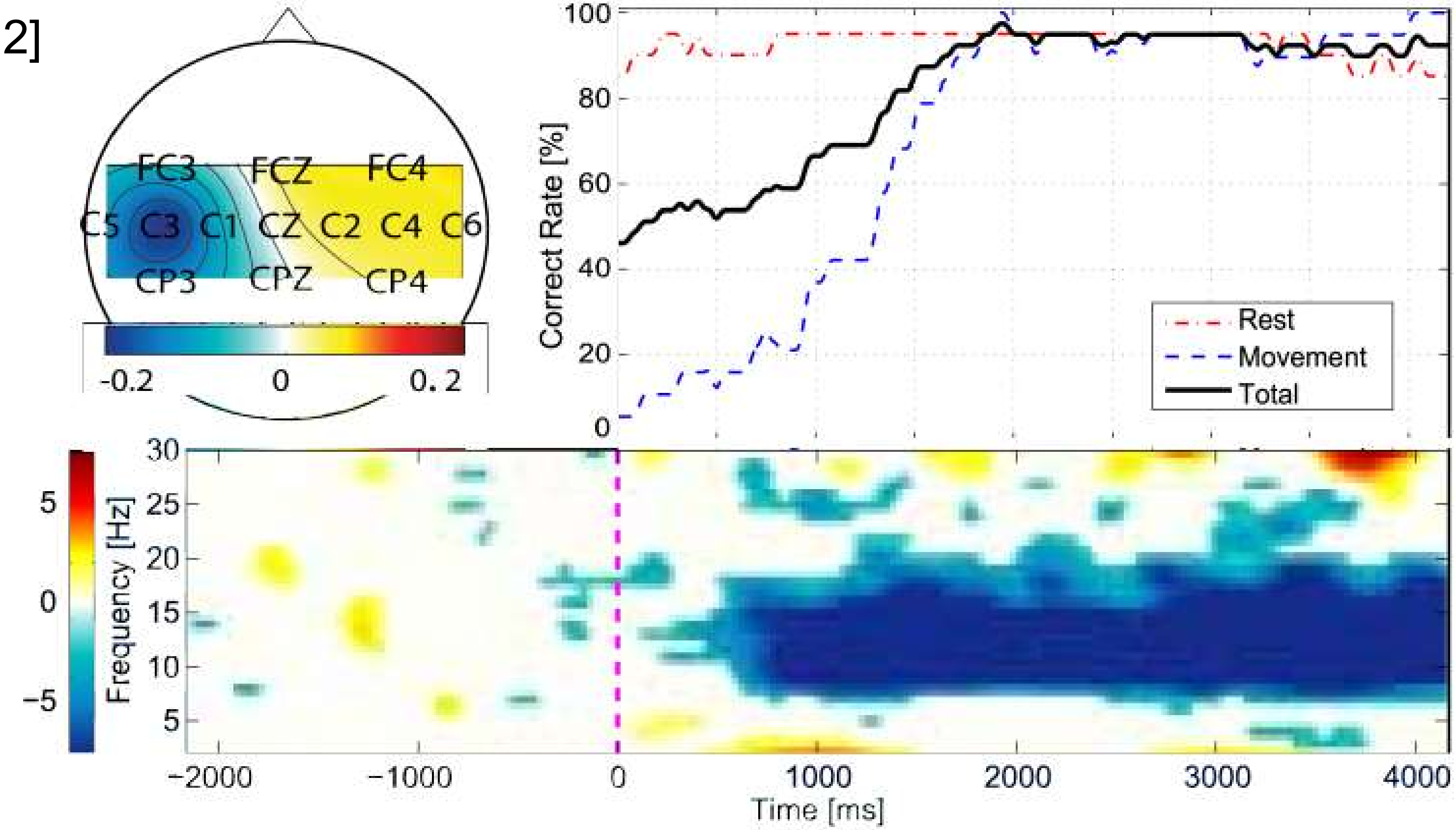


Fig. 9: ERD maps during the visual feedback condition for patient #2 (bootstrap p< 0.05). The vertical dotted line marks the beginning of the task execution. Top left panel shows the CSP extracted activation pattern on the scalp associated to motor imagery. Top right panel shows the performance of the classifier expressed in terms of correct rate during the task execution.

BCI FOR COMMUNICATION

- **p300** (Face Speller)

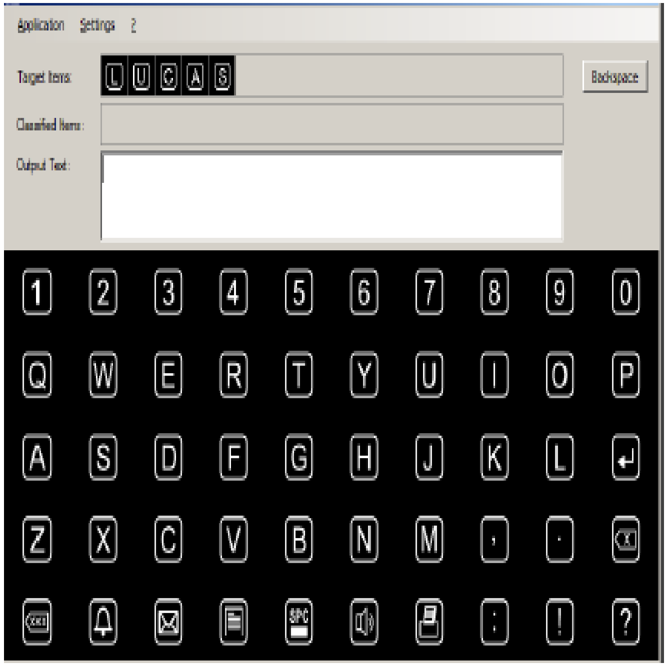
P300 (potenziale evento correlato)

➢ Feature extraction

Signals - time-locked to stimuli presentation – are collected in correspondence of the visual cortex and an ERP trace is constructed for each stimulus.

➢ Paradigm

Subjects are asked to fixate a matrix of letters/commands, with flashing rows and columns



1. Feature classification

   Acquired data is classified into two classes, to discriminate the expected stimulus from the others.

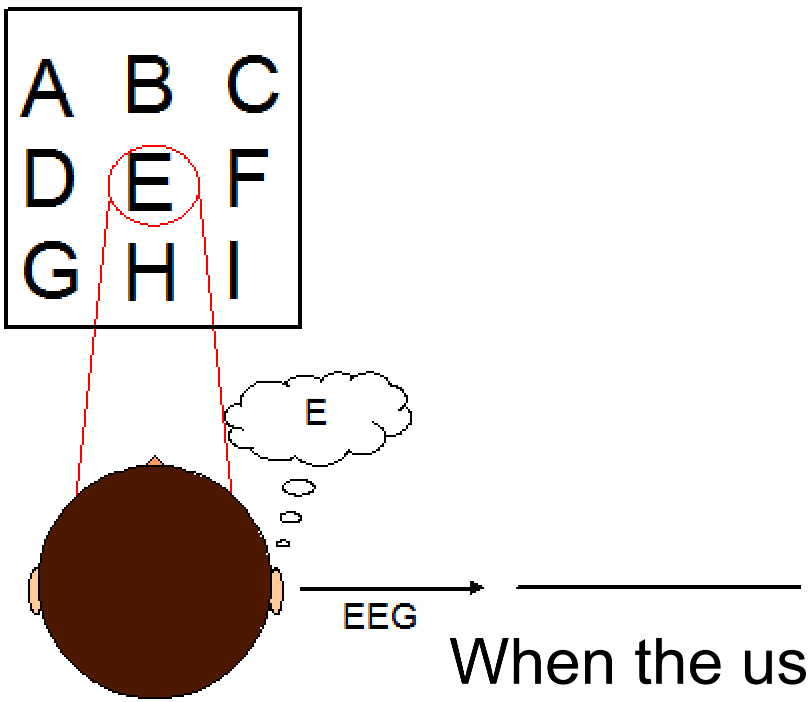
2. Subject training

   Training simply consists in reaching a level of concentration sufficient to allow detection of the expected stimulus.

   A good subject needs only 4 row/column presentation to select a letter.

P300

- A classifier is used to determine if this signal correspond to a positive response or not.
- In order to set the classifier a training session is needed



•Determining the presence or absence of a P300 evoked potential from EEG features can be considered a binary classification problem with a discriminant function having a decision hyper-plane defined by

$$w \cdot f(x) + b = 0$$

When the user target is illuminated a p300 potential appears

BCI
For Commication

- Steady State Visual Evoked Potential - **SSVEP**

Steady State Visual Evoked Potential - SSVEP

• The SSVEPs are a natural responses to visual stimulation at specific frequencies higher than 6 Hz.

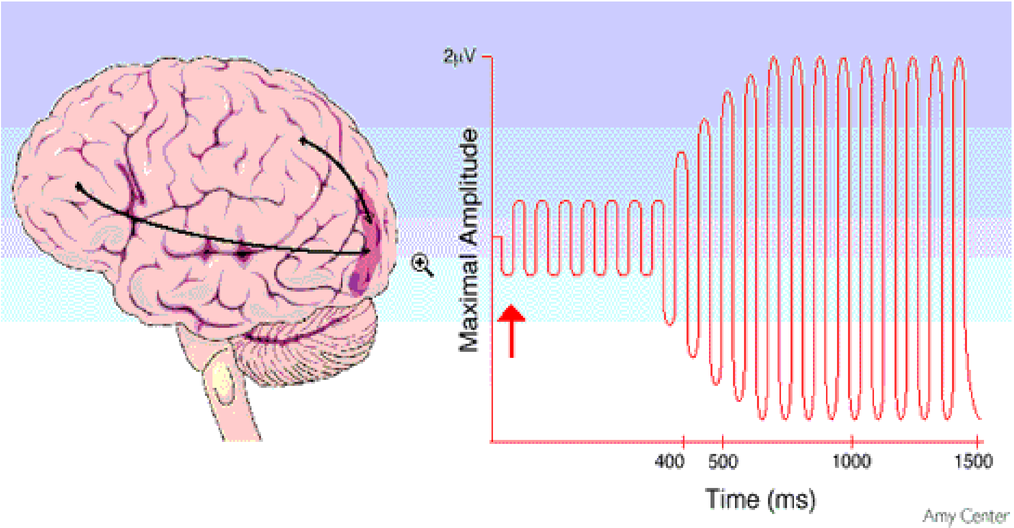
.

• Using EEG electrodes placed over the occipital area the user's gazed target is recognized by analyzing the frequency or phase characteristic of the measured SSVEPs.

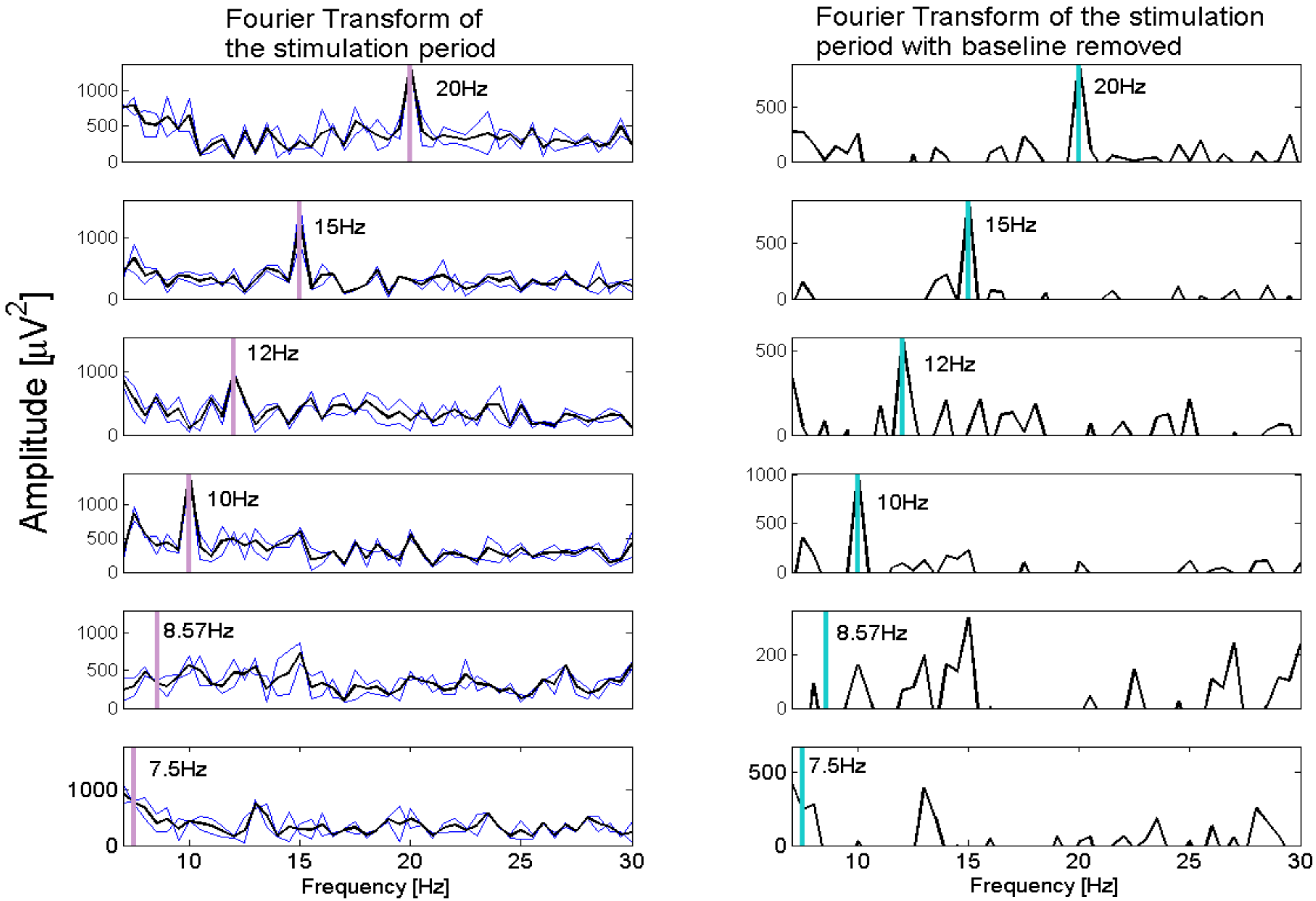
• Users focus their attention on a LED/screen flashing at a known frequency

• Habituation can lower the signal to noise ratio (SNR)

A periodic response elicited by the repetitive presentation of a visual stimulus



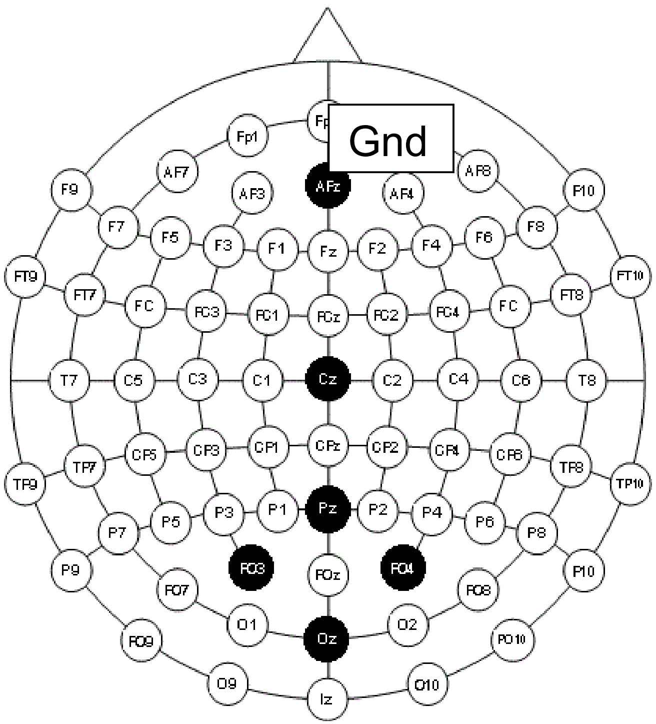
SSVEP - SCREENING ON ONE SUBJECT



SSVEP – EEG acquisition

The BCI-SSVEP approach for navigation task

- The electrodes are placed over the ***occipital area*** in proximity of the ***visual cortex***, according to the standard 10-20 positioning (**Cz, Pz, PO3, PO4, Oz**)
- Channels are referenced to **AFz** and the amplifier is grounded to the earlobe

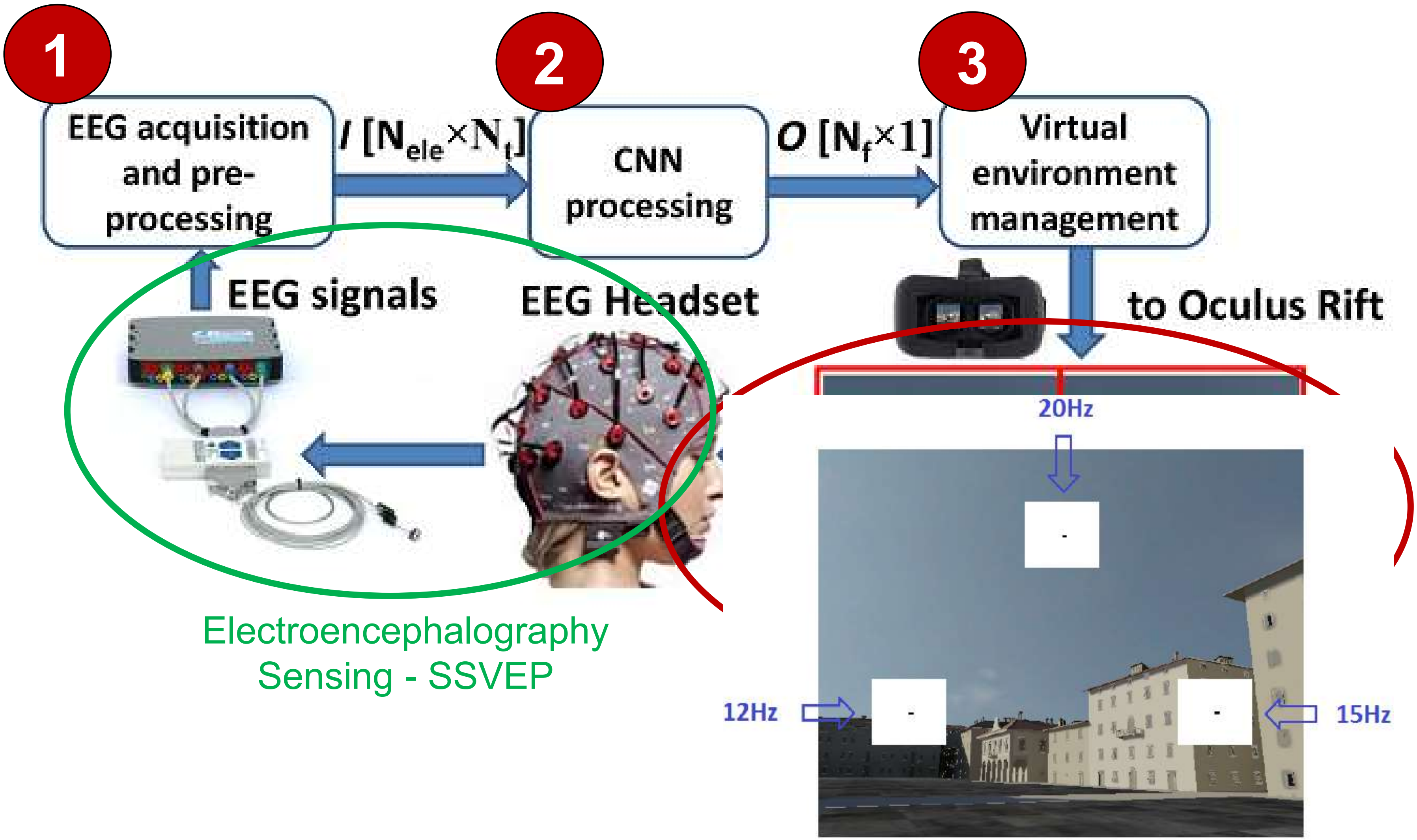


Pre- processing

- band-pass filter in the range 2-60 Hz
- notch-filter at 50 Hz - were applied internally to the amplifier with the purpose of limiting the presence of artifacts and noise in the EEG signals
- signals were sampled and digitally converted at a frequency of Fs = 256 Hz

SSVEP – system description

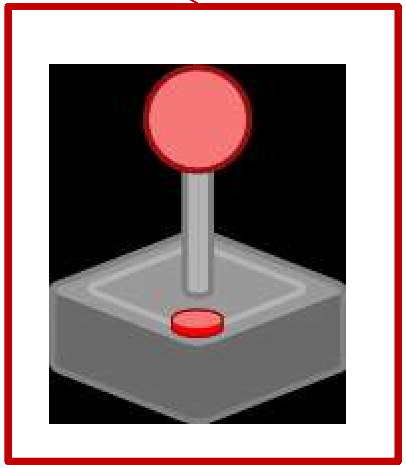
The BCI-SSVEP approach for navigation task

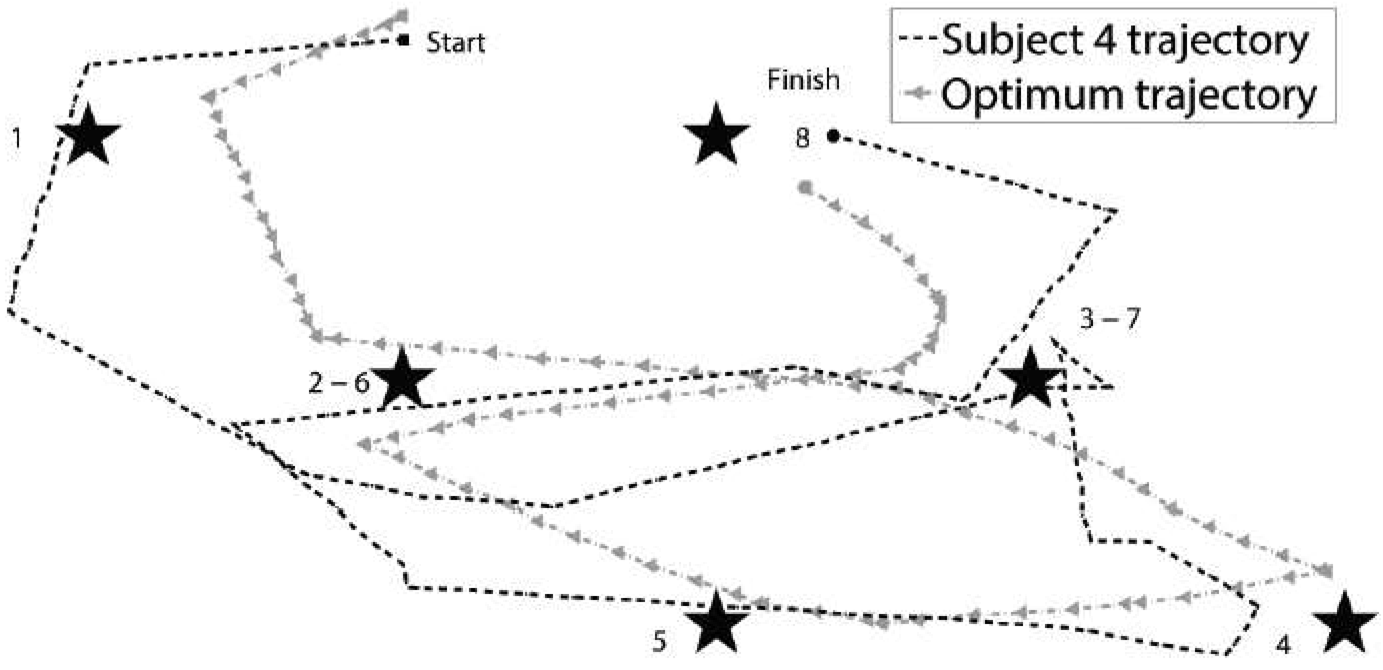


SSVEP – results

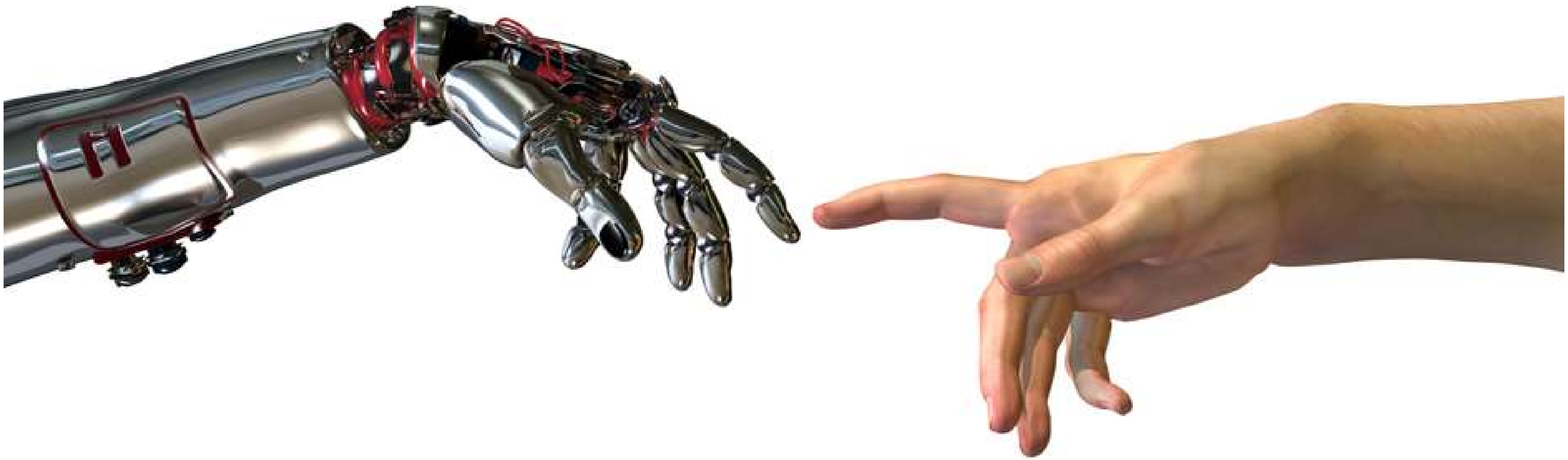
The BCI-SSVEP approach for navigation task

Subjects	Time [s]
S1	470 s
S3	483 s
S4	260 s
mean	333 s
std	178 s
JoyCtrl	120 s





CONCLUSIONs



OPEN QUESTIONS

- Quali sono I paradigmi BCI più effettivi non solo per indurre la plasticità ma anche per migliorare le funzionalità motorie?
- Come l'attività cognitiva di uno specifio task BCI accoppiata con un feedback appropriato influenza la plasticità neurale?
- Dopo un training con BCI è possibile trattenere e portare I risultati raggiunti al di fuori del laboratorio sperimentale?

thank you!

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TREND ON BCI AND NEUROREHABILITATION

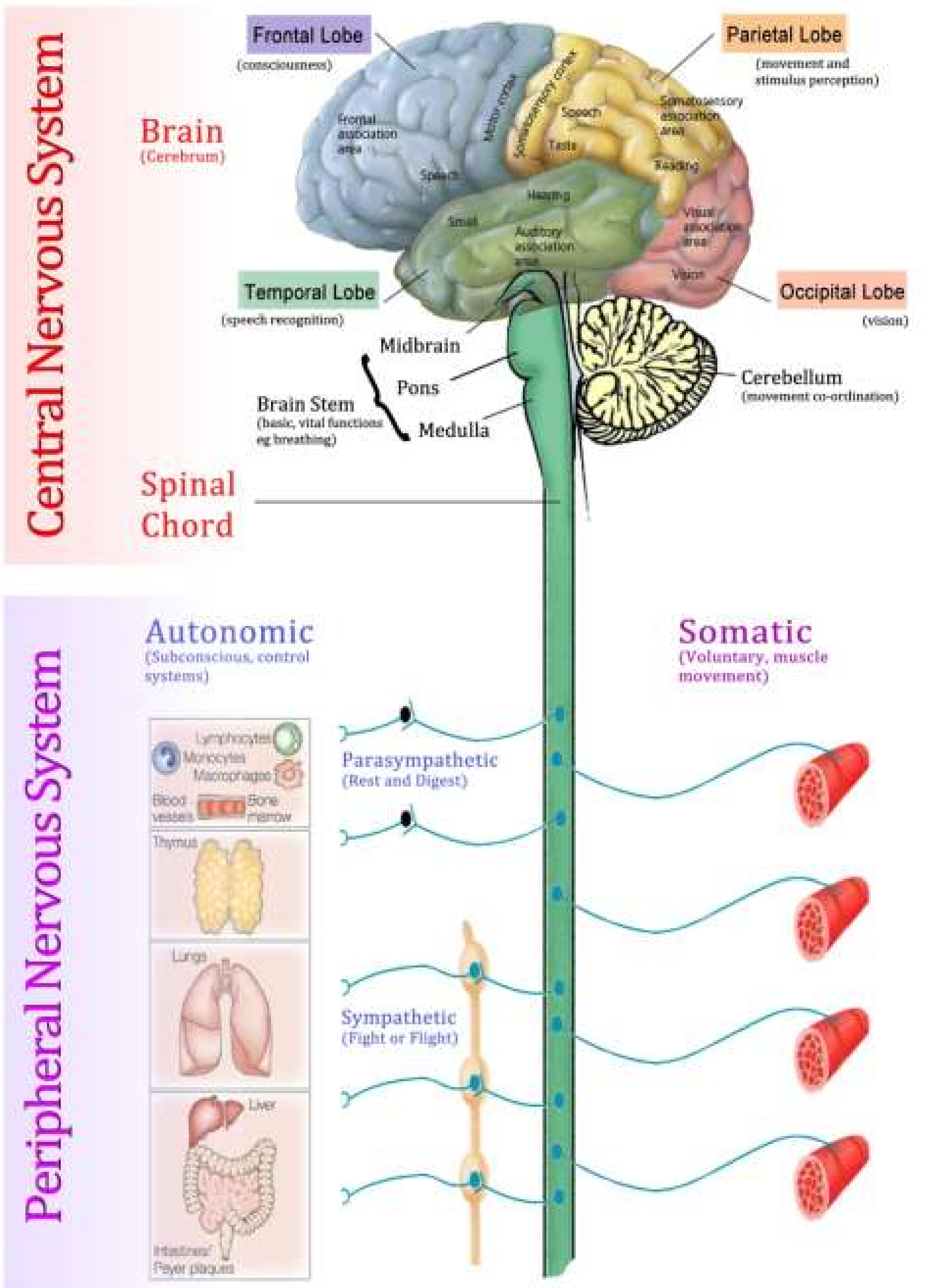
STATE OF THE ART

Michele Barsotti : m.barsotti@sssup.it

OPEN QUESTIONS

- how the cognitive activity required in a BCI task influences neuroplastic processes when coupled with a specific feedback;
- whether BCI training itself might produce significant improvement in clinical outcomes (with reduced or absent physical practice);
- whether and how ipsilesional/contralesional cognitive activity itself is useful to promote new neuronal connections;
- whether and how generalization of achieved behavioral improvement is possible outside the laboratory after a BCI training;
- larger clinical studies are needed to further investigate mechanisms underlying BMI-related stroke recovery and predictors of treatment response;
- Should one therefore focus on the resemblance with activations of the non-paretic side? Or on activations associated with imagined movement that are used frequently but are lacking the motor execution component?
- What are the most effective BCI paradigms to not only induce plasticity but also improve motor function?
- Will using external devices have a larger impact on motor function than motor imagery, virtual realities or other forms of feedback? Or does it depend on the post-injury treatment window?
- When should BCI be applied to gain most plasticity? At which moment in time post-injury or at what stage of “natural” or “training- induced” plasticity is its application the most beneficial?
- And what is the best timing between BCI training combined with more conventional movement-based physiotherapy?

The Nervous System



CENTRAL NERVOUS SYSTEM INJURIES

SPINAL CORD INJURY (SCI)

Characterized by an irreparable nerve fiber lesion at spinal level.

Restoring movement in patients with SCI would require a **bypass of the spinal** injury.

STROKE

Occurs when blood supply to the brain is blocked or when blood vessels in the brain burst.

Motor recovery was proven to be feasible in stroke patients depending on both the possibility to positively affect the **neuroplastic changes** associated with the brain lesion and to provide motor training to maximize functional outcomes..

Structural and metabolic brain imaging and electrophysiological recording of the primary motor cortices have been used to document **reorganization of neural activity** after stroke.

Since stroke does not impair the capacity to perform Motor Imagery, MI provides a substitute for Active Motor Training as a means to activate the motor network in stroke.

STRATEGY TO PROMOTE PLASTICITY

Pharmacological Intervention

Researchers have postulated that exogenous treatments that stimulate neurogenesis could improve recovery after stroke.

Nervous System Stimulation

Devices that provide electrical stimulation to peripheral nerves and muscles might assist stroke patients with hemiparesis move their affected limbs.

Ongoing study combination of anodal tDCS delivered to the motor cortex of the affected hemisphere combined with training over a period of two weeks in the subacute stage after stroke will significantly enhance cortical plasticity, functional regeneration

http://clinicaltrials.gov/ct2

Neuroprosthesis

Research into both invasive and noninvasive **BCI** has shown that patients with stroke can control exogenous systems through training.

CURRENT STANDARD CARE

International guidelines have been developed on the basis of available data to promote best
clinical practice in poststroke rehabilitation [Quinn et al., 2009]

Constraint induced movement therapy CIMT—a regimen involving comfortable restraint of the non paretic limb in conjunction with 'forced' use of the paretic limb in activities of daily living, and in intensive functional training—has been shown to be associated with an immediate decrease in disability rating scores in several metaanalyses. [Sirtori et al., 2009]

Other techniques suchas **motor imagery**, [Page et al., 2009, Sharma et al., 2009] **bilateral arm training** [Coupar et al., 2010] and **robotassisted therapy** [Volpe et al., 2009, Lo et al., 2010] might also improve motor function in patients with stroke, but the limited number of studies that have investigated these techniques precludes the formulation of meaningful guidelines for their use.

BCI IN NEURO-REHABILITATION

(BCI/BMI) can utilize electric, magnetic, or metabolic brain signals recorded invasively or noninvasively to control, (robotic arm or exoskeleton), allowing to engage in daily life activities.

- **ASSISTIVE BCI**: continuous high-dimensional brain control of robotic devices or functional electric stimulation (FES) to assist in performing daily life activities
  (SCI patients)

- **RESTORATIVE BCI**: aiming at augmentation of neuroplasticity facilitating recovery of brain function (stroke patients).
  The development of restorative BCI systems is tightly associated with the development and successes of neurofeedback (NF) and its use to purposefully up-regulate or down-regulate brain activity -- a quality that showed to have some beneficial effect in the treatment of various neurological and psychiatric disorders associated with neurophysiologic abnormalities

BRAIN SIGNALS FOR NON-INVASIVE BCI

1. sensorimotor rhythms (SMRs, 8 -15 Hz), , (2) slow cortical potentials (SCPs) ,
2. event-related potentials (ERPs, visual, auditory and tactile Evoked potentials, ie p300) ,
3. steady-state visually or auditory evoked potentials (SSVEP/SSAEP) ,
4. blood-oxygenation level dependent (BOLD)-contrast imaging using functional MRI ,
5. concentration changes of oxy-/deoxyhemoglobin using near-infrared spectroscopy (NIRS)

BRAIN ACTIVATION MONITORING can also be used to monitor

- the global level of attention directed towards the tasks and
- the level of inter-hemispheric (dis)balance.

[Derosière et al., 2013] showed that NIRS measured activity over the prefrontal cortex (PFC) could discriminate between low and moderate levels of workload, with a plateau effect towards higher levels of workload. In addition, NIRS has been shown to be sensitive to attention decrement regardless of task duration

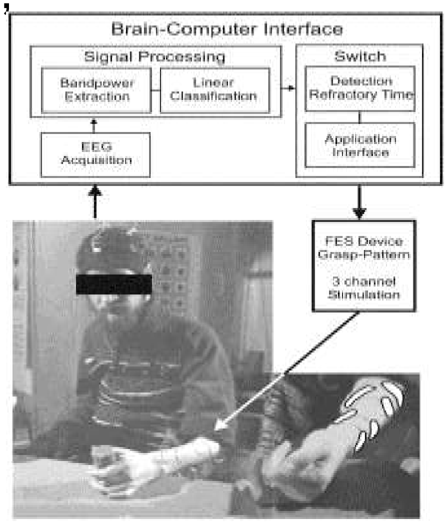
BCI-BASED REHABILITATION STRATEGIES

- **Substitutive Strategy**: all technologies and modalities used to bypass an interrupted neural pathway or connection.
- **Classical Conditioning**: Attempts to promote neuroplasticity and consequently motor functional recovery. It relies on the contingency of coupling a conditioned stimulus and an unconditioned stimulus attached to a response.
  Repeatedly associating the ERD (Conditioned Stimulus 1, CS1) to the robot-mediated movement (Unconditioned Response UR), causing a proprioceptive stimulus (CS2), one can theoretically obtain at the end of the training a voluntary movement (Conditioned Response, CR) using the ERD (CS1)
- **Operant (instrumental) Conditioning:** The promotion of neuroplasticity is realized in a different way with operant learning. It relies on the contingency of coupling a response and a reward-feedback.
  Repeatedly associating the ERD (response, R) to the proprioceptive afferent perception (Reinforcing Stimulus, RS) using the FES stimulation (Discriminative Stimulus DS) one can theoretically obtain an increased probability of excitation of the perilesional region, leading to the facilitation of functional recovery. In this context, the stimulation-induced feedback becomes a discriminative stimulus that facilitates functional recovery.

Studies of bci in motor(neuro)- and post stroke-rehabilitation

[Rozelle and Budzynski, 1995] case study suggested 1 BMI in Stroke Neurorehabilitation that learned regulation of ipsilesional SMR can be beneficial after stroke

[Pfurtscheller et al., 2003] described a patient with SCI who learned, via MI, to control delivery of electrical stimulation to hand and arm muscles using SMR modulation.



[Hochberg et al., 2006] reported a patient able to move a computer cursor on a screen and control a multi-jointed robotic limb with neuronal spike activation of single cortical cells (INVASIVE: 96-microelectrode array implanted in primary motor cortex)

[Bai et al., 2008] reported the performance of a sensorimotor β-rhythm-based BCI with visual feedback but without BCI training on a stroke patient.

[MullerPutz and Pfurtscheller, 2008] proposed the use of a SSVEP based BCI to control a two-axes electrical hand prosthesis.

Studies of bci in motor(neuro)- post stroke-rehabilitation

[Daly et al., 2009] (CASE REPORT) demonstrated the feasibility of combining BCI and FES for motor learning in a post stroke patient. Brain signal was used to activate a FES device delivering an electrical stimulus to the index finger extensor muscles. Sustained motor-related ERD was translated in activation of the FES device. During the BCI sessions the patient achieved good BCI control (over 88% in 8 of 9 sessions for attempted movement) and regained 26 degrees of volitional isolated index finger extension after session nine.

[Broetz et al., 2010] (CASE REPORT) MEG-based BCI with visual and orthosis feedbacks intervention coupled with daily life-oriented physiotherapy on 1 stroke patient for a year, and motor improvements measured using a battery of assessments such as FMA, Wolf Motor Function Test (WMFT), Ashworth, 10-m Walk and Goal Attainment Score (GAS), etc. showed positive improvements.

[Prasad et al., 2010] EEG-BCI rehabilitation protocol combining physical practice with MI. 5 chronic stroke patients first performed/tried to execute the movement physically, followed by the MI of the same movement. This was done for the non-impaired and impaired upper limb respectively. The neurofeedback of MI performance was provided by means of a "'ball-basket" game. 2 sessions per week for 6 weeks, all participants tended to improve their motor function of the impaired arm around the minimally clinical important difference on the ARAT.

Studies of bci in motor(neuro)- and post stroke-rehabilitation

[Ang et al. 2010] in a large clinical study on hemiparetic stroke patients, compared an MI BCI-based robotic feedback neurorehabilitation training (11 patients) with a simple robotic rehabilitation (14 patients). All patients showed an improvement of motor function, although no significant differences between groups were found. (Uncertainty about the protocol)

[Caria et al., 2011] (CASE REPORT) of EEG and MEG-based BCI intervention coupled with physiotherapy on a stroke patient, and showed evidence of recovery as a result of brain plasticity using DTI and fMRI. Efficacy in terms of clinical motor improvements as well as neuroimaging. The patient underwent two main rehabilitation trainings using magnetoencephalography [4 weeks MEG-BCI between month 14 (S1) and 18 (S2) after stroke] and EEG based BCI [4 weeks EEG-BCI between month 18 and 22 (S3) after stroke] in combination with physiotherapy. BCI training coupled with goal-directed physiotherapy might induce beneficial used-dependent plasticity in the perilesional areas facilitating motor recovery.

[Ang et al., 2011] presented a study on the extent of detectable EEG signals from a large population of 54 stroke patients. A majority of but not all stroke patients could use EEG-based MI BCI, and hence suggested that a BCI screening is required to screen the stroke patient's capability of using BCI before enrolling them for BCI-based stroke rehabilitation intervention.

Studies of bci in motor(neuro)- and post stroke-rehabilitation

[Gomez-Rodriguez et al., 2011] proposed the use of haptic feedback, provided by a 7-DoF robotic arm, directly controlled by decoded movement intention in an MI-BCI-task. The authors found that artificially closed sensorimotor feedback loop facilitates on-line decoding of movement intention. These results, observed in six healthy subjects and two stroke patients, demonstrated that SMR is modulated by the haptic feedback. Moreover, in this report a BCI-driven robotic arm was guided during each trial, and not at the termination of it. However, the authors did not report coexistence of traditional physical therapy for stroke patients and their clinical outcomes.

[Frisoli et al., 2012] high technological upper-extremity robot-assisted rehabilitation (Eye tracker+L-exos+MI-BCI, gaze bci-driven robotic assistance). Experimentally evaluation of the system with 3 healthy volunteers and 4 chronic stroke patients.

Studies of bci in motor(neuro) post stroke-rehabilitation

[Varkuti er al., 2013] upper-extremity robot-assisted rehabilitation (MANUS) versus an EEG-MI EEG-BCI and compared pretreatment and posttreatment Resting State-fMRI. Both the Fugl-Mayer gain and Functional Connectivity Changes were numerically higher in the MI-BCI group.

[Soekadar et al., 2013] , combining tDCS and BMI, showed for the first time that a chronic stroke patient without residual finger movements can utilize SMR of the primary motor cortex (M1) hand knob to control an orthotic device to perform grasping motions, while this region, the ipsilesional M1, underwent anodal tDCS.

[Ramos-Murguialday et al., 2013] 32 chronic stroke, 2 patient groups underwent physiotherapy following BMI or sham-BMI training sessions with robot assisted hand opening. Successful SMR control resulted in concurrent movements of the arm and hand orthoses (in the control group-> random movement). Immediately following a BMI training session, patients in both groups received 1 hour of behavioral physiotherapy focused on transferring arm reaching and hand movements to real life situations. Superior Motor improvements has been observed in the SMR-feedback group. Confirm that the combination of BCI-MI plus orthosis with physical training may help to improve upper limb motor control post-stroke. Outcomes: FM, GAS, MAL, Ashworth, EMG, fMRI