Laurea Magistrale in Matematica

Università degli Studi di Trento

Biomedical Applications of Mathematics AA 2013-2014

EEG data analysis

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Outline

1. EEG signal and artifacts

2. EEG during motor task
    a. Event-Related Desynchronization/Synchronization
    b. Modulation of ERD in robot-assisted hand performance

3. Time-frequency analysis of short modulation of EEG induced by transcranial magnetic stimulation (TMS)

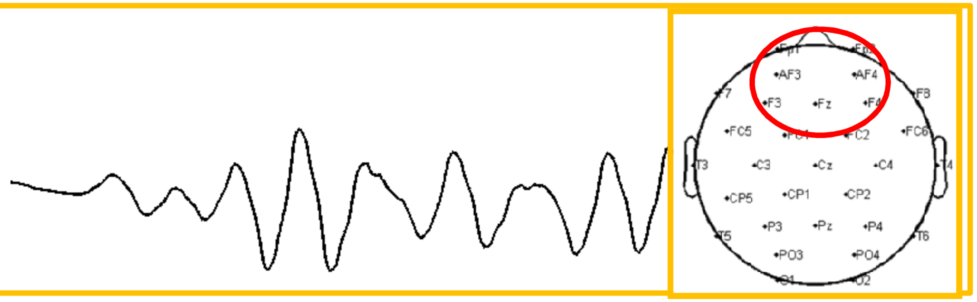
4. EEG connectivity

EEG rhythms

Ritmi	Frequenze (Hz)	Ampiezza (μV)
Delta	0.5-4	20-200
Theta	4-8	5-100
Alpha	8-13	10-200
Beta	13-30	1-20

Delta

Deep sleep,
pathological
condition

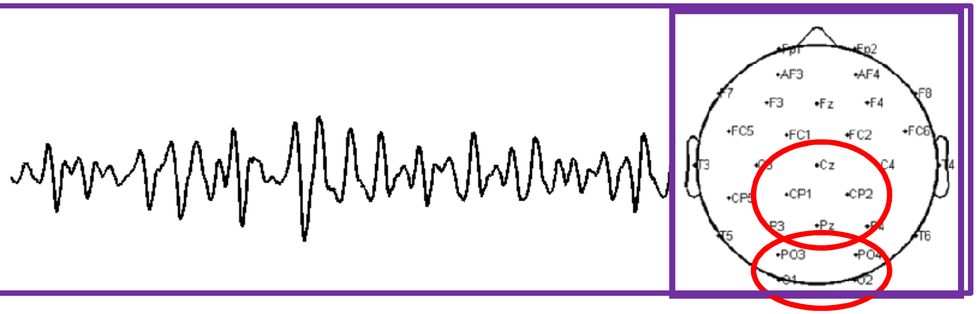


Theta

Sleepiness

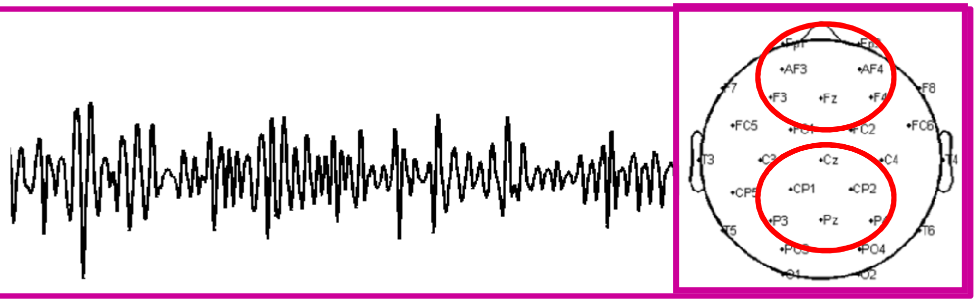
Alpha

Relax,
Closing the eyes

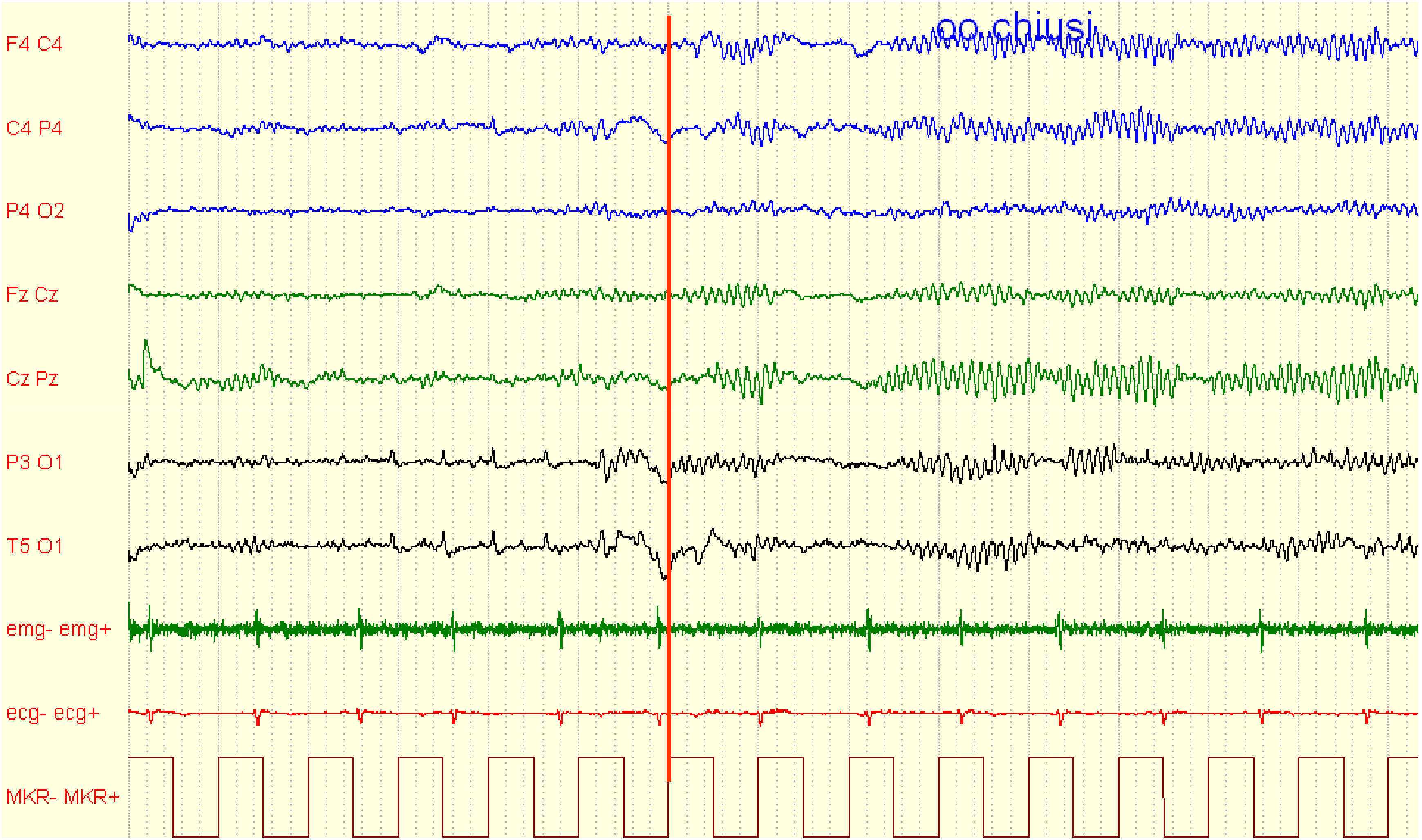


Beta

Active, busy,
anxious thinking,
active
concentration

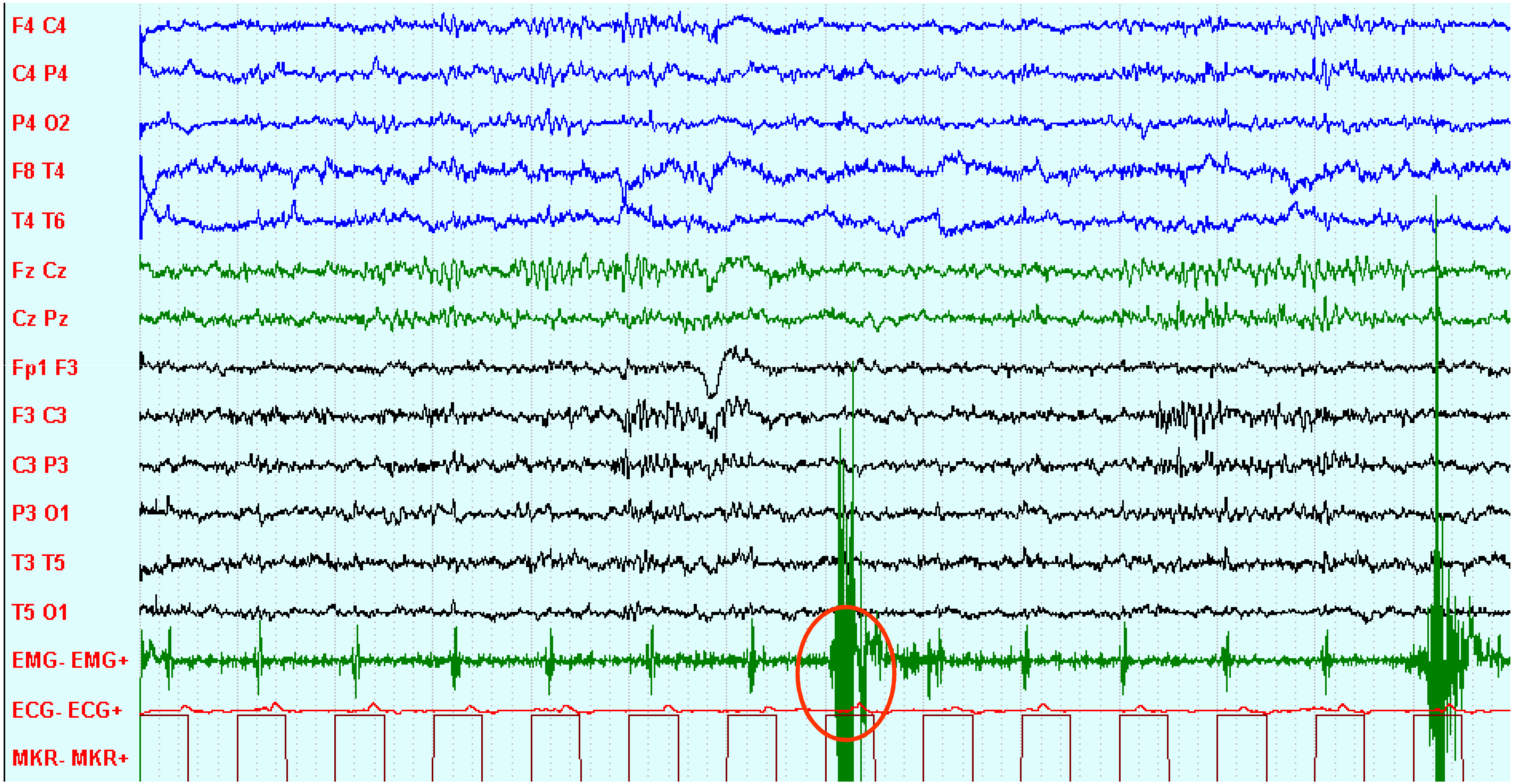


Alpha rhythm

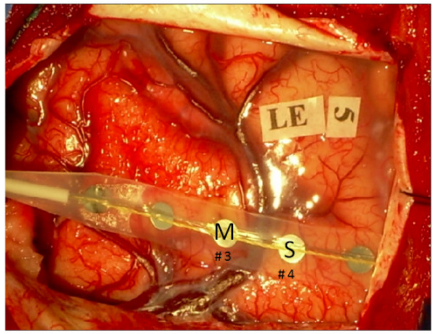


Eyes open Eyes closed

Alpha rhythm



rest vs movement



Alpha rhythm

Electrocorticography in awake surgery
Rest vs movement

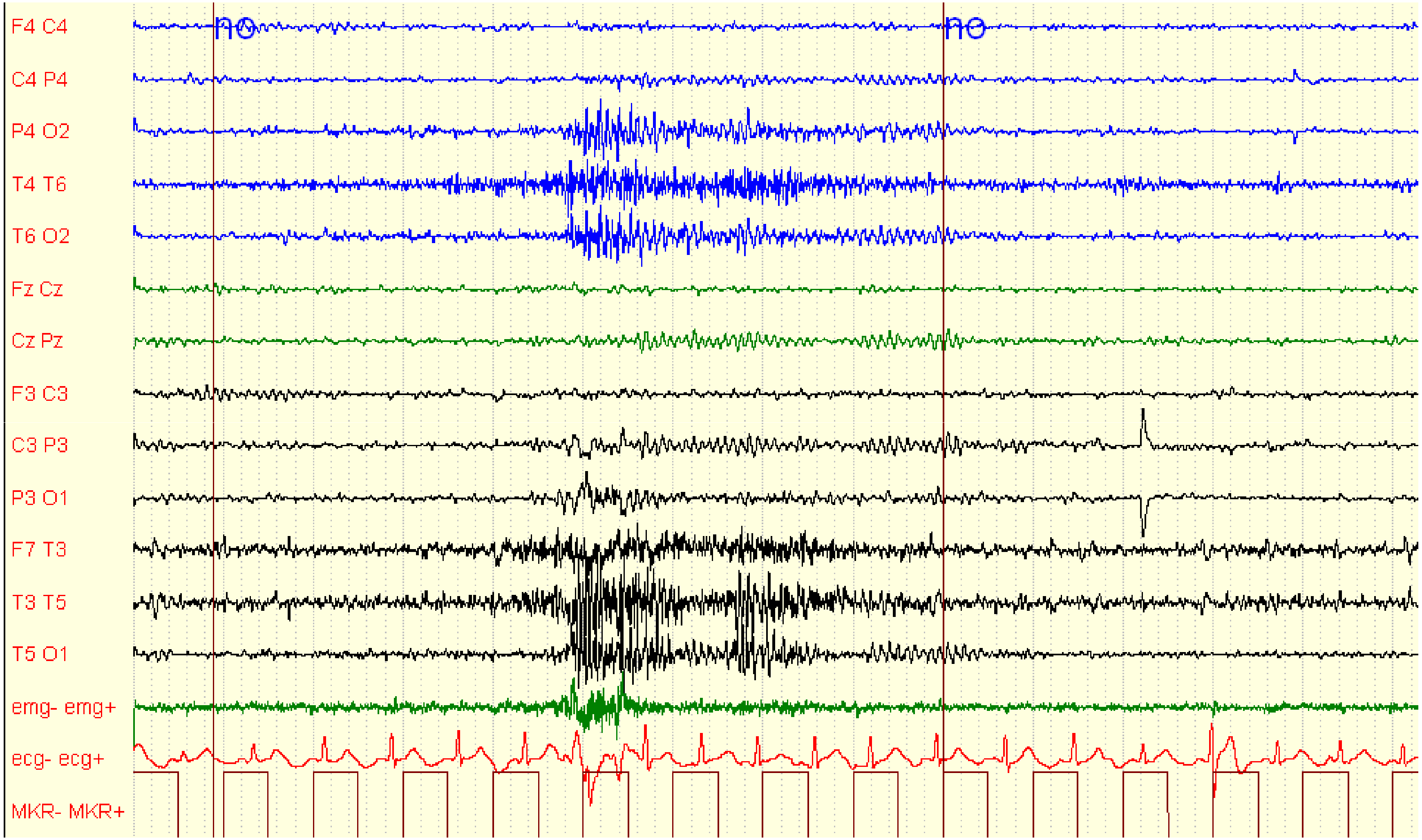
Artifacts

Artifact = electrical activities arising from sites other than the brain.

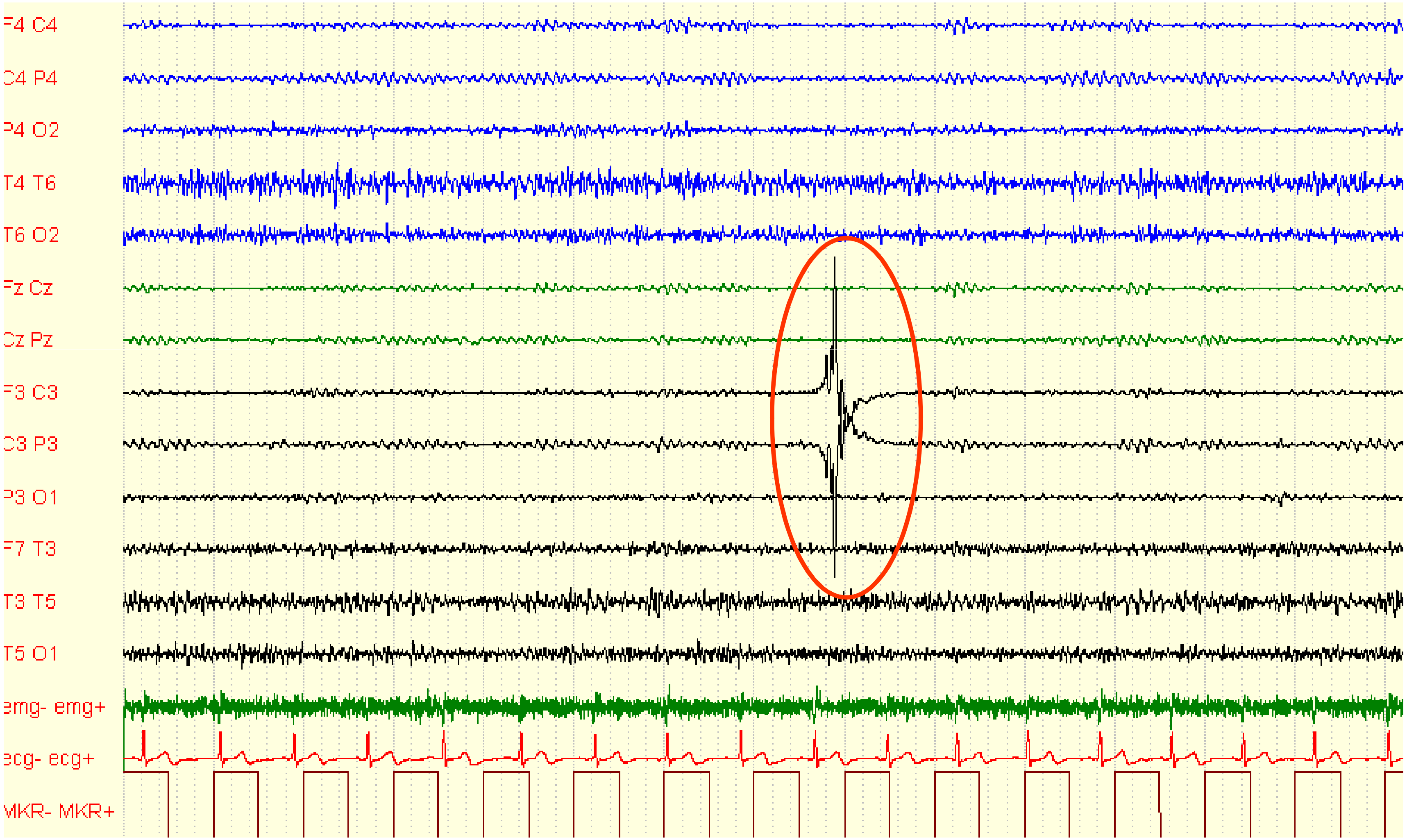
Physiologic artifacts are generated from the patient, they arise from sources other than the brain:
eyes movement; electrocardiographic activity; legs, arms, head movement; sweat; muscle activity…

Extraphysiologic artifacts arise from outside the body:
bad contact between skin and electrode; bad contact between electrode and cable; electromagnetic interferences; environment artifacts (50 or 60 Hz); artifact due to external maneuvers; instrumental artifacts.

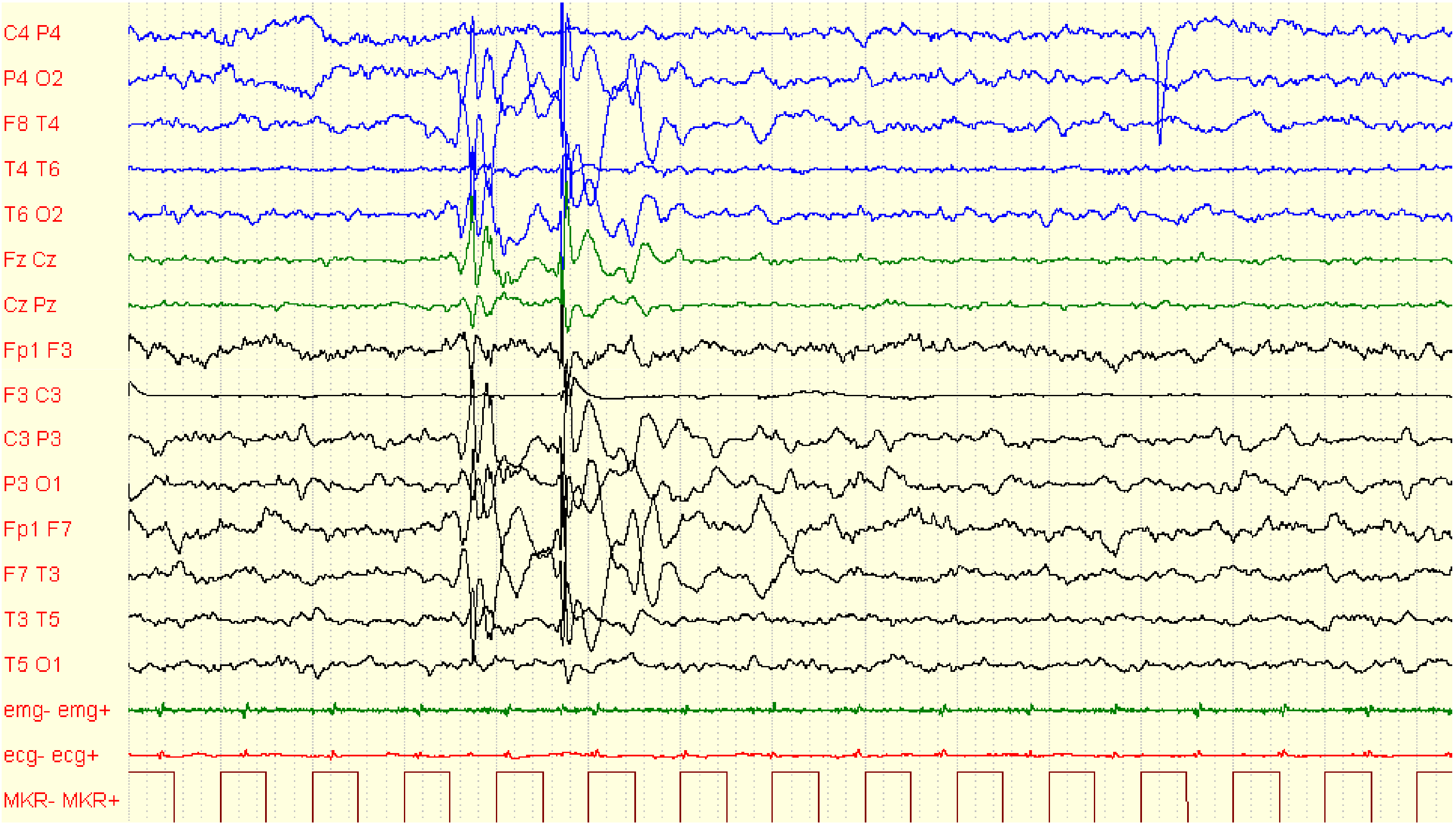
Movement Artifact



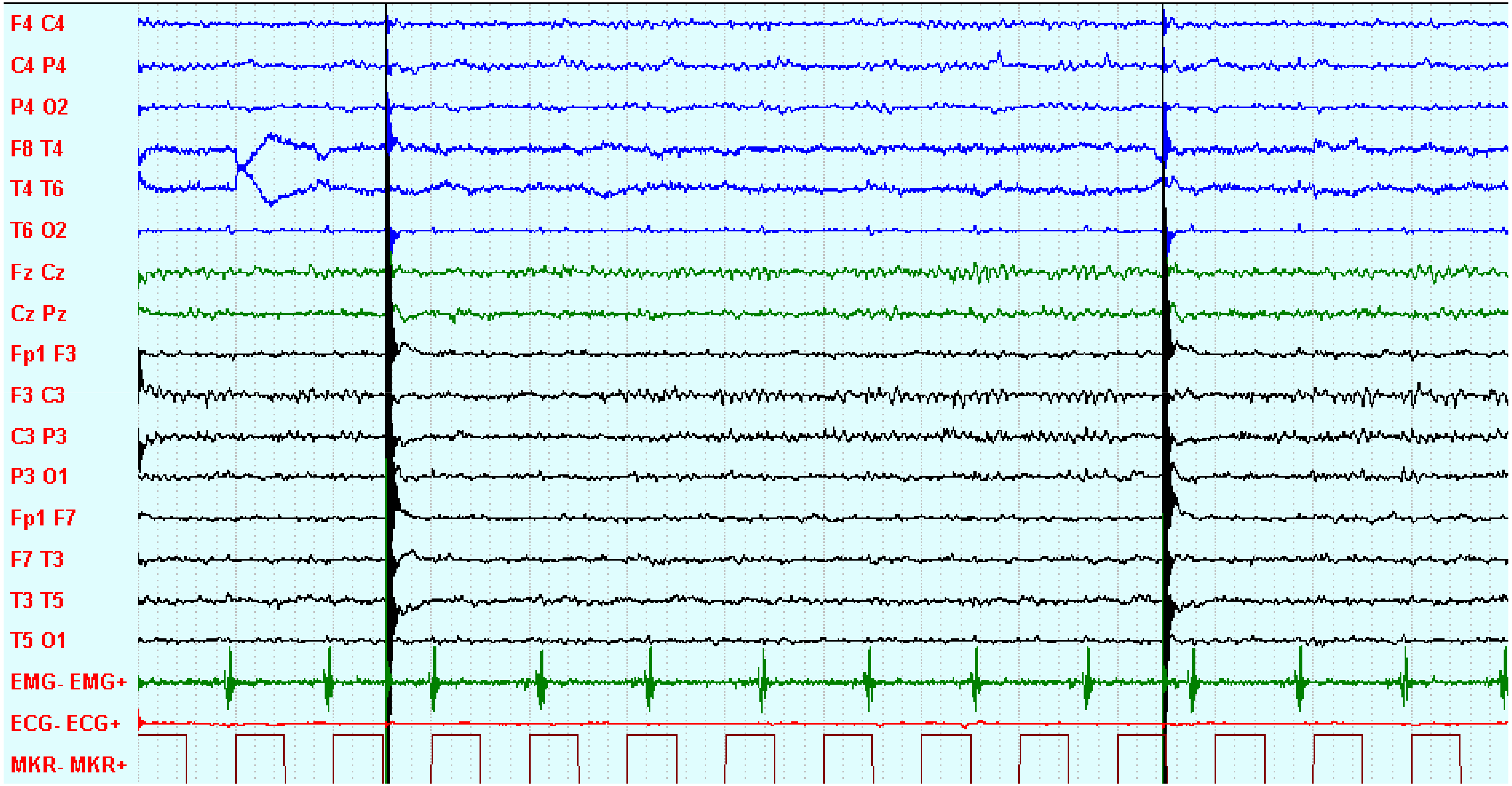
Artifacts: bad contact between skin and electrode



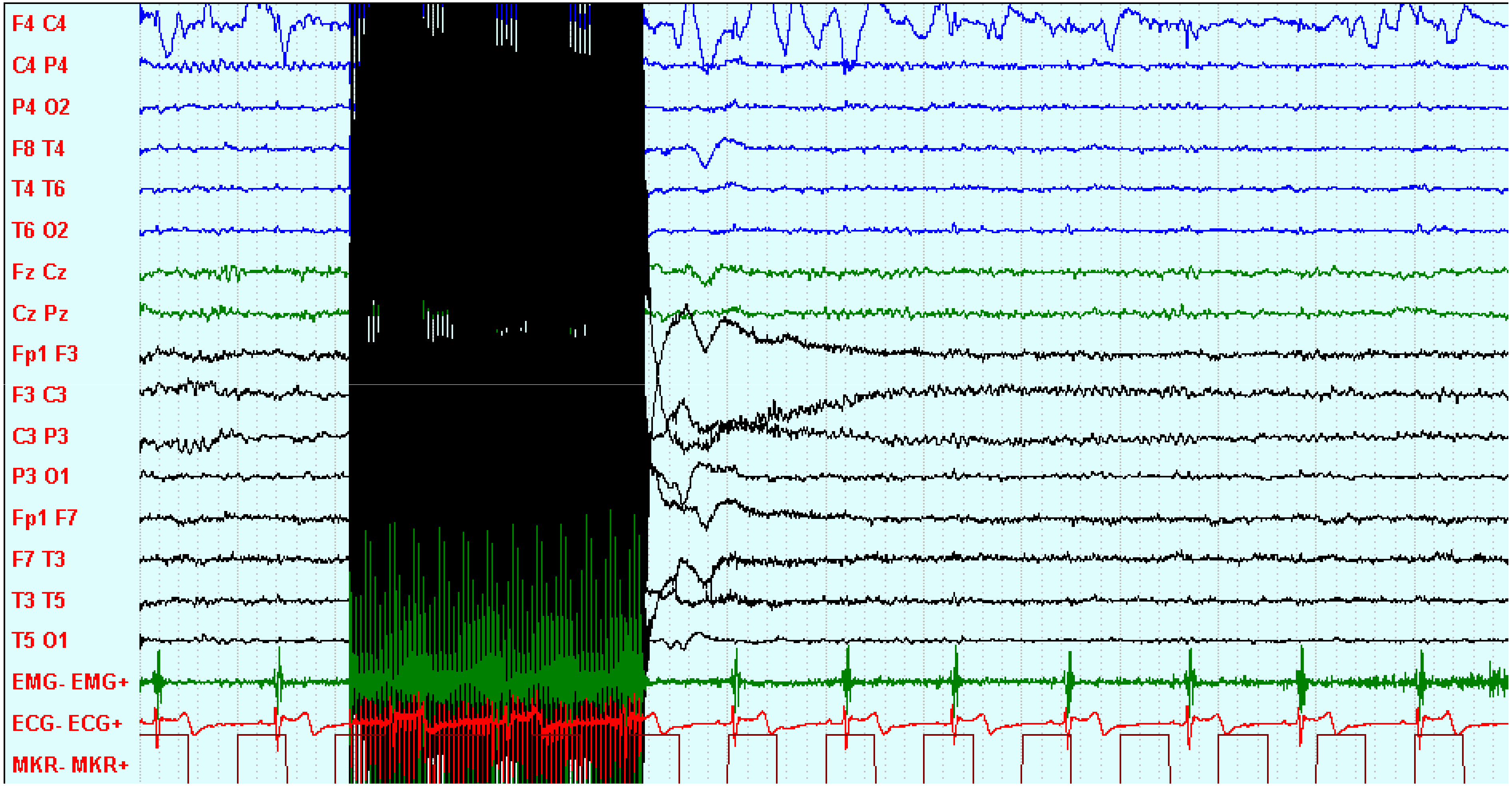
Artifacts: bad contact between electrode and cable



Artifacts: single-pulse TMS



Artifacts: repetitive TMS



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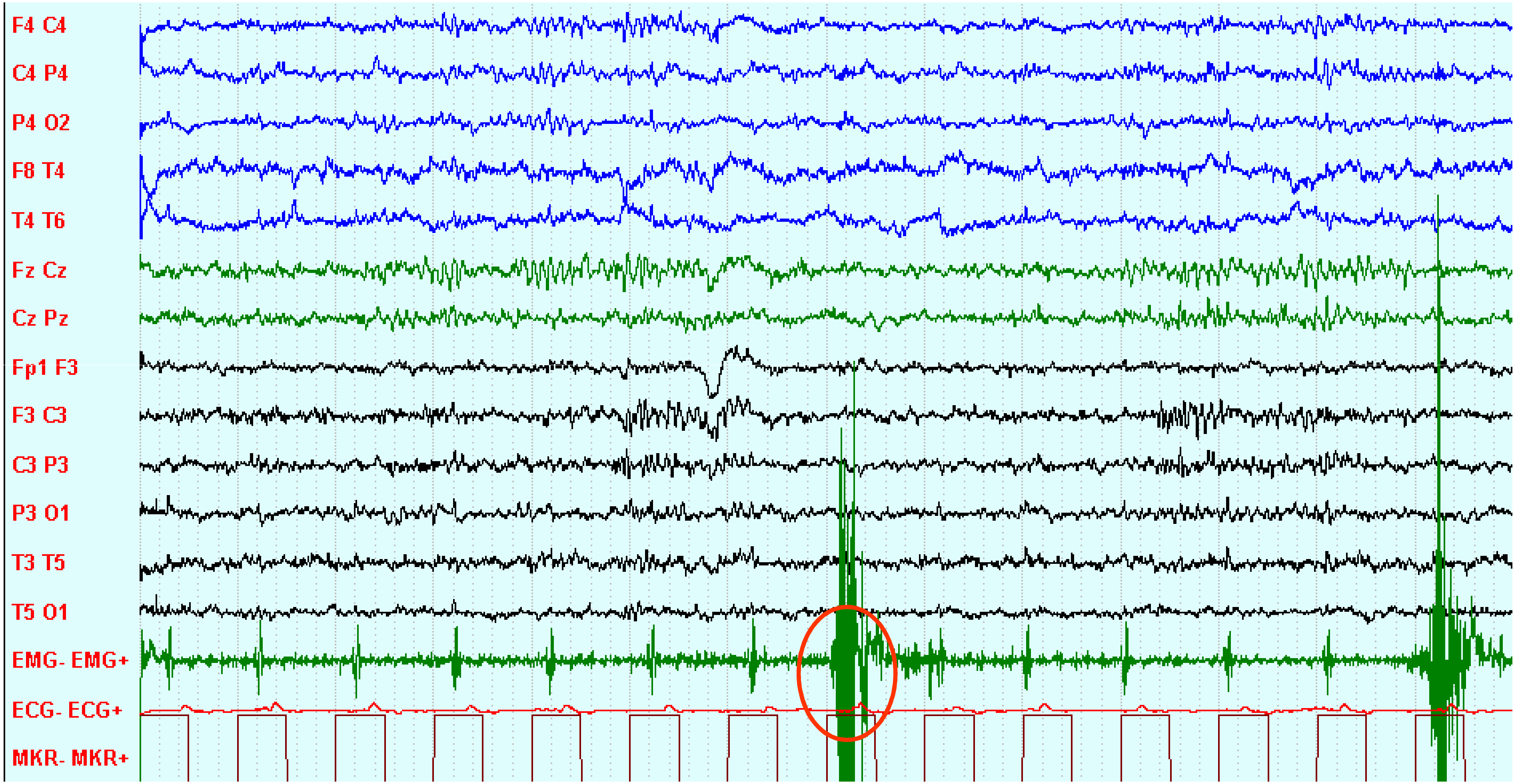
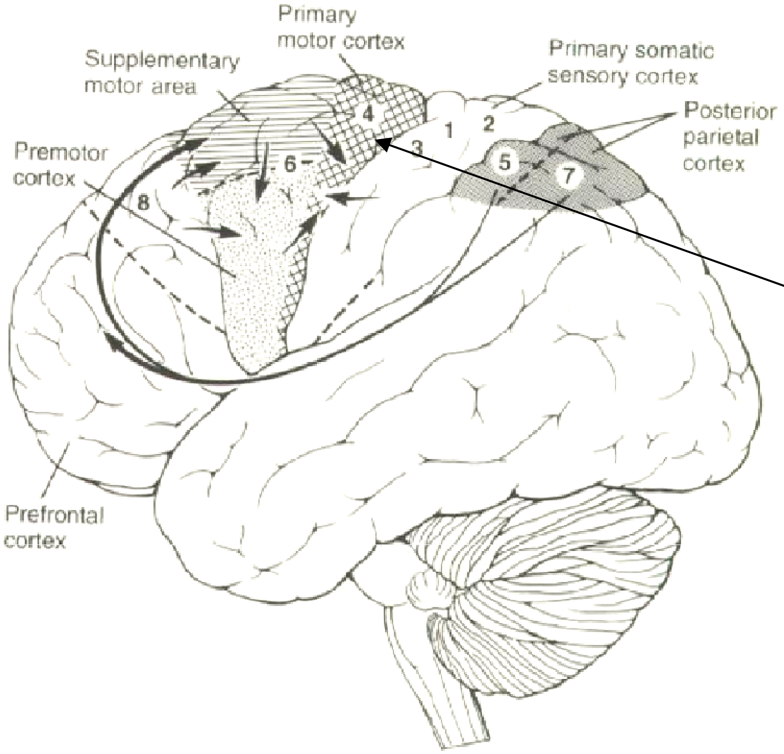
Alpha rhythm



rest vs movement

Mu rhythm



Cortical generator
Ritmo mu
(C3, Cz, o C4)

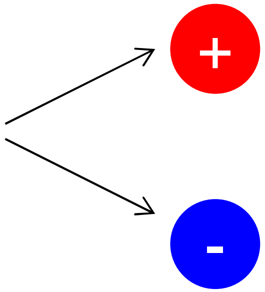
Mu rhythm (8-13 Hz) is localized over primary sensorimotor cortex.

Movement preparation suppresses the cortical activity in alpha (mu rhythm: 8-13 Hz) and beta (13-30 Hz) bands starting before the onset of finger movement.

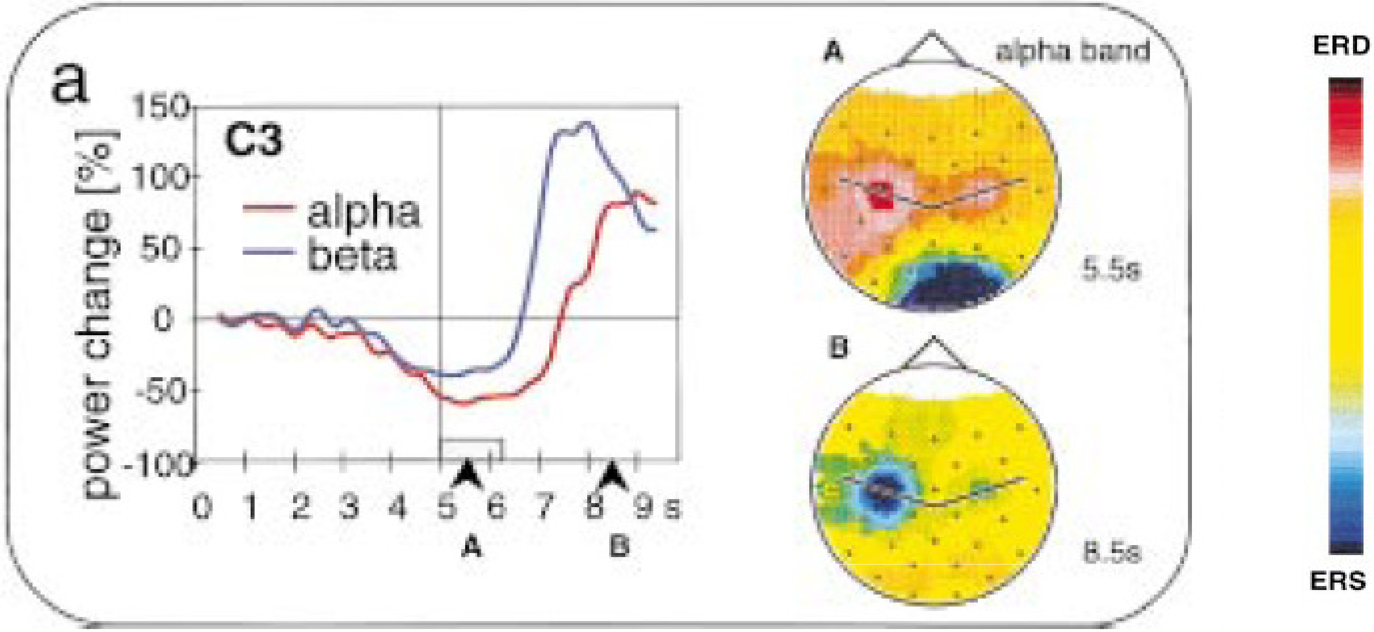
Event-related-synchronization/desynchronization (ERS/ERD)

- event related synchronization (ERS)
  - reflects a cortical “idling state”
  - sincronous activation of the neuronal network
  - associated with activity increase (positive values)
- event related desynchronization (ERD)
  - indicates oscillations in cortical activation
  - asincronous activation of the neuronal network
  - associated with activity decrease of the underline neuronal population (negative values)

$$ERP_x = \frac{\left(P_{xactivation} - P_{xrest}\right)}{P_{xrest}} \cdot 100$$



Pfurtscheller and Aranibar, 1979; Pfurtscheller and Neuper, 1994

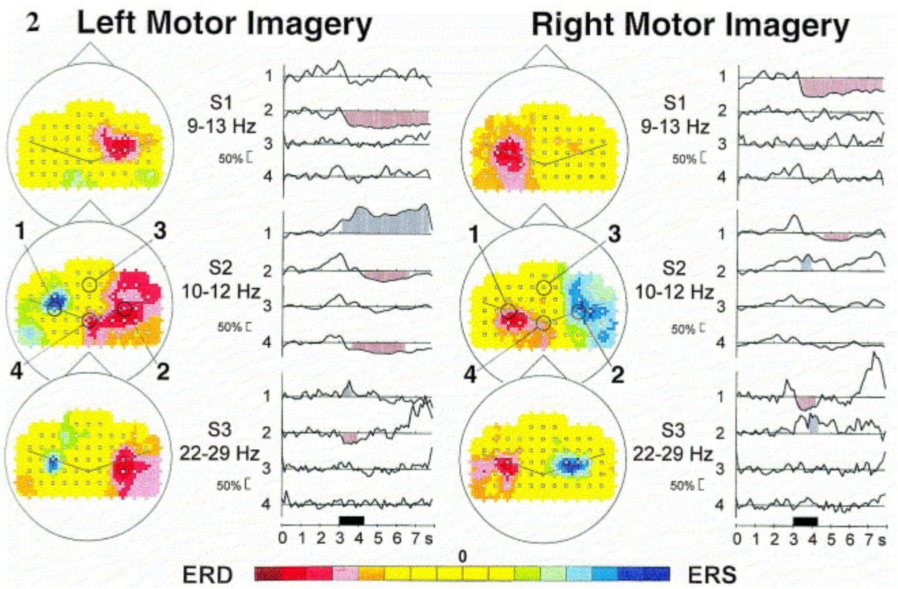


A group study on nine normal subjects performing self paced right hand movement.

- Contralateral alpha ERD localization, occipital alpha ERS localization
- Contralateral alpha ERS localization after movement

Pfurtscheller and Lopes da Silva, 1999

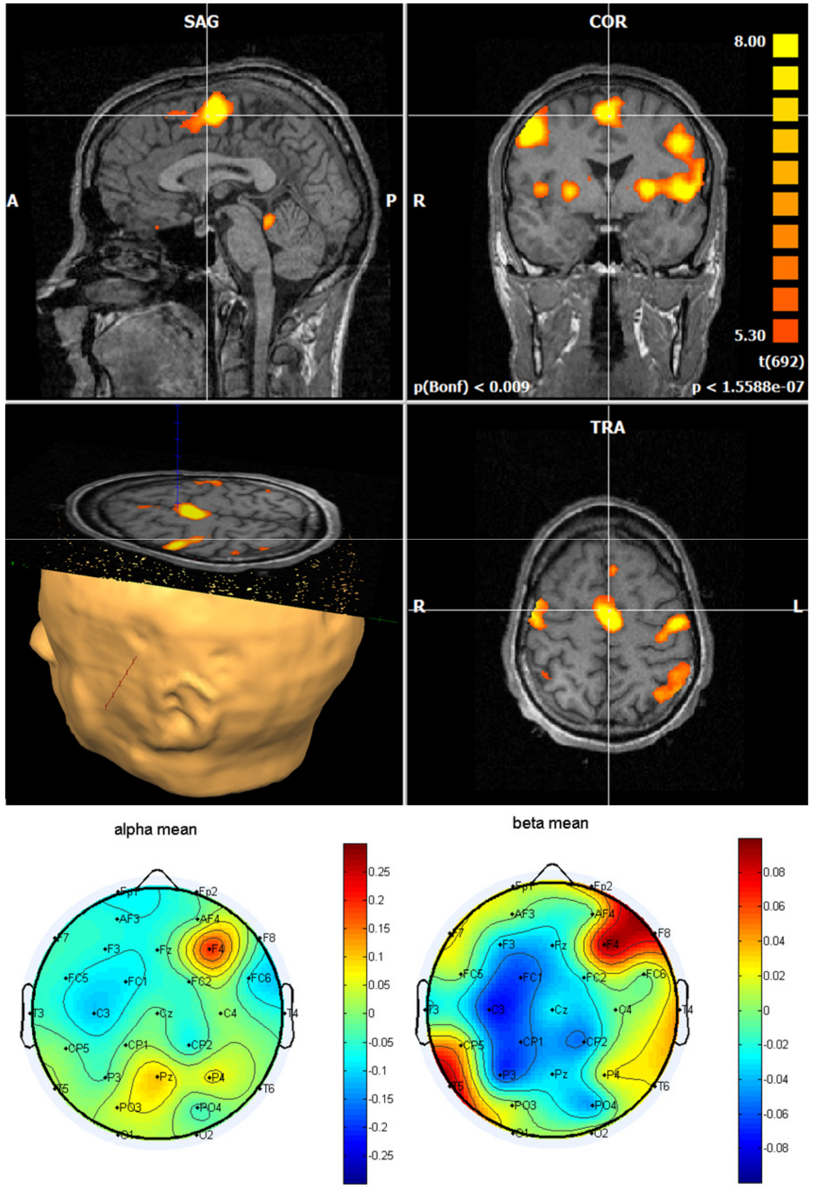
Motor imagery



Pfurtscheller and Neuper, 1997

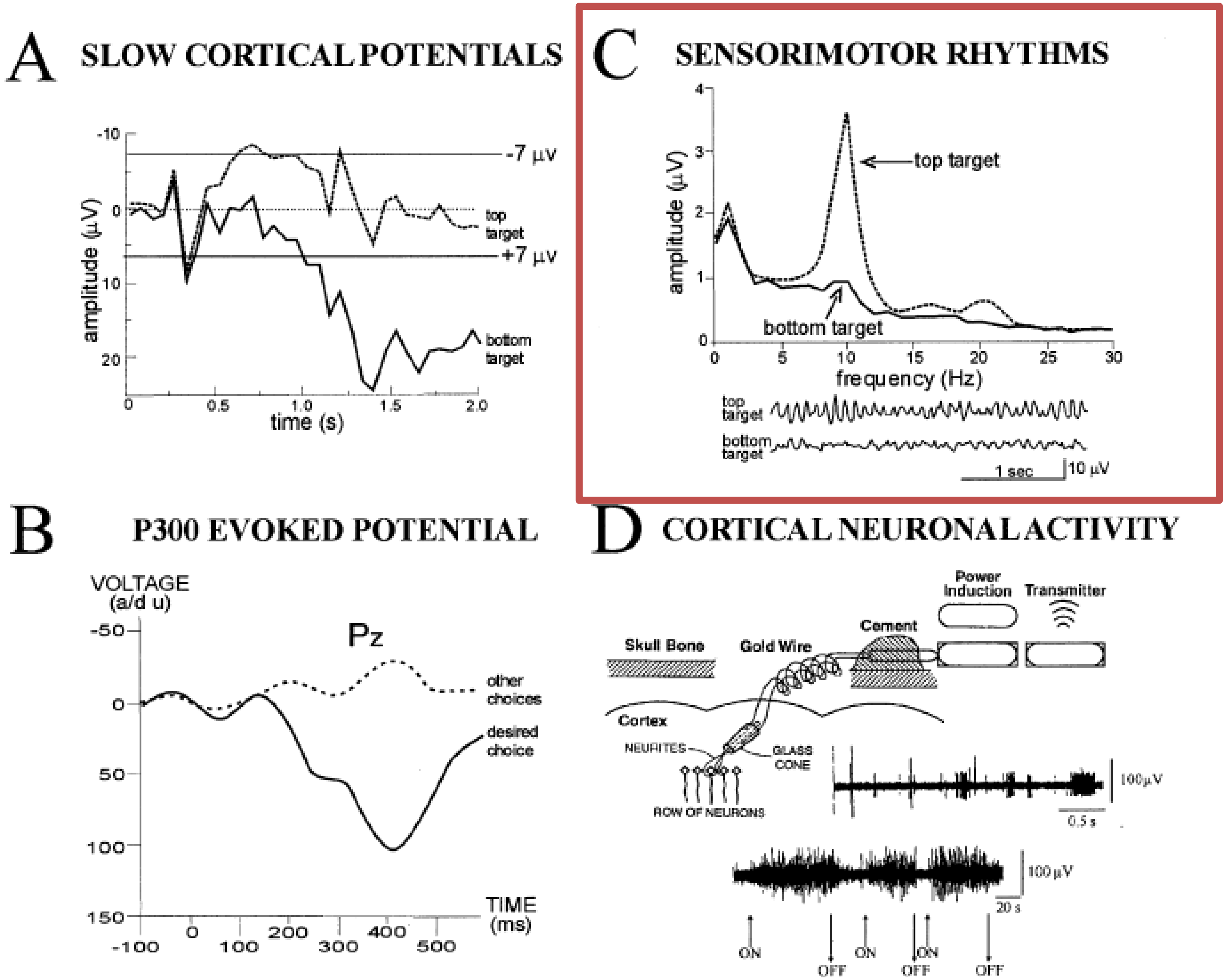
Motor imagery results in ERD and ERS without active movement

Sensorimotor rhythms are used in Brain Computer Interface (BCI)



Formaggio et al., Magn. Reson. Imag. 2010

Brain Computer Interface (BCI): Features



Wolpaw et al., 2002

Brain Computer Interface (BCI)

Tetraplegic patient attempts left or right hand movements and tries to move the circle from the middle of the screen to the target

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Aim

- To evaluate the modification of cortical activity during voluntary active movement, passive robot-assisted movement, and motor imagery performed under unimanual and bimanual protocols.

- A better knowledge of cortical modifications after robotic therapy could inform the design and development of stroke rehabilitation protocols.

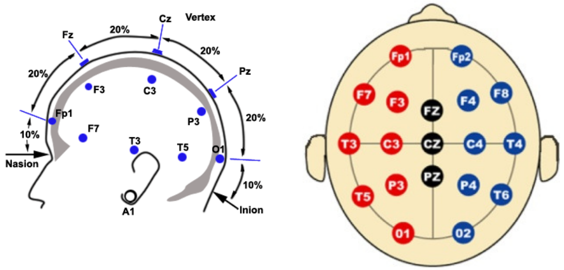
Equipment

Bi-Manu-Track arm trainer works on more distal arm movements, practicing bilateral elbow prosupination and wrist flexion (Hesse et al., 2003).

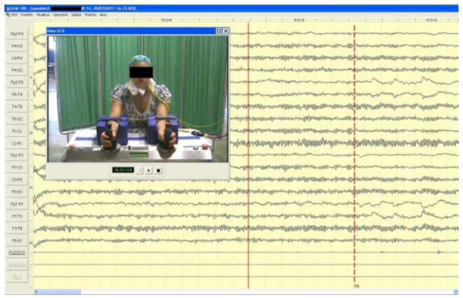
Material and Methods

8 subjects 3M/5W
Age: 26.12 ± 2.64 (range: 22-31)

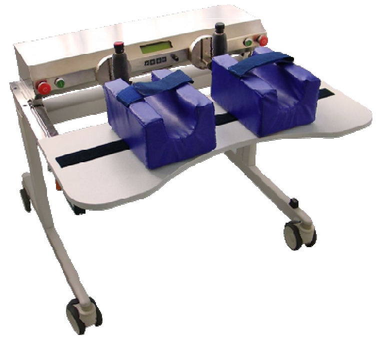
EEG cap 21 channels
(SEI EMG s.r.l, Padova, Italy)



Video EEG system
(Ates Medica Device, Verona, Italy)



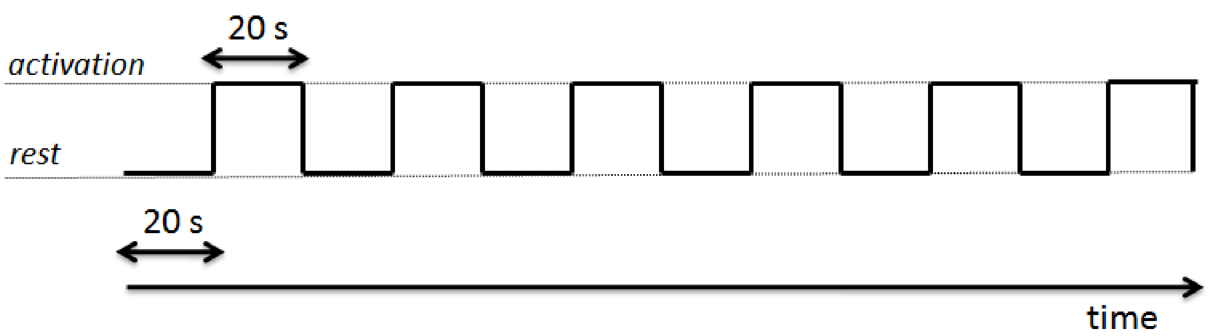
Bi Manu Track®
(Reha-stim Co, Berlin)

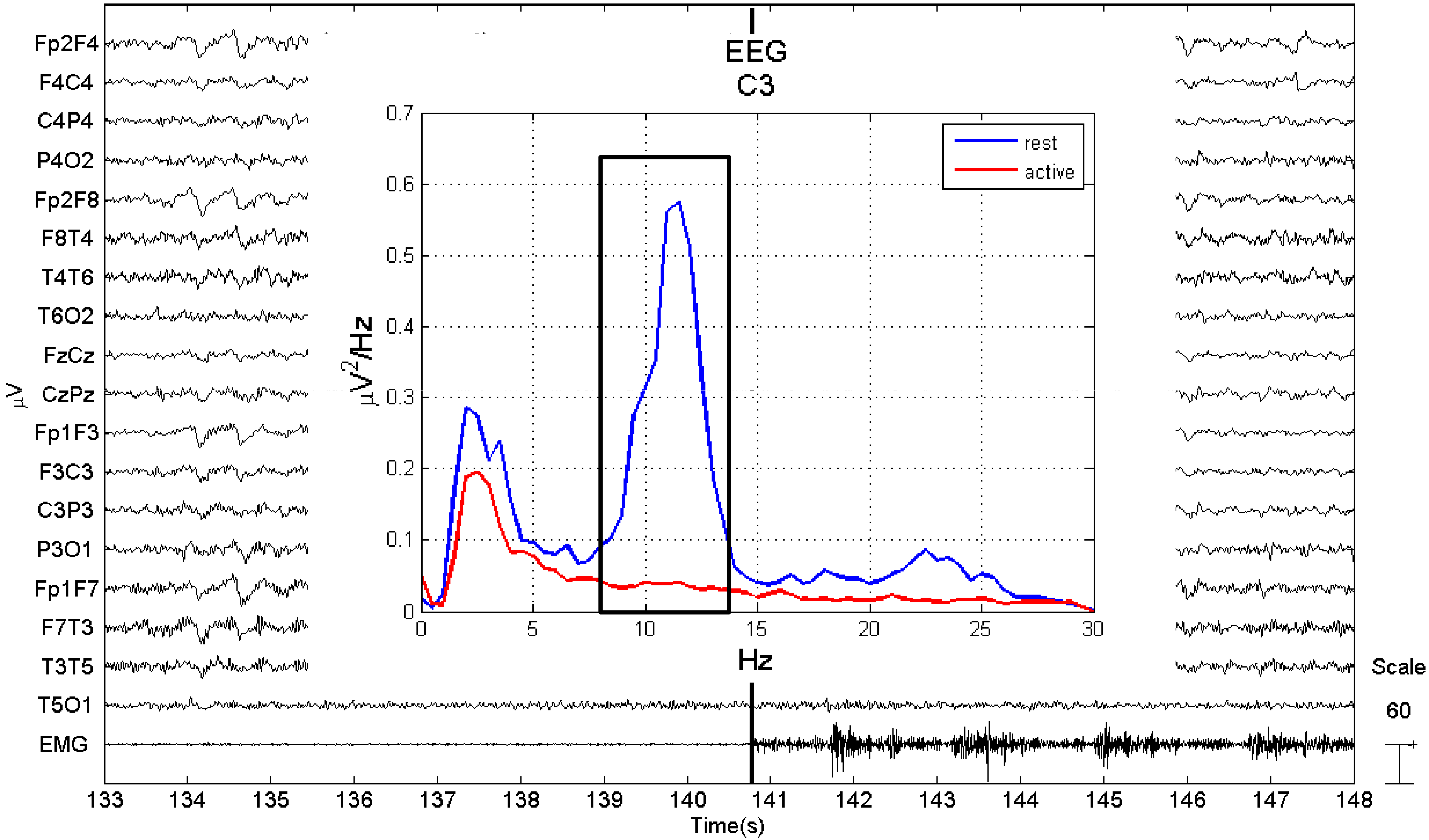


Data acquisition

Design protocol:

- active movement with the right/left hand;
- bimanual active movement;
- passive movement with the right/left hand (right/left hand moved by the BMT);
- bimanual passive movement (both hands moved by the BMT);
- active – passive movements (the right/left hand drives the left/right hand in a mirror-like fashion);
- imagination of movement with the right/left hand;
- imagination of bimanual movement.



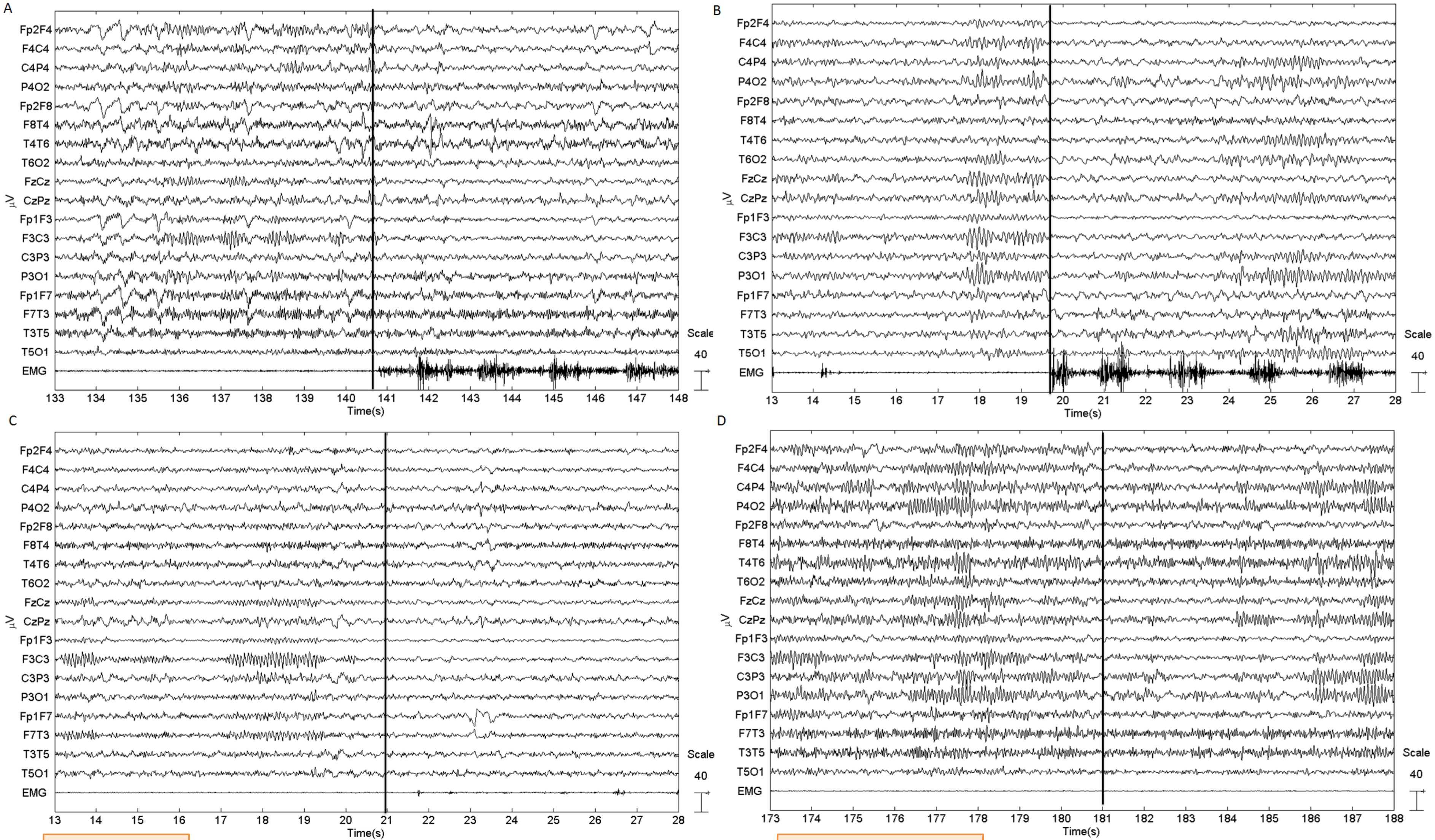


Fp2F4
F4C4
C4P4
P4O2
Fp2F8
F8T4
T4T6
T6O2
FzCz
CzPz
Fp1F3
F3C3
C3P3
P3O1
Fp1F7
F7T3
T3T5
T5O1
EMG
μV
EEG
C3
rest
active
μV²/Hz
Hz
Scale
60
Time(s)

EEG during tasks

Active R

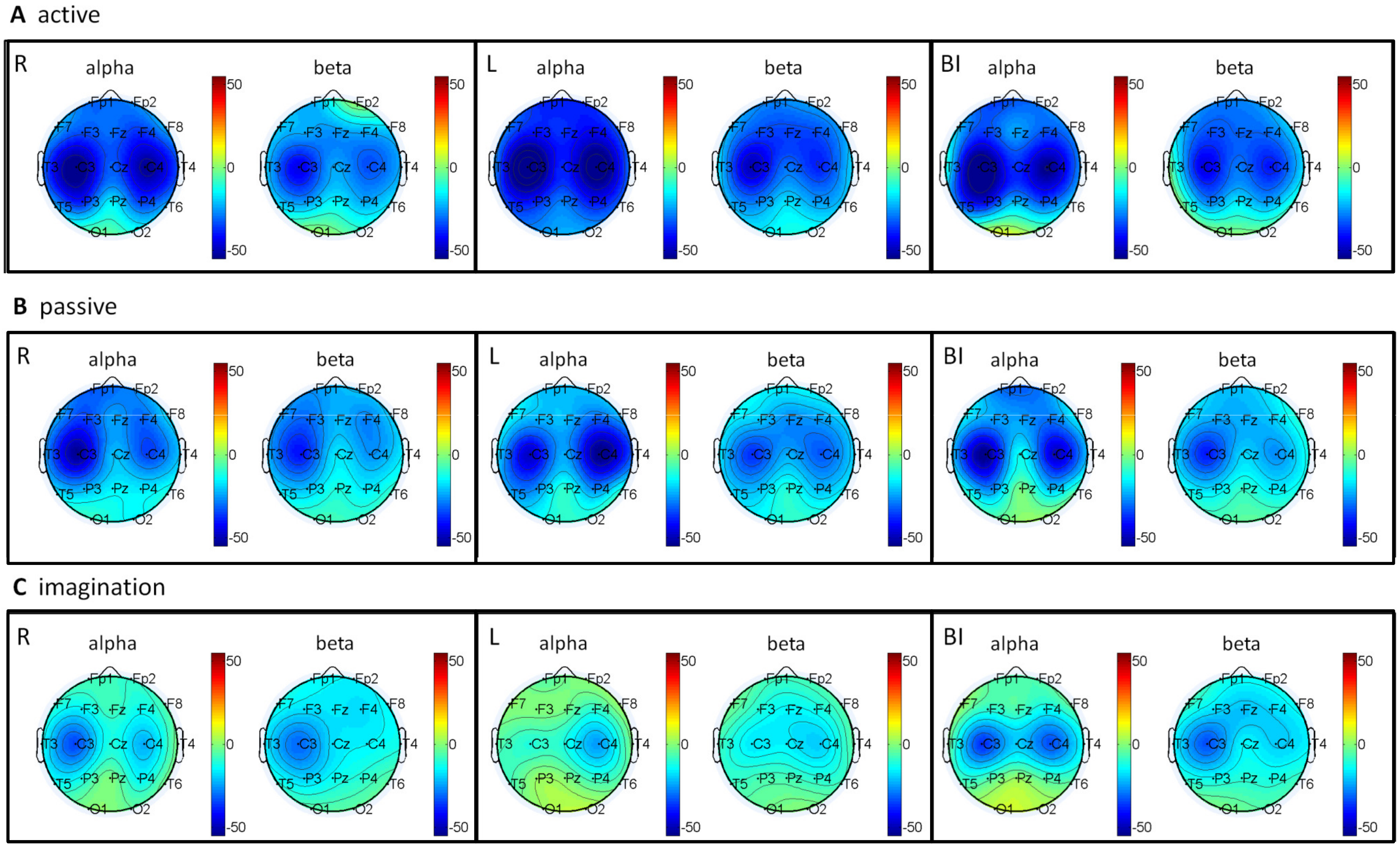
Active BI



Passive R

Imagination R

Results


A active
B passive
C imagination
R
L
BI
alpha
beta
50
0
-50
Fp1 Fp2 F7 F3 Fz F4 F8 T3 C3 Cz C4 T4 T5 P3 Pz P4 T6 O1 O2

Conclusions

- This study suggests new perspectives for neurological assessment by evaluating cortical oscillatory activity in stroke patients, presenting either with motor or sensitive deficit due to lesions of different systems involved in motor control, or without motor deficit, e.g., patients with aphasia or neglect.

- We are evaluating stroke patients under the same experimental conditions in order to study their cortical responses before and after rehabilitation therapy.

- This future study may lead to a greater understanding of the mechanisms underlying motor recovery and inform the development of a new clinical approach to upper limb rehabilitation in stroke patients.

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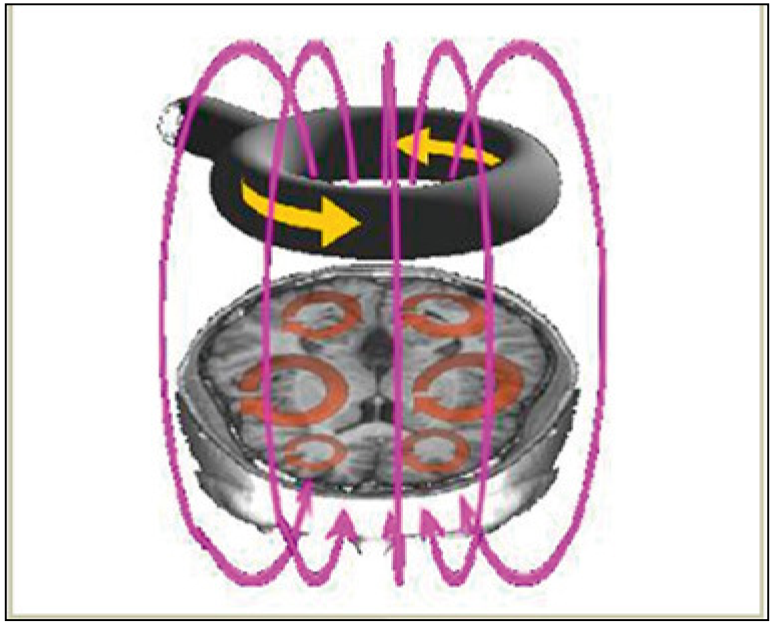
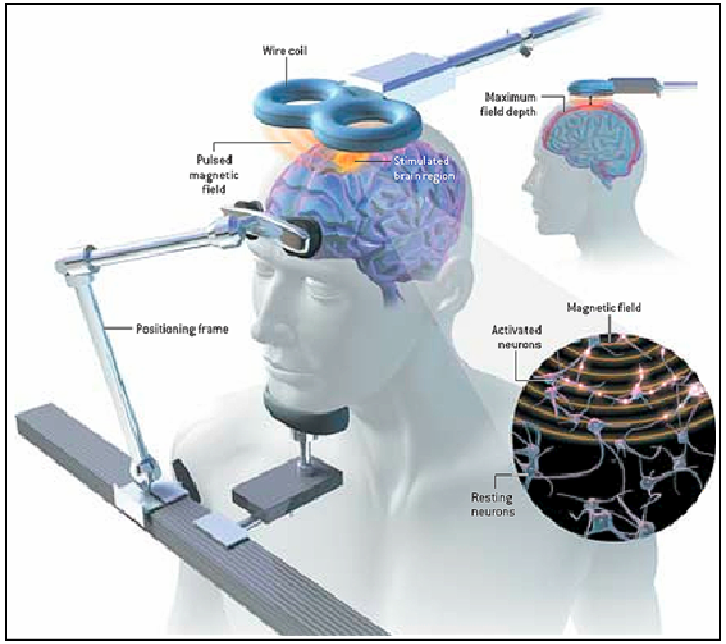
Transcranial Magnetic Stimulation (TMS)

TMS is a noninvasive method to stimulate cerebral cortex causing depolarization or hyperpolarization in the neurons.
TMS uses electromagnetic induction to induce weak electric currents using a rapidly changing magnetic field (**Electromagnetic Induction Faraday's law**).





Transcranial Magnetic Stimulation (TMS)

Electric current can cause activity in specific or general parts of the brain allowing for study of the brain's functioning and interconnections.

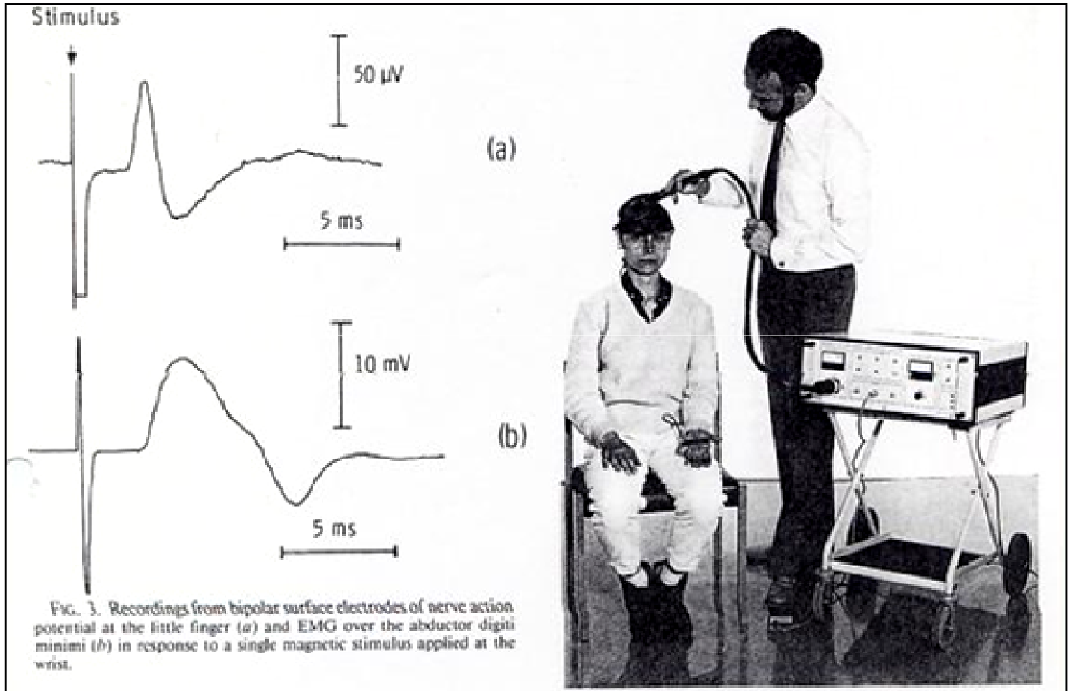


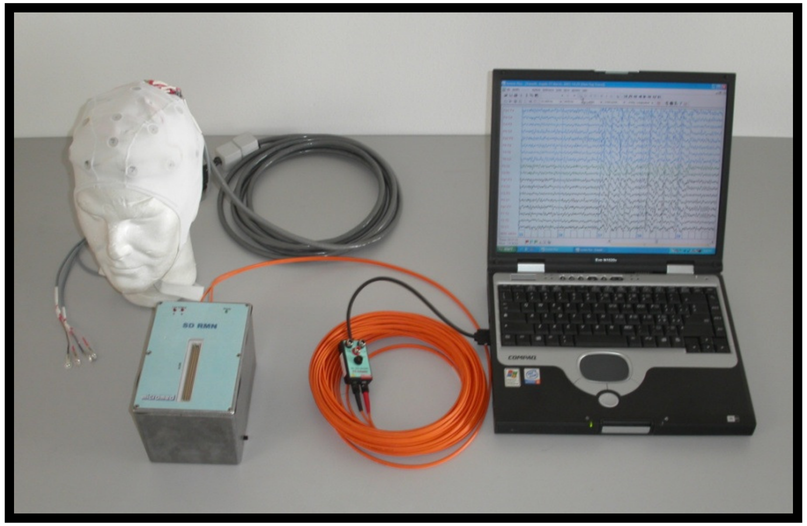
FIG. 3. Recordings from bipolar surface electrodes of nerve action potential at the little finger (*a*) and EMG over the abductor digiti minimi (*b*) in response to a single magnetic stimulus applied at the wrist.

FIG. 5. The magnetic stimulator in use.

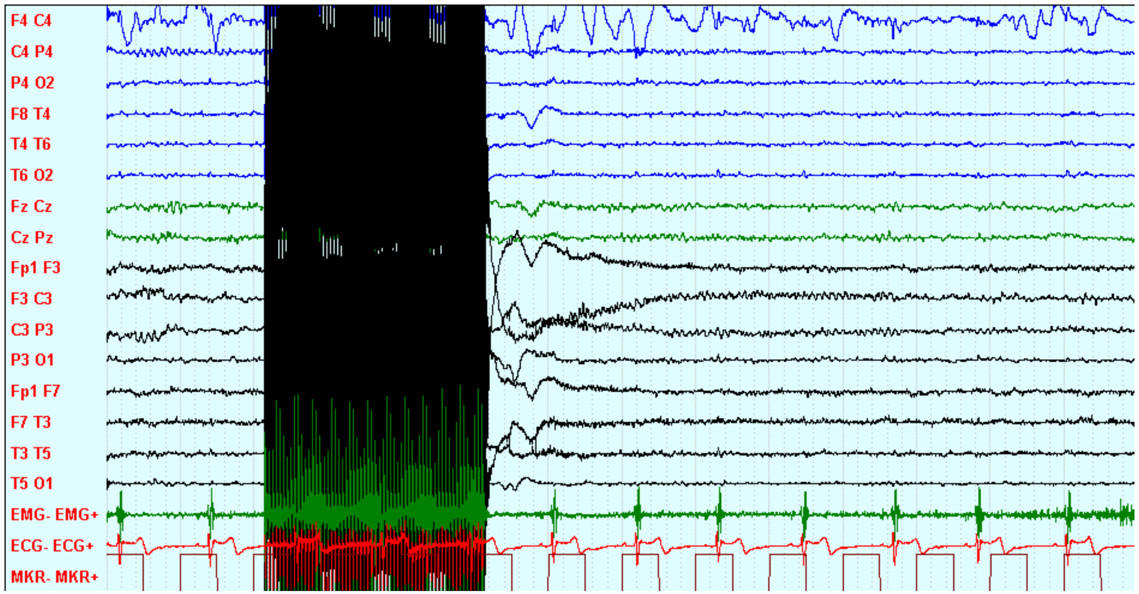
A variant of TMS, **repetitive transcranial magnetic stimulation (rTMS)** has been tested as a treatment tool for various neurological and psychiatric disorders including strokes, Parkinson's disease, dystonia and depression.

EEG-TMS

An innovative method to study brain function is by triggering oscillatory brain activity with a perturbation method such as direct stimulation.



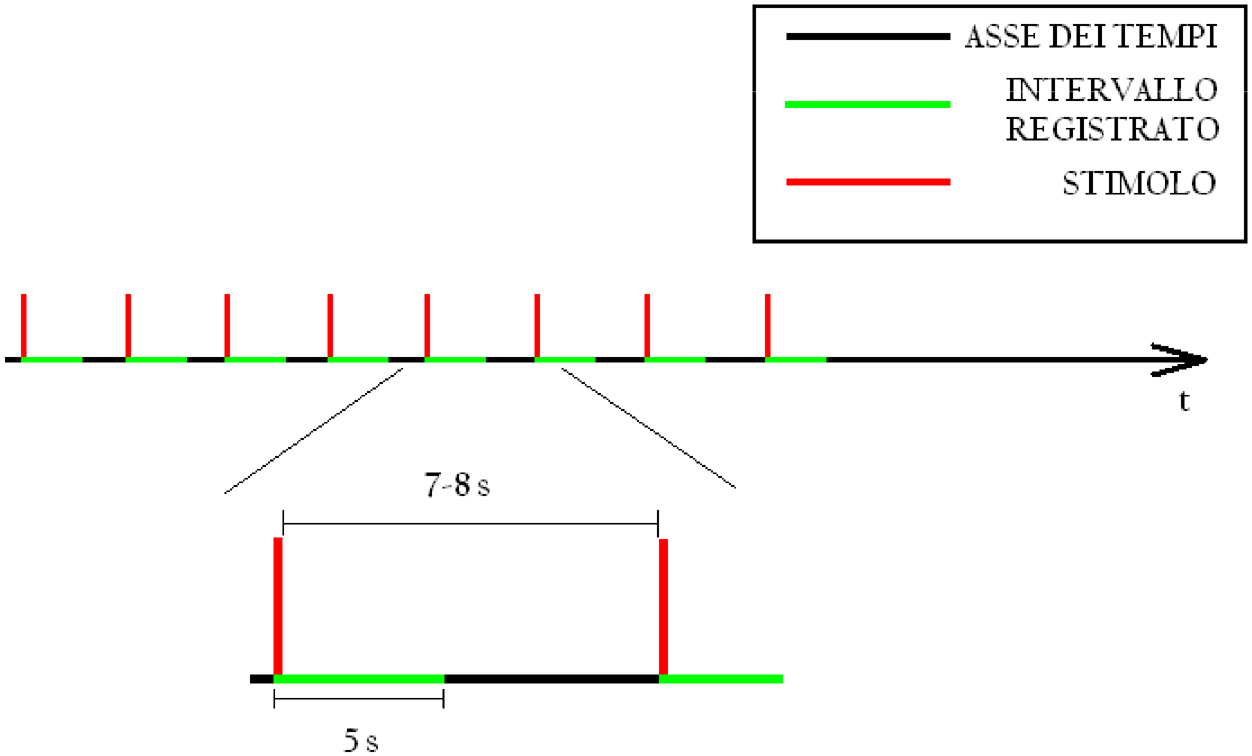
Recent advances in EEG-TMS coregistration have shed new light on EEG reactivity in humans.



Data acquisition

EEG-TMS coregistration was performed during the same experimental session:

1. **Single-pulse** stimulation over the left M1 area
2. **Paired-pulse** stimulation over the left M1 area with an ISI of 3ms
3. **Transcallosal stimulation** over the left and the right M1 areas with an ISI of 10 ms



Wavelet analysis

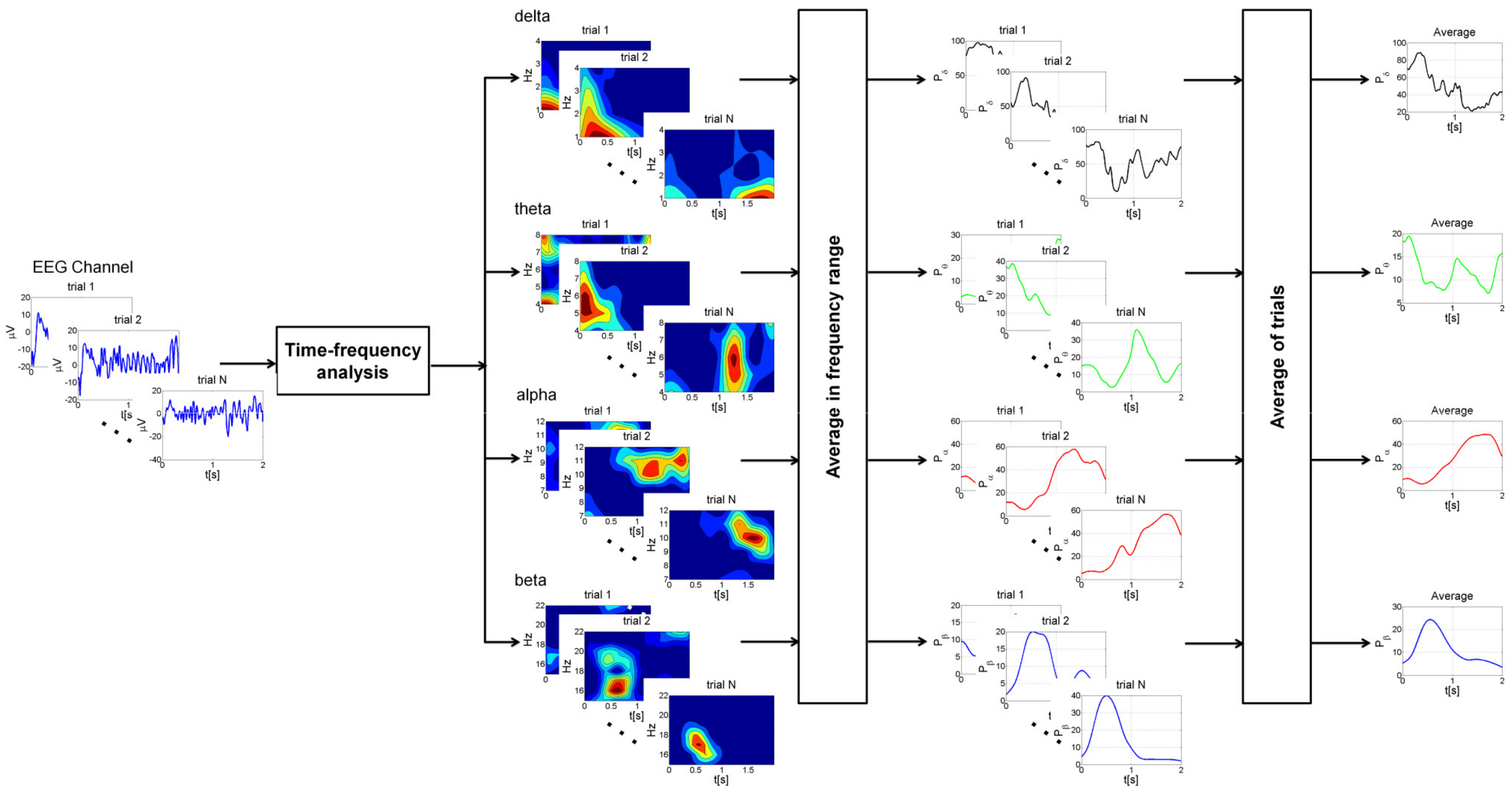
- EEG traces were analyzed 35 ms after magnetic stimulation
- Time-frequency analysis was performed using Continuous Morlet Wavelet Transform:

$$C_x(a,\tau) = \int_{-\infty}^{+\infty} x(t) h^*_{a,\tau}(t) dt$$

relative power in delta (1-4 Hz), theta (4-8 Hz), alpha (7-12 Hz) and beta (15-22 Hz) bands were computed.

- Only the most representative channels were considered in the analysis (F3, Fz, F4, C3, Cz, C4, P3, Pz, P4).
- About 20 epochs of basal EEG were selected for each subject, the mean and SD of relative power were computed.
- The relative power for each post-stimulus signal was computed, averaged among trials, and normalized to the baseline values.

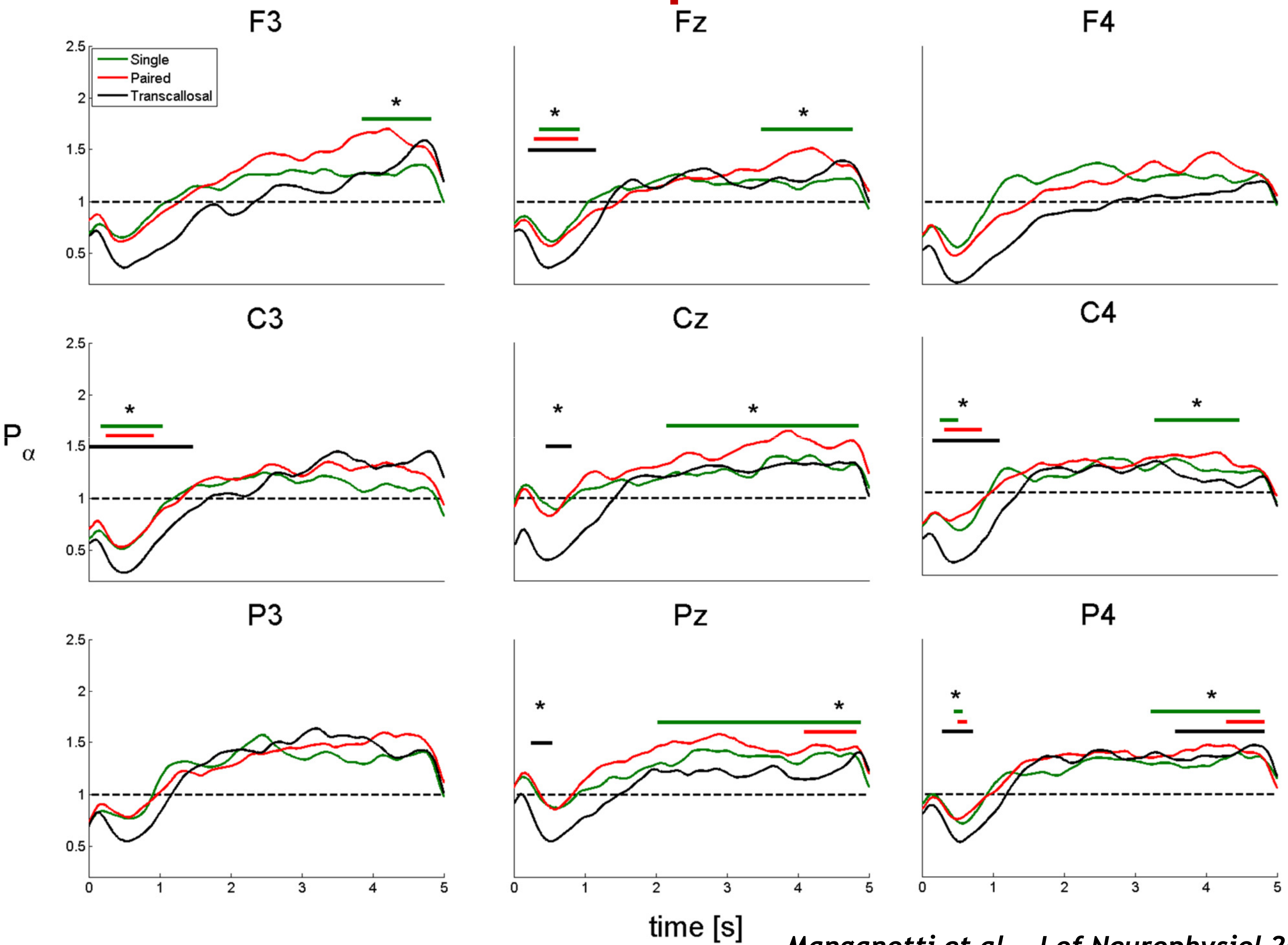
Wavelet analysis



Wavelet power

$$P_x(t,f) = |C_x(t,f)|^2$$

Results: alpha band



Manganotti et al., J of Neurophysiol 2012

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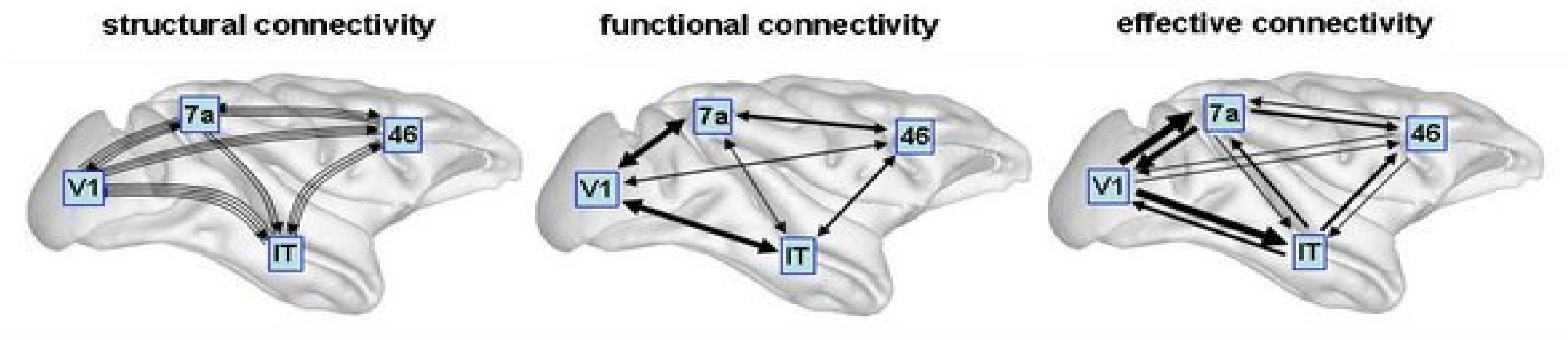
Connectivity: structural, functional and effective



Sporns 2007, *Scholarpedia*

- **Structural/anatomical connectivity**
  presence of axonal connections

- **Functional connectivity**
  statistical dependencies between regional time series

- **Effective connectivity**
  causal (directed) influences between neuronal populations

Connectivity:
Effective Vs Functional

Effective Connectivity

- The influence one neuronal system exerts over onother
- The mechanism of coupling
- How the dependences are expressed

⇩

Captures casual relationship

Functional Connectivity

- Temporal correlation between spatially remote neurophysiologic event

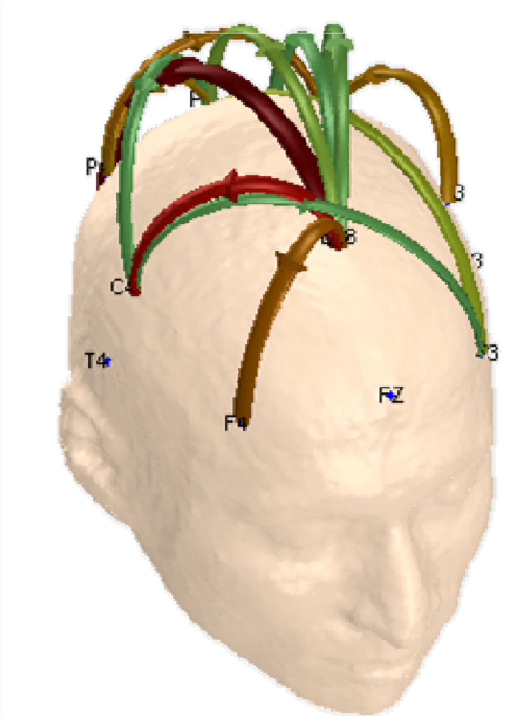
⇩

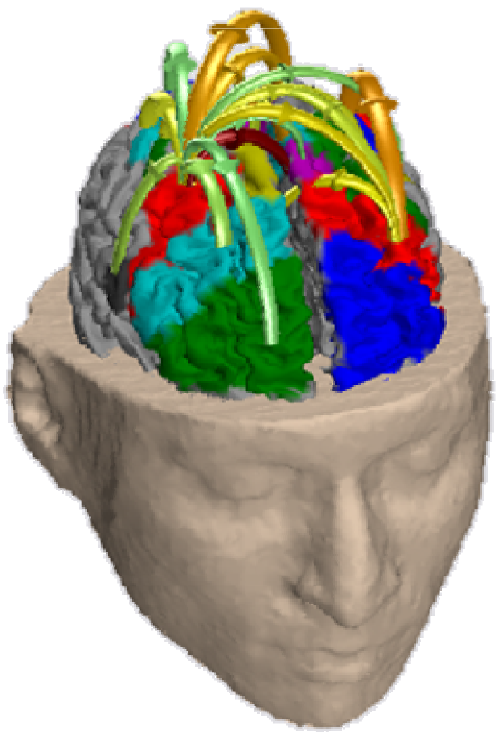
Involves the estimation of covariance properties

Determination of EEG propagation in the brain

The determination of the biological signals propagation and in particular directions of flow of the brain activity are crucial for the understanding of information processing in organisms. Several methods have been proposed for estimation of the directionality.

- Connectivity on EEG signal recorded by scalp electrodes
- Connectivity on cortical activity (after the source localization)





MultiVariate Autoregressive (MVAR) model

All the data channels are treated as one process and are analyzed simultaneously

$$X(t) = \sum_{i=1}^{p} A(i) X(t-i) + E(t)$$

in another form:

$$\sum_{i=1}^{p} A(i) X(t-i) = E(t)$$

transforming the model to frequency domain we get:

$$A(f) X(f) = E(f)$$

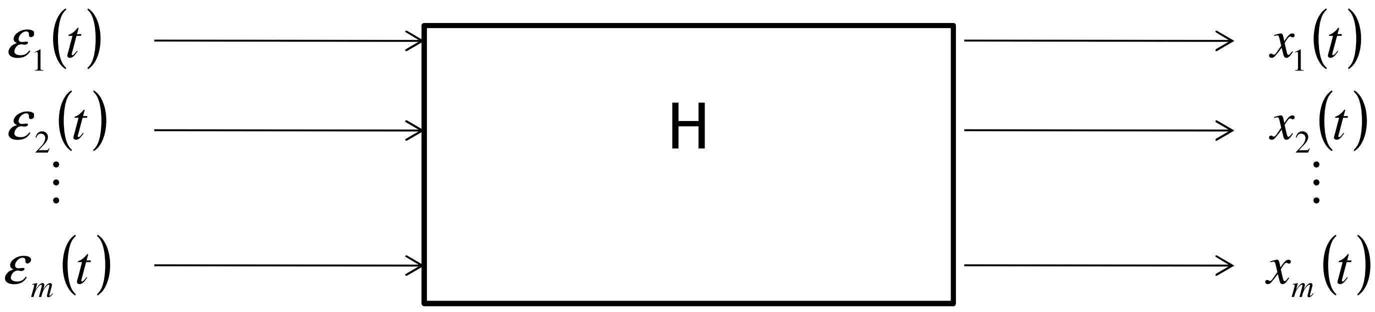
which can be presented as:

$$X(f) = A^{-1}(f) E(f) = H(f) E(f)$$

MultiVariate Autoregressive (MVAR) model

$$X(f) = A^{-1}(f)E(f) = H(f)E(f)$$

MVAR can be treated as a black-box model with the noises at the input and the signal as the output



All the information about the spectral properties and interrelation between channels is contained in the transfer matrix H(f) of the model.
From the transfer matrix power spectrum, ordinary, multiple and partial coherences can be easily calculated.

Power spectrum:

$$S(f) = X(f)X^*(f) = \ldots = H(f)VH^*(f)$$

Functional Connectivity: Coherence

EEG coherence is a measure of neural synchronization between two different time series. It is a measure of functional association between two brain regions.

Magnitude-square coherence

$$Coh_{xy}^{2}(f) = \frac{\left|S_{xy}(f)\right|^{2}}{S_{x}(f)S_{y}(f)}$$

$$S_{x}(f) = \frac{1}{K}\sum_{k=1}^{K}\left|X_{k}(f)\right|^{2}$$

$$S_{y}(f) = \frac{1}{K}\sum_{k=1}^{K}\left|Y_{k}(f)\right|^{2}$$

$$S_{xy}(f) = \frac{1}{K}\sum_{k=1}^{K}\left|X_{k}(f)Y_{k}^{*}(f)\right|^{2}$$

Functional Connectivity: Coherence

Values of coherence will always satisfy in the range [0 1].

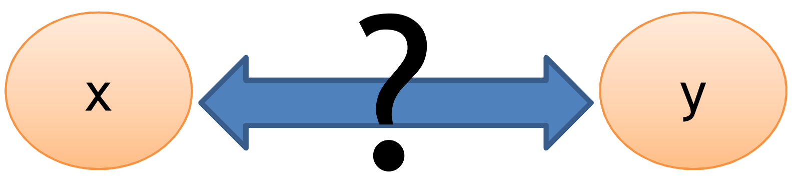
$Coh_{xy}^{2} = 1$ the two time series are related

$Coh_{xy}^{2} = 0$ the two time series are unrelated

The matrix S(*f*) is symmetric: $\left|Coh_{xy}(f)\right|^{2} = \left|Coh_{yx}(f)\right|^{2}$

Analysis technique based on coherence is not sufficient to adequtely describe the interdipendence within the neural system.

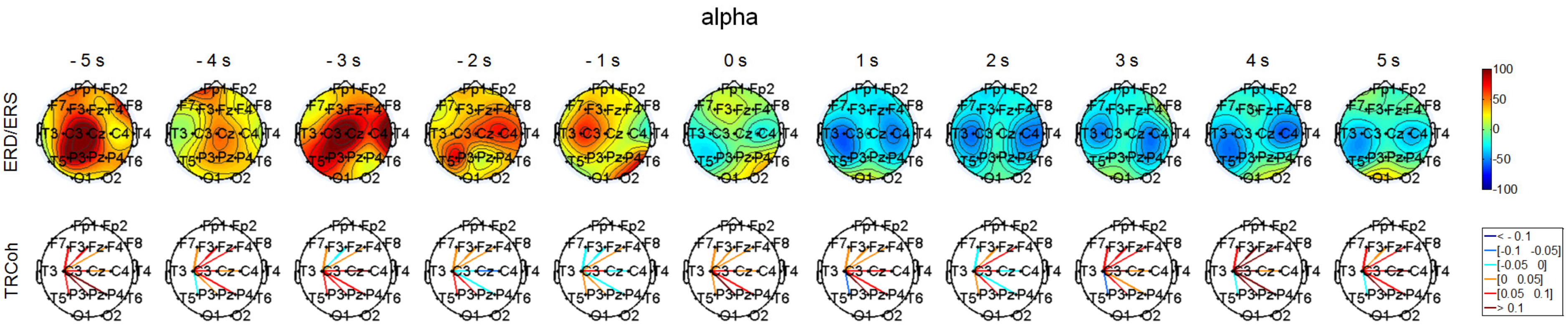
Coherence is not able to distinguish between direct and indirect influences.



Time - frequency ERD and Task - related Coherence

$$ERD_x(\tau, f) = \frac{P_{x\,Activation}(\tau, f) - P_{x\,\mathrm{Re}\,st}(\tau_0, f)}{P_{x\,\mathrm{Re}\,st}(\tau_0, f)} \times 100$$

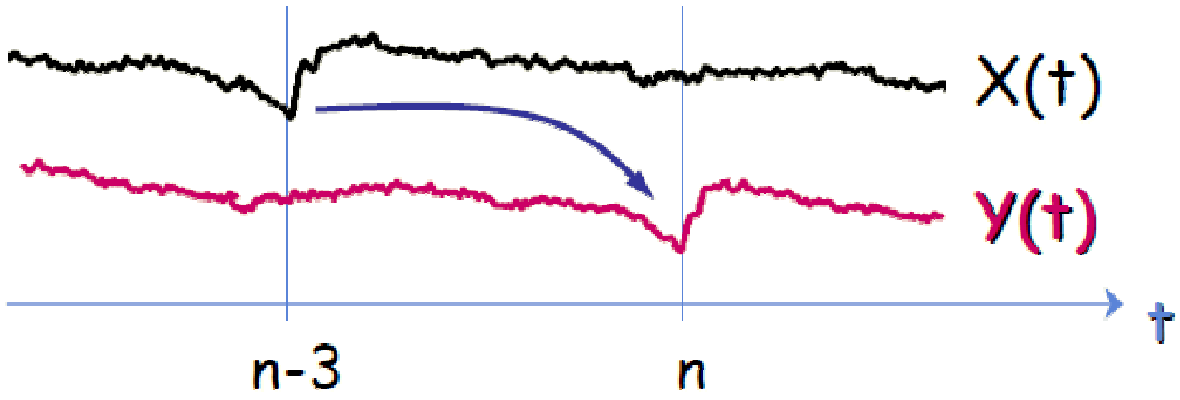
$$TRCoh(\tau, f) = Coh_{xy\,Activation}(\tau, f) - Coh_{xy\,\mathrm{Re}\,st}(\tau_0, f)$$



Effective connectivity

Granger causality (a cause must precede its effect):

For dynamic systems a process X is said to Granger-cause a process Y if knowledge of the past of process X improves the prediction of the process Y compared to the knowledge of the past of process Y alone.



Class of parametric techniques:

- Granger Causality index (GC)
- The Partial Directed Coherence (PDC)
- The Directed Transfer Function (DTF)

Directed Transfer Function (DTF)

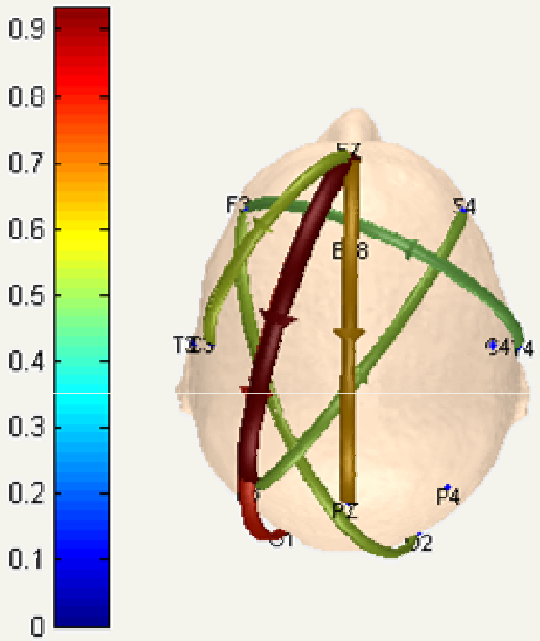
DTF has been introduced to detect casual relationship between processes in multivariate dynamic systems. The DTF is constructed from transfer matrix of the MVAR model.

Based on the Fourier transformation of the coefficient matrices:

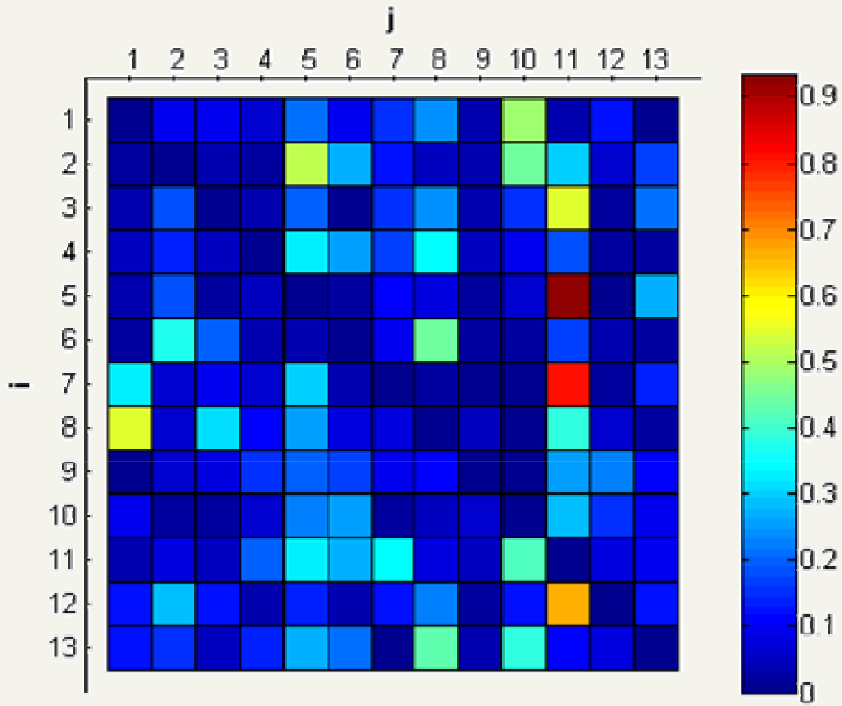
$$\left|DTF_{xy}(f)\right|^2 = \frac{\left|H_{xy}(f)\right|^2}{\sum_{k=1}^{m}\left|H_{xk}(f)\right|^2} \qquad H_{xy}(f) = A_{xy}^{-1}(f)$$

Normalized between 0 and 1, an interaction from process y to x is detected if DTF_{xy} is unequal to zero.

Directed Transfer Function (DTF)



Information Flow Graphics



Information Flow Image (A[i,j]: j ==> i)