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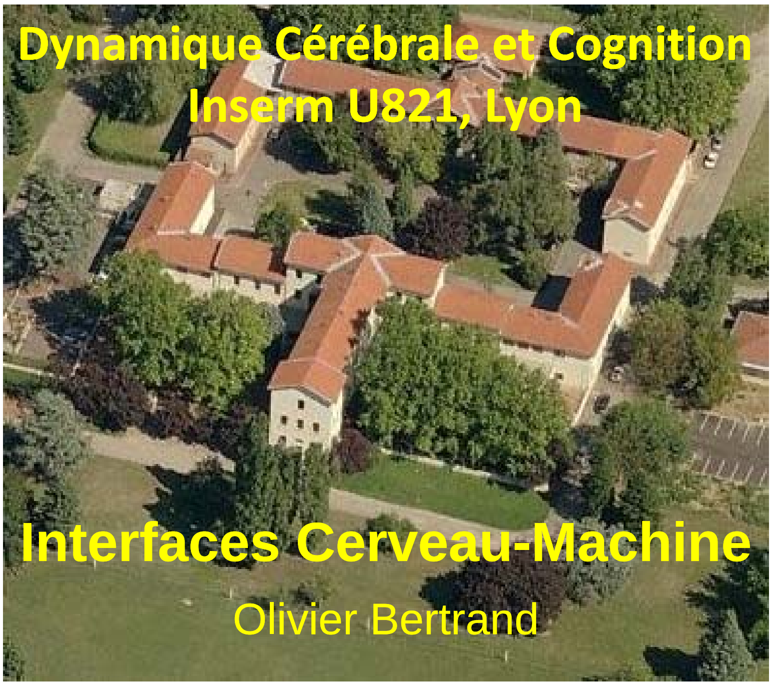
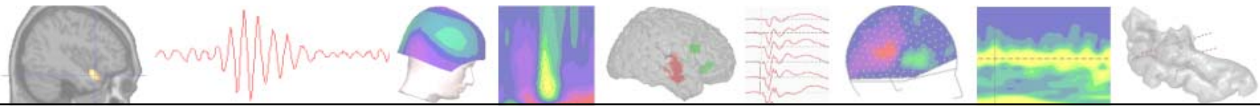
Institut national
de la santé et de la recherche médicale

DHSS – Ecole Polytechnique
Cerveau et Cognition
12 novembre 2009





Interfaces Cerveau-Machine

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Les Interfaces Homme-Machine (IHM) :

Interactions avec la machine via une commande motrice (interrupteur, souris, clavier, capteurs de mouvement, orientation du regard, parole, …).

Les Interfaces Cerveau-Machine (ICM) :

Interactions avec la machine par la seule mesure de l'activité cérébrale et sans commande motrice.

La mesure la plus utilisée : l'activité électrique cérébrale

→ **électrophysiologie en temps-réel**

Real-time electrophysiology

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To measure in real-time electrophysiological components (spike, LFP, EEG, MEG) specific to a particular mental process or state, with multiple (potential) applications :

Brain-Machine Interface (BMI) to control external devices

- to restore communication in patients with strong motor disabilities

NeuroFeedback Training (NFT) and Rehabilitation

- self-regulation of specific brain activities
- domains : attention disorders, motor rehab., depression, epilepsy, pain, …

Basic Neuroscience

- to better understand the « neural code » and brain plasticity
- dynamic manipulation of an experimental protocole according to brain state

Video-games

- enriched game-play or « serious games »

Paper production

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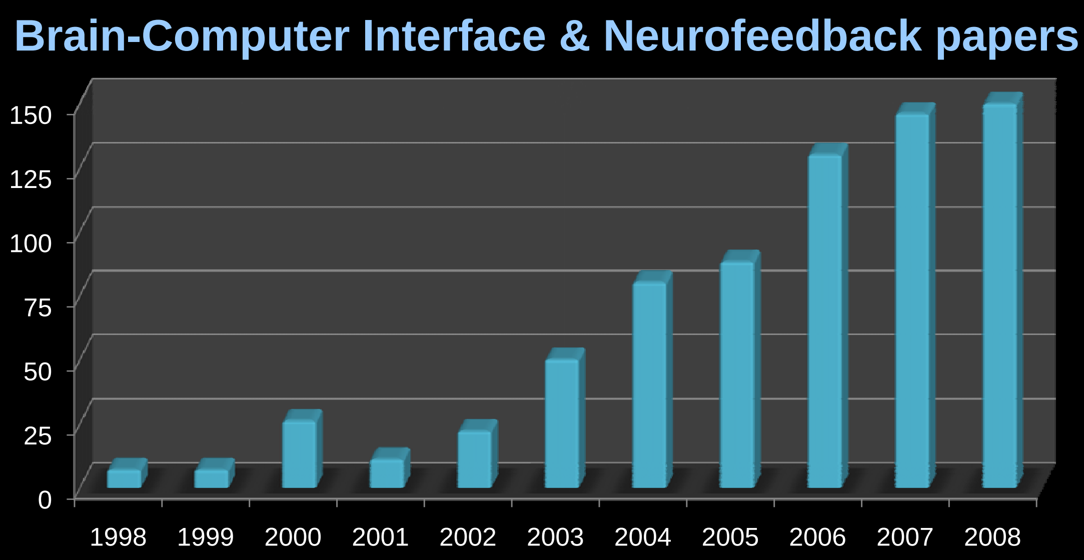

20 years ago : 3-4 groups world-wide
10 years ago : 6-8 groups
2009 : ~ 100 groups

Brain-Machine Interface – BMI (BCI)

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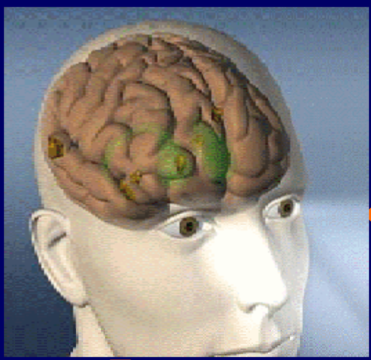

feedback

closed-loop BCI

signal acquisition

real-time signal processing
(feature extraction, classification)

translation to commands

Electrophysiological signal recordings

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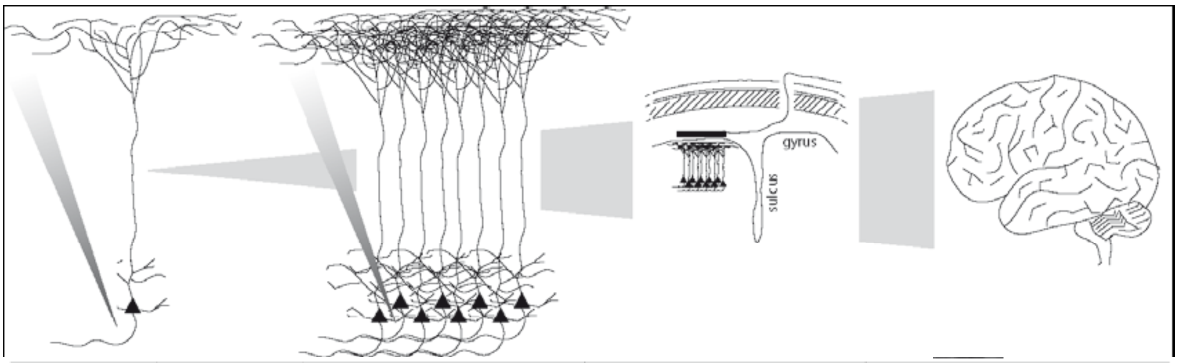
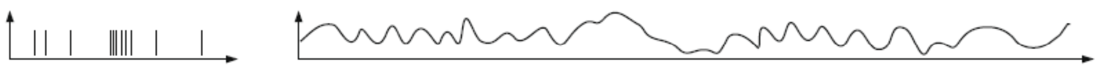
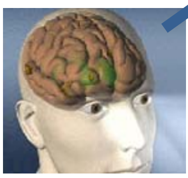


SUA	MUA	LFP	ECoG	MEG & EEG

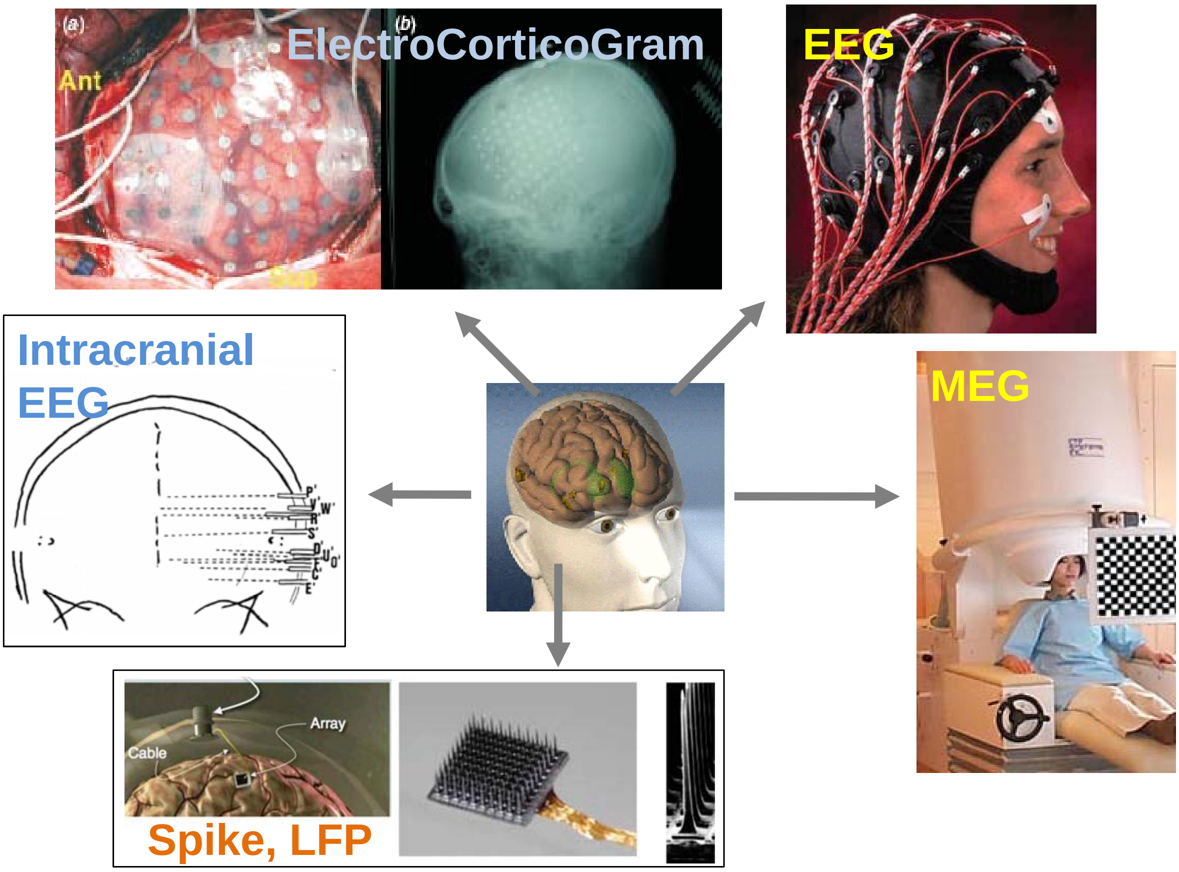


1 ← >1 —— size of neuronal cluster ——→ >100.000
high ←—— spatial resolution ——→ low
invasive ←——→ non-invasive



Waldert, 2009

Electrophysiological signal recordings



Brain-Machine Interface (BMI)

- **BMI as a communication aid without movement.**
- **Clinical goals** ⇨ to restore communication and control to people with severe motor disorders:
  - amyotrophic lateral sclerosis (ALS)
  - spinal cord injury
  - muscular distrophies
  - brainstem stroke, locked-in syndrome.
- **Invasive or non-invasive BMIs**
- to learn how to associate a mental state to a desired action

  (good mental processes and good markers ?)

  - **endogeneous processus:** e.g., motor imagery

Non-invasive BMIs (motor imagery)

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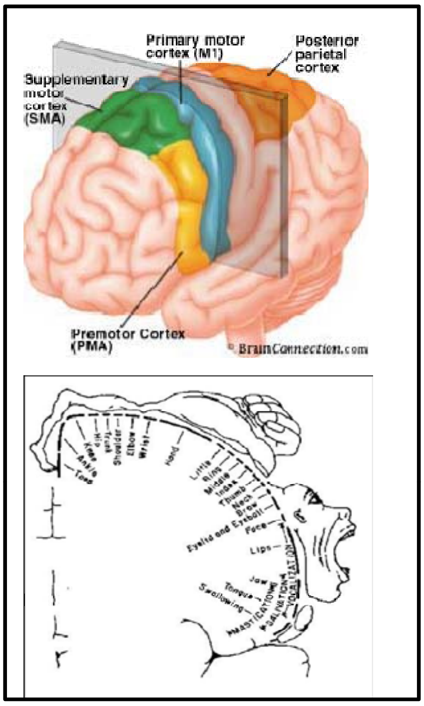
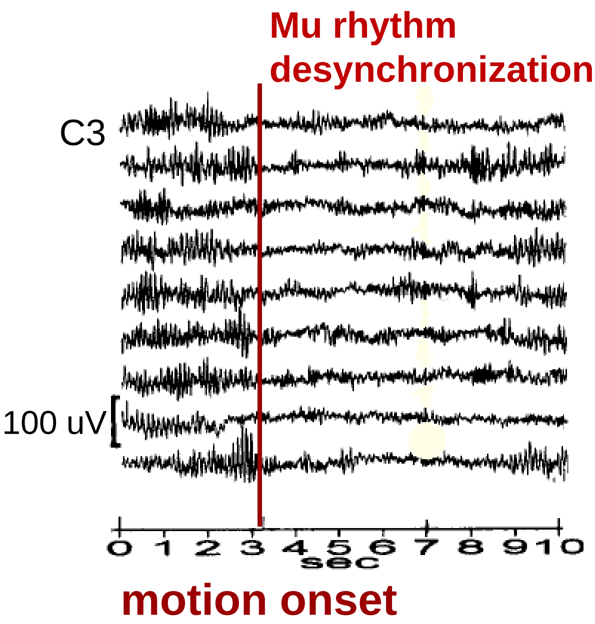
Sensorimotor rhythms:
mu (~10 Hz) and **beta** (15-25 Hz) ERD





Pfurtscheller

Non-invasive BMIs (motor imagery)

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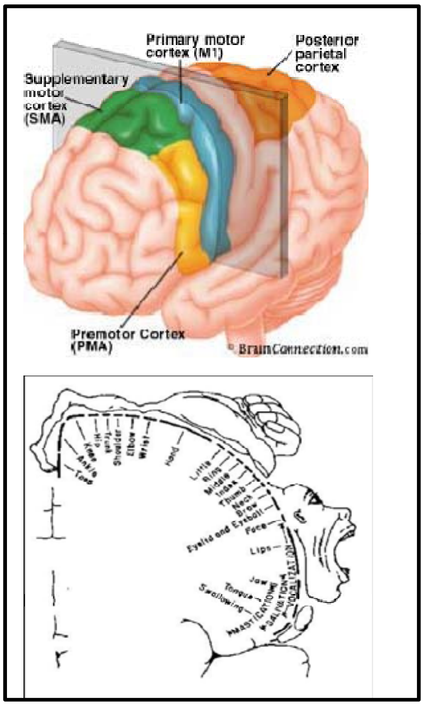
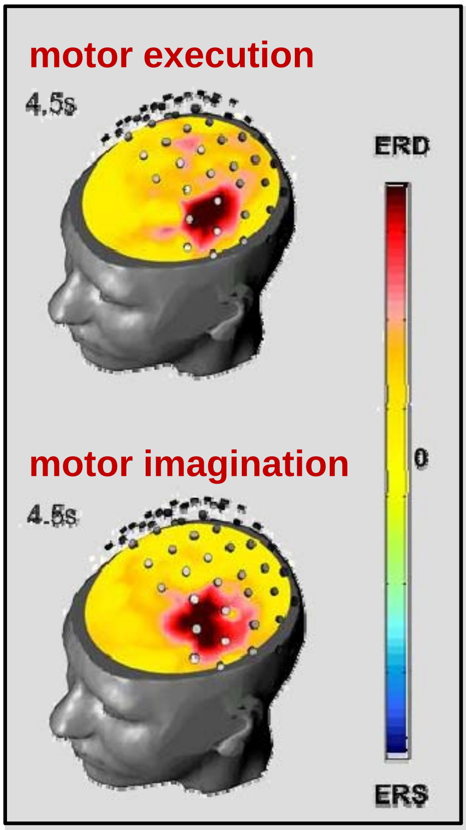
Sensorimotor rhythms:
mu (~10 Hz) and **beta** (15-25 Hz) ERD





Pfurtscheller

Non-invasive BMIs (motor imagery)

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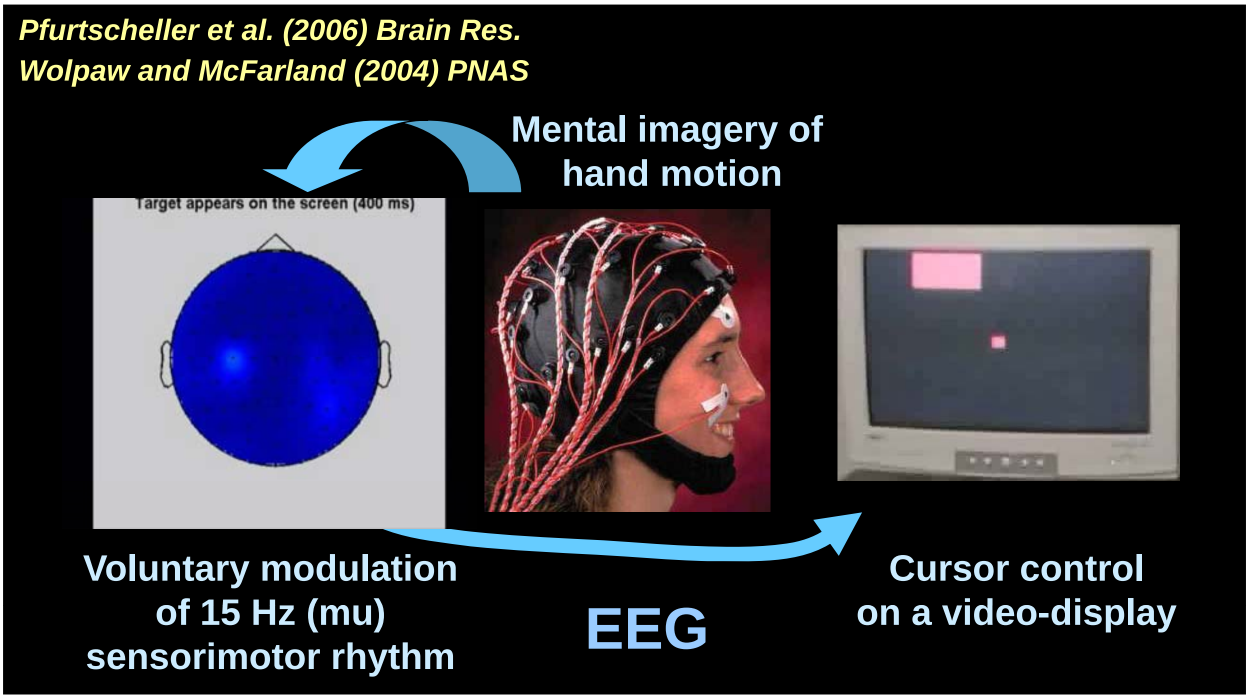

This approach requires extensive training

ICM non-invasive (imagerie motrice)

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- **Phase de calibration (off-line)**
  - Instructions au sujet (imagerie main droite, main gauche)
  - choix de la fréquence et des électrodes du rythme mu
  - calcul du gain, ex : déplacement curseur/puissance du mu
- **Phase d'utilisation (on-line)**
  - estimation du mu en temps-réel (fenêtre ~ 0.5 à 1 s)
  - transformation en temps-réel :

    puissance mu → déplacement du curseur
- **Problèmes**
  - variabilité interindividuelle importante
  - apprentissage difficile, recalibrations régulières

Non-invasive BMIs (motor imagery)

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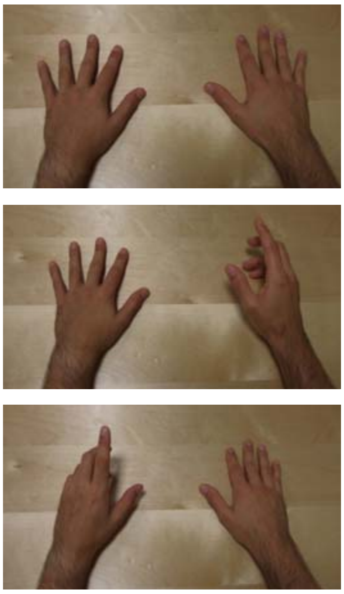
10-15 Hz mu rhythm analysis

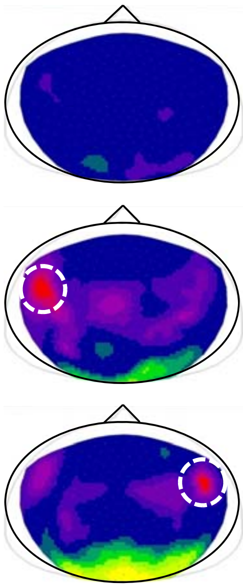
MEG

rest

real right hand movement

real left hand movement





real movement

Non-invasive BMIs (motor imagery)

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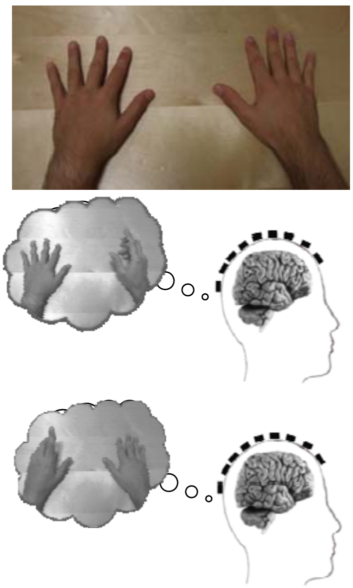
10-15 Hz mu rhythm analysis

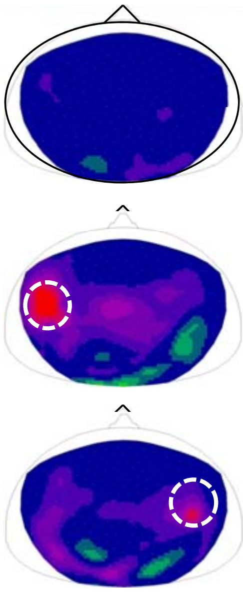
MEG

rest

imagination of right hand movement

imagination of left hand movement





imagination of movement

Non-invasive BMIs (motor imagery)

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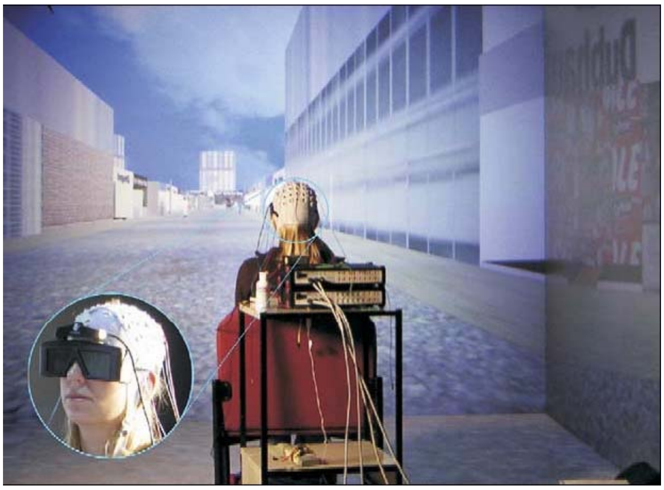

Foot vs hand movement (go/stop)
in virtual reality environement
after extensive BMI training

Pfurtscheller et al 2006

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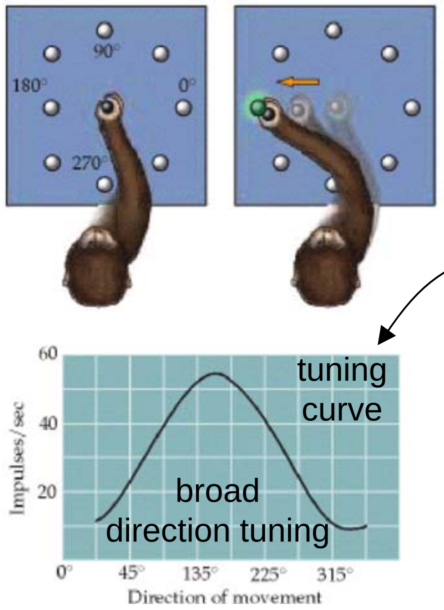
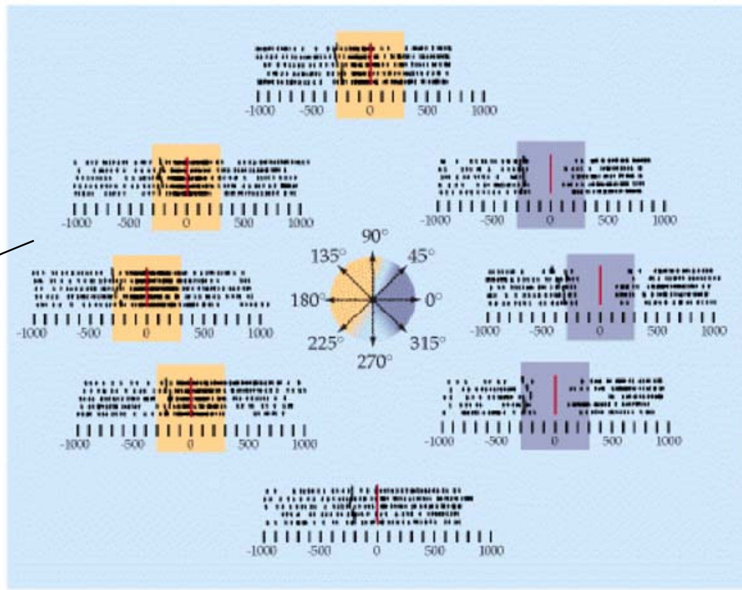
Invasive BMI

Codage par population de la direction du mouvement

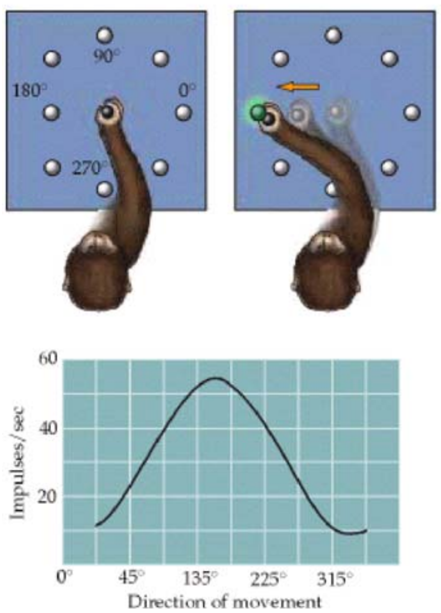


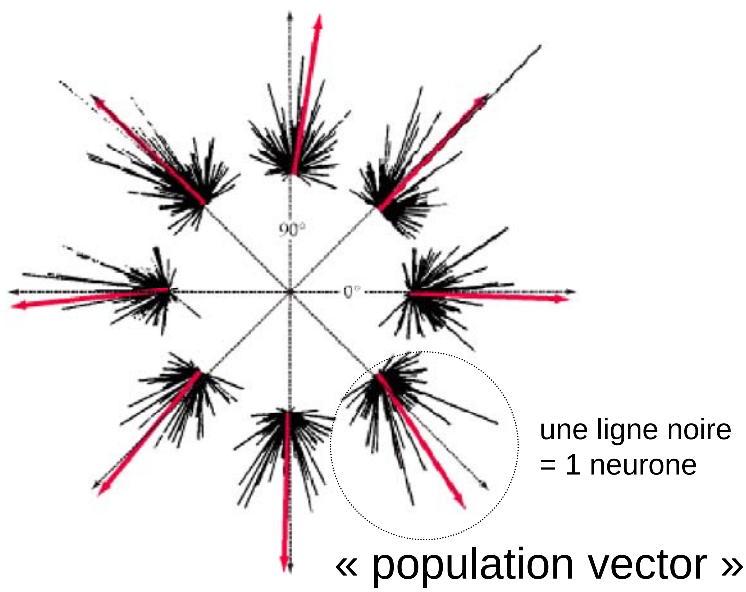


un neurone du cortex moteur primaire
(faible sélectivité à la direction du mouvement)

Georgopoulos et al., 1986

Codage par population de la direction du mouvement





prédiction possible
de la direction du mouvement

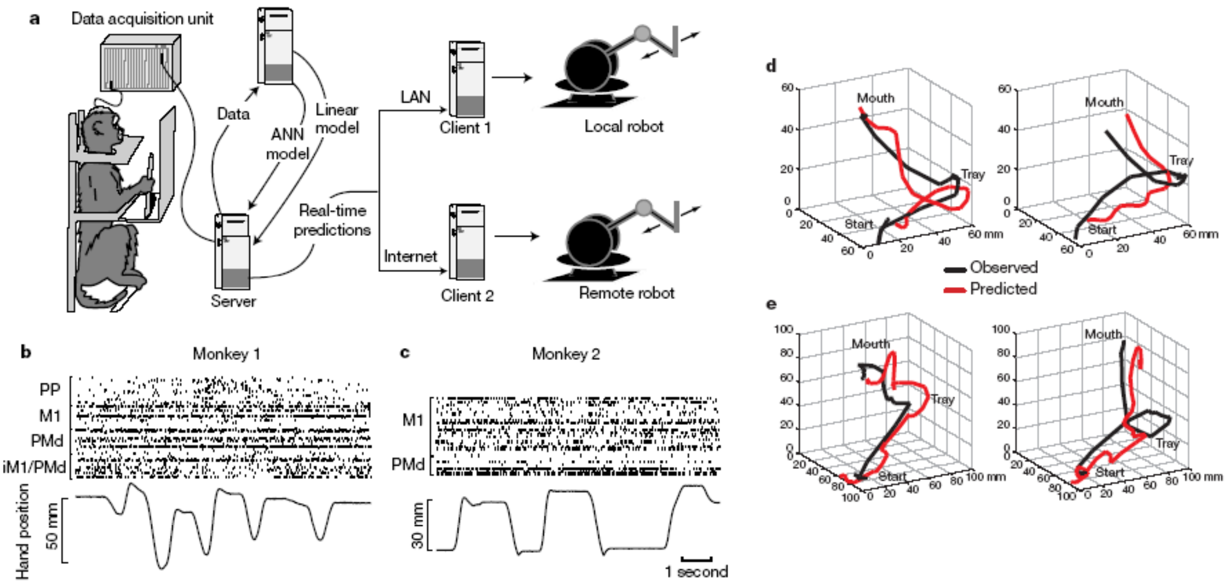
Georgopoulos et al., 1986

Real-time prediction of hand trajectory by ensembles of cortical neurons in primates

Johan Wessberg*, Christopher R. Stambaugh*, Jerald D. Kralik*, Pamela D. Beck*, Mark Laubach*, John K. Chapin†, Jung Kim‡, S. James Biggs‡, Mandayam A. Srinivasan‡ & Miguel A. L. Nicolelis*§||

Nature, 2000

movement prediction from electrodes in premotor, primary motor, and posterior parietal cortical areas



Equipe Nicolelis, USA – Wessberg et al, Nature, 2000

Robotic arm control with micro-electrode array (5 degrees of freedom)

Velliste et al., 2008

Invasive BMIs

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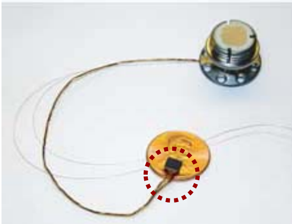
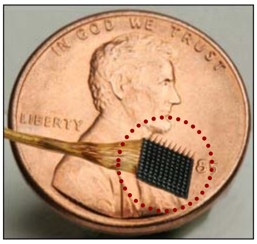
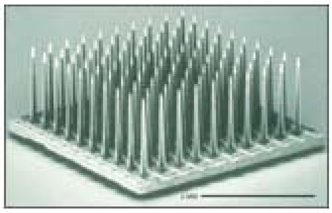

- Motor cortex implant,
- Records spiking activity from 100 neurones,
- **Intention-driven neuronal activity**
- Computes a linear model after training session
- Cursor control
- Short training period

Donoghue's Team– Hochberg et al., Nature, 2006

Non-invasive BMIs

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- **Other BMIs for restoring communication**
  - **stimulus-driven activity:**

    Voluntary orientation of attention on certain stimuli

    Specific modulation of certain evoked components

    - P300,
    - steady-state responses

P300 Speller BMIs

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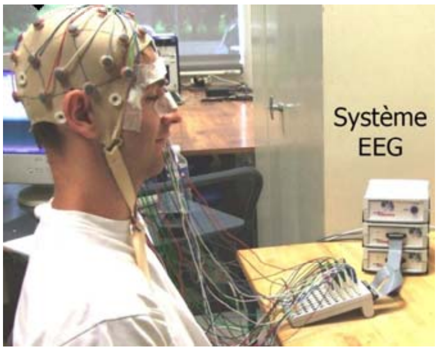
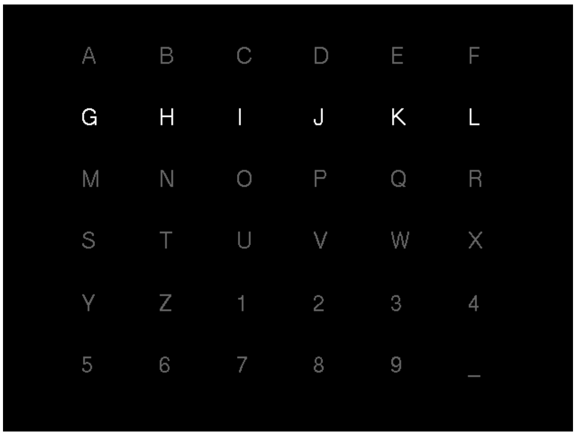
Selective attention on the letter to select ⇨ P300

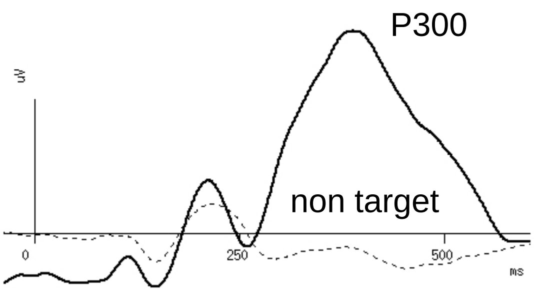
Task : to count the selected letter when it flashes (10 to 15)

Stimulus : flashing by lines or columns (ISI ~150 ms)





EEG



P300 Speller BMIs

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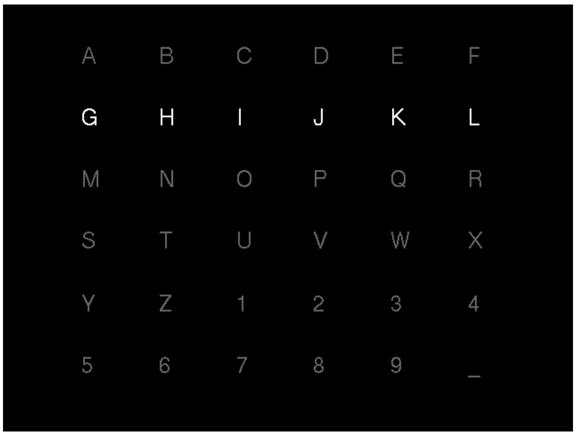
Selective attention on the letter to select ⇨ P300

Trade-off between robustness and speed

~ 5 letters /minute



Current improvements :

- Adaptive classification to optimize bit-rate

- Word selection instead of spelling letter by letter (word prediction algorithm coming from mobile phone world).

Visual Steady-State response

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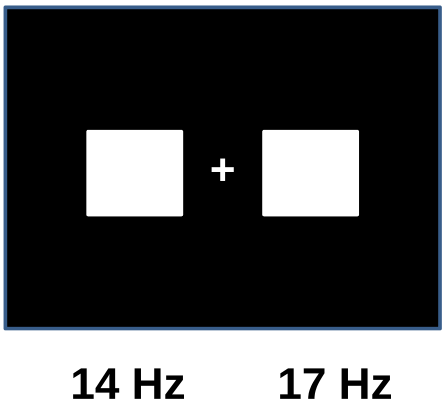
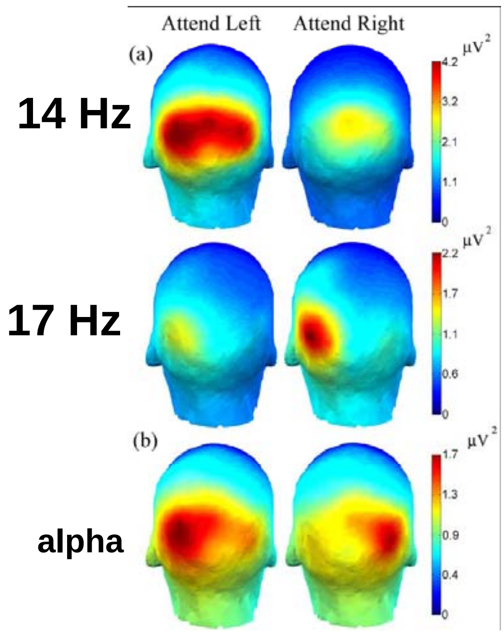
Frequency tagging of visual stimuli and selective attention

Un stimulus périodique engendre une réponse cortical périodique (même fréquence)

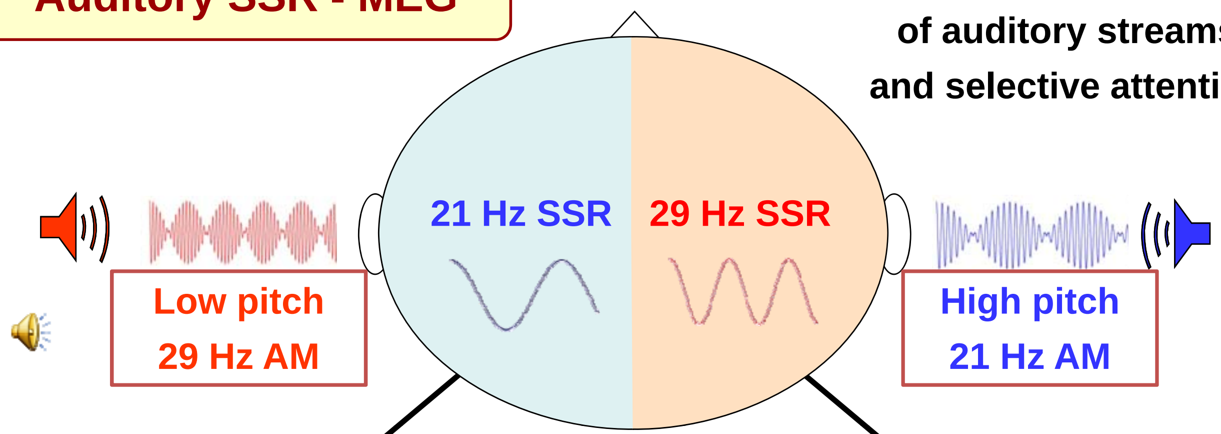


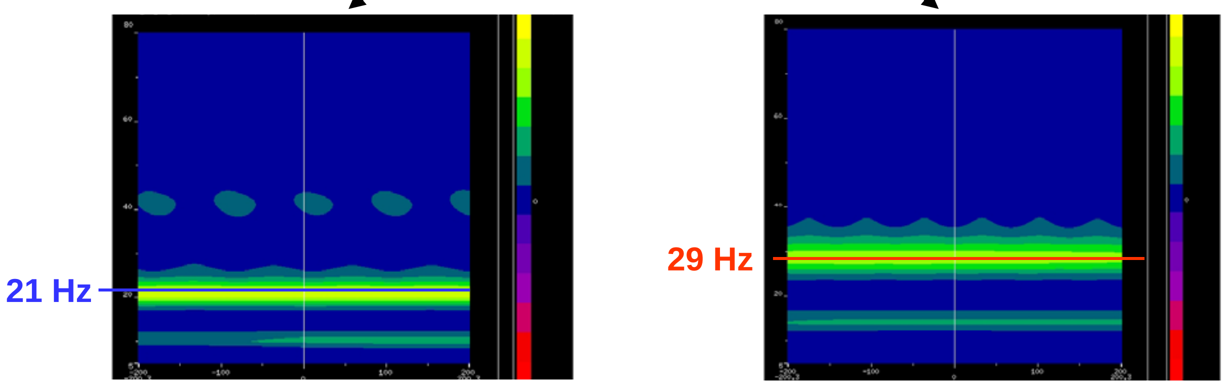


Kelly et al, 2005

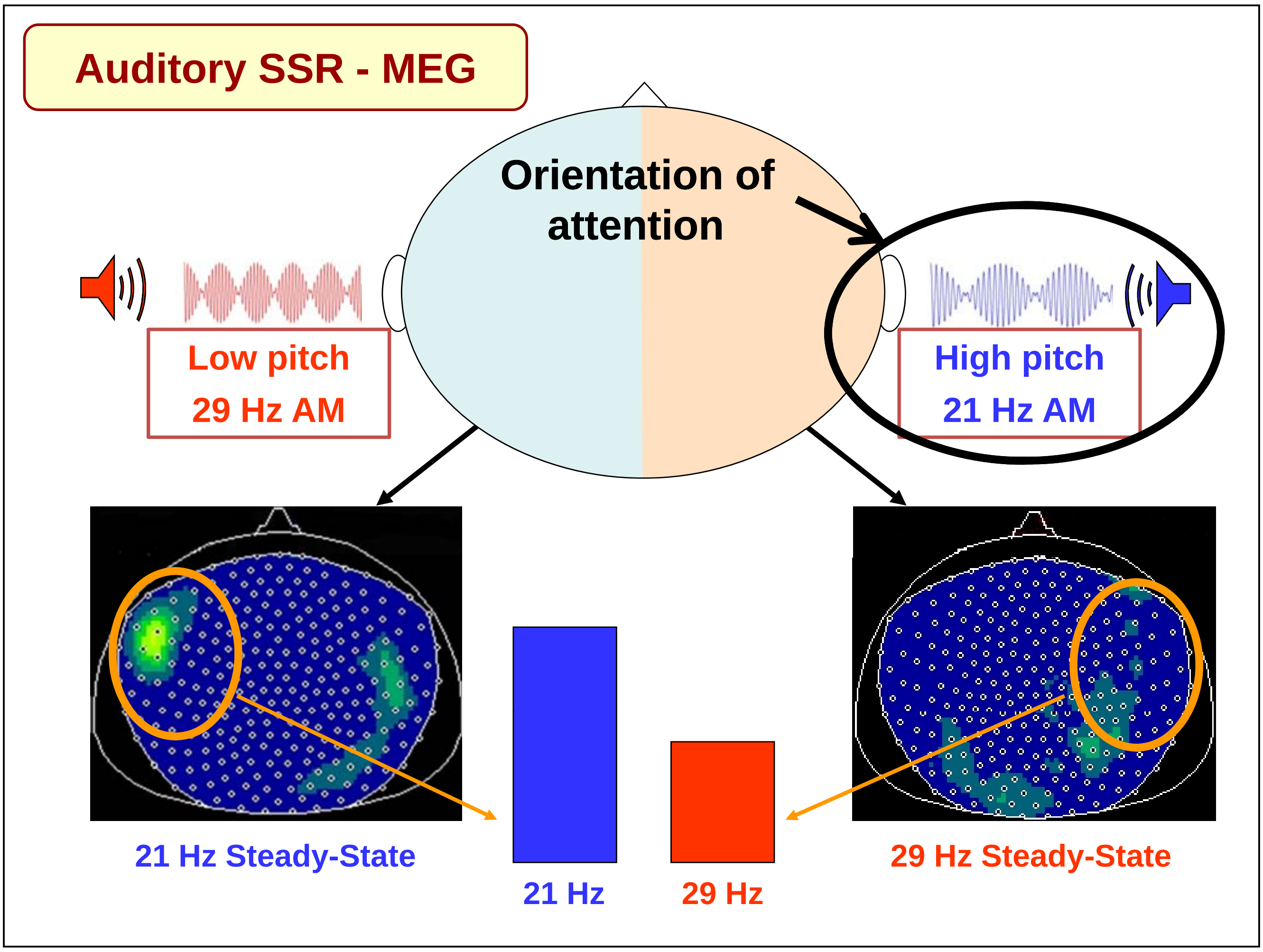
Auditory SSR - MEG

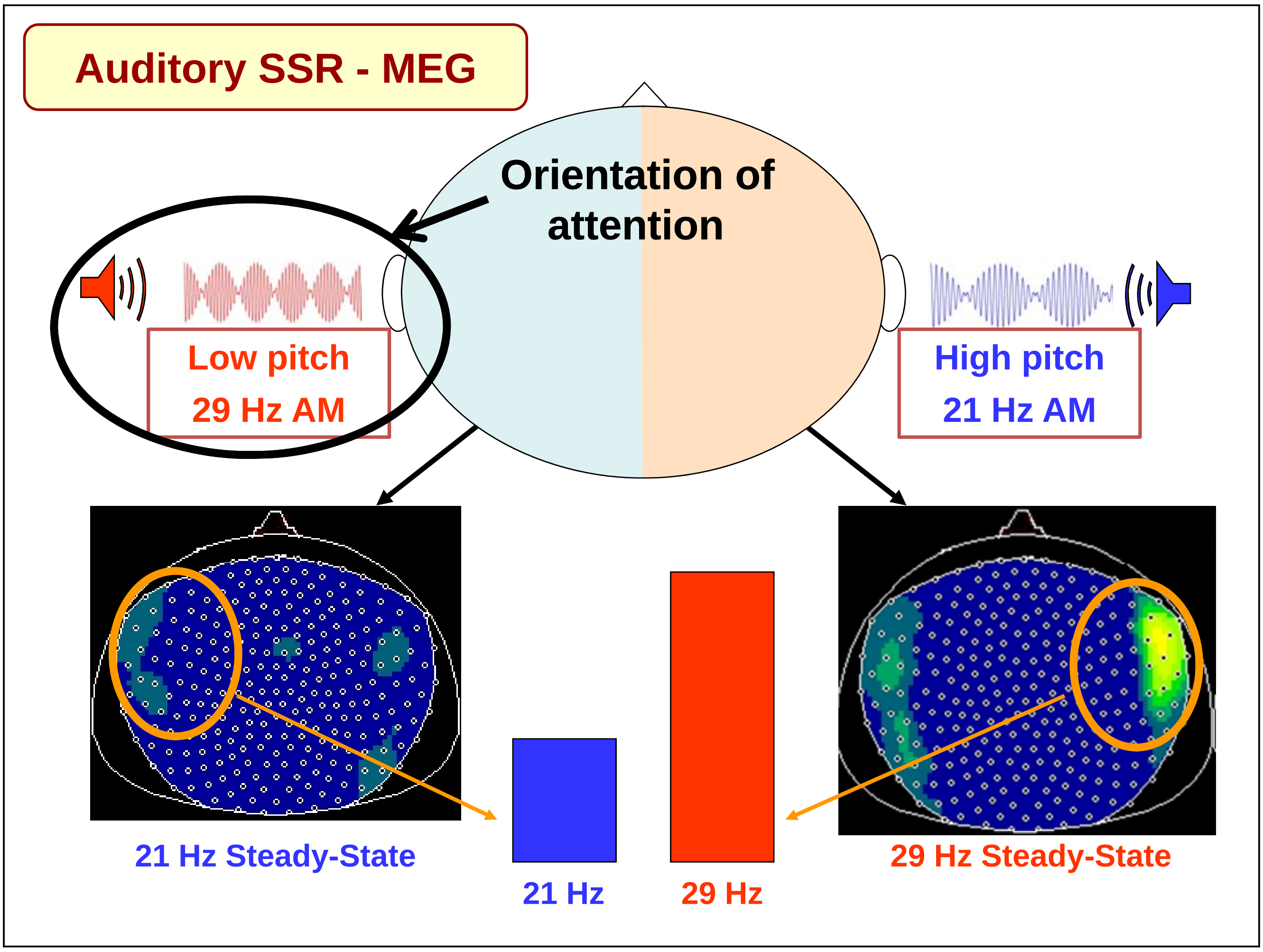
Frequency tagging of auditory streams and selective attention





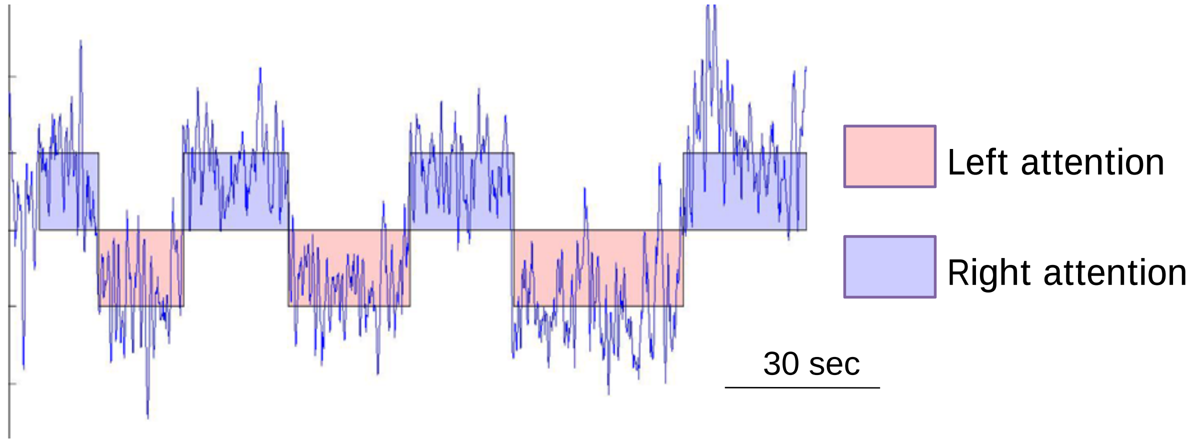
Time-frequency plot of averaged SSR


Auditory SSR - MEG
Orientation of attention
Low pitch
29 Hz AM
High pitch
21 Hz AM
21 Hz Steady-State
29 Hz Steady-State
21 Hz
29 Hz


Auditory SSR - MEG
Orientation of attention
Low pitch
29 Hz AM
High pitch
21 Hz AM
21 Hz Steady-State
29 Hz Steady-State
21 Hz
29 Hz

Auditory SSR - MEG

LDA classification on 2-sec moving time-windows based on spectral power at f and 2f over temporal regions



Auditory SSR as a possible marker for real-time attention monitoring/control

Remarques sur les différents BMI

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- **Imagerie mentale motrice**
  - ***non-invasif (EEG, MEG) :***
    - difficultés d'apprentissage, concentration nécessaire
    - variabilité inter- et intra-individuelle
    - ~60% des sujets sont capables de faire la tâche
  - ***invasif (micro-electrode array) :***
    - apprentissage plus rapide
    - moins sensible aux autres activités mentales
- **Attention sélective (visuelle, auditive)**
  - ***non-invasif (EEG, MEG) :***
    - peu d'apprentissage, plus naturel
    - débit lent, fatigue

Non-invasive BMIs

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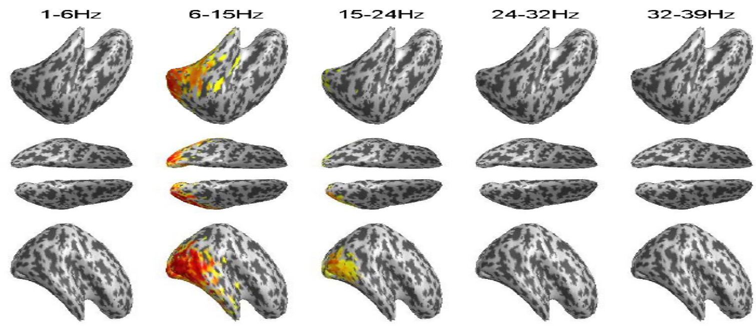
- **Other BMIs for restoring communication**
  - **endogeneous processus:** other types of imagery

To consider various types of mental tasks (verbal, visual, spatial) to benefit from better contrasts due to hemispheric specialization

To include **source reconstruction and coherence/synchrony** measures to improve selection of the most discriminant features.



e.g., visuo-spatial navigation imagery task

M. Besserve, PhD 2007

Magnetoencephalography and BMI ?

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- **MEG is obviously not an appropriate device for an operational BMI dedicated to communication and control in disabled** (size, price, complexity, …)
- **MEG could certainly help to identify new markers for BMI, during an exploratory phase, that could then be adapted to EEG recordings.**
- **MEG could be useful to efficiently train subjects to learn a BMI** (good compromise between temporal and spatial resolution, and functional specificity)**.**
- **MEG is quick to install, and non-invasive**

BMIs for rehabilitation purposes

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- **Use of the plasticity properties of the brain**
- **NeuroFeedback training (NFT) based on BMI:**
  - Self-regulation of a specific brain activity (oscillatory, transient responses, slow waves)
  - Same technical principles as BMI
  - Training of occipital alpha and frontal theta
    - attention disorders, relaxation
    - epilepsy
    - pain

Very empirical, no strong study on the neurophysiological mechanisms of NFT

Revival with fMRI and MEG

fMRI Neurofeedback Training

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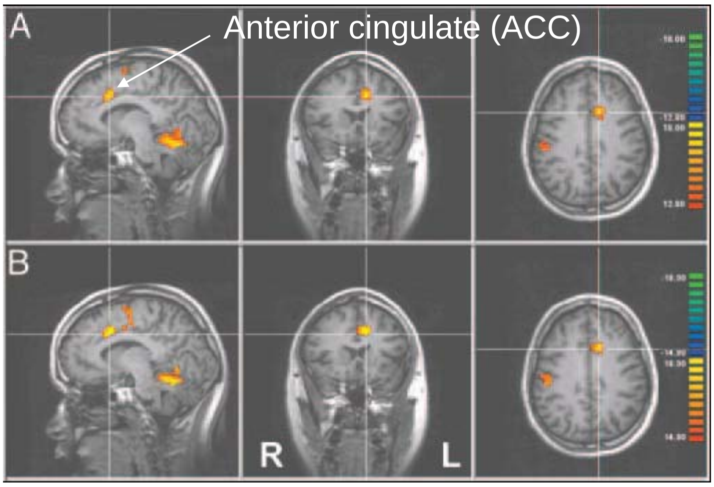
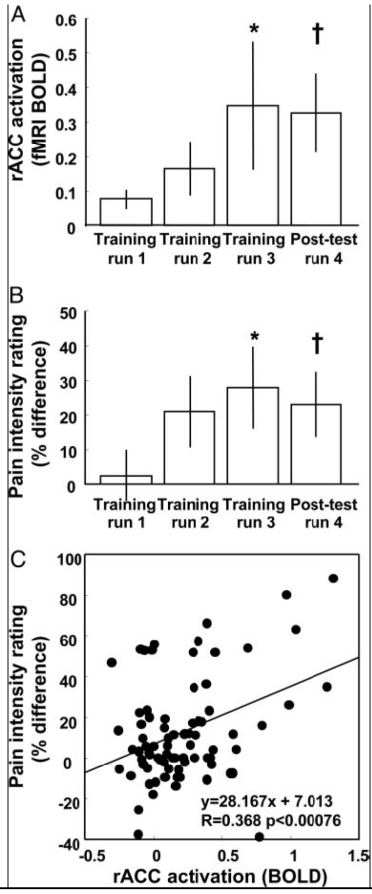
Control over brain activation and pain learned by using real-time functional MRI
deCharms et al. PNAS, 2005

Delay of ~8s for the feedback





- voluntary control over activation in a specific brain region (ACC),
- leads to control over pain perception,
- Impact on severe, chronic clinical pain.

MEG Neurofeedback Training

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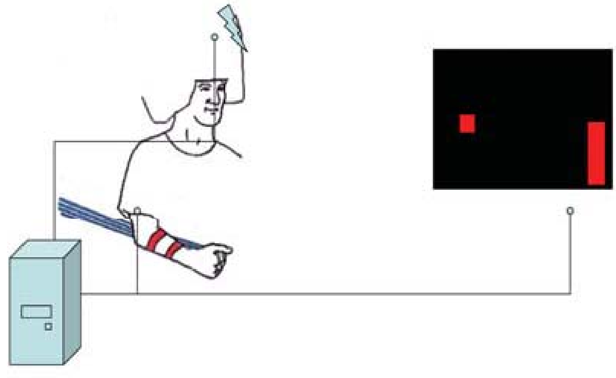
Motor deficits after stroke

MEG recordings



Task : Self-modulation of sensorimotor rhythm (mental imagery)

Feedback by up-down motion of the cursor on the screen

\+ Feedback by proportional motion of the orthosis on the paralysed hand

→ *Sensory input related to motor control*

Birbaumer, 2007

MEG Neurofeedback Training

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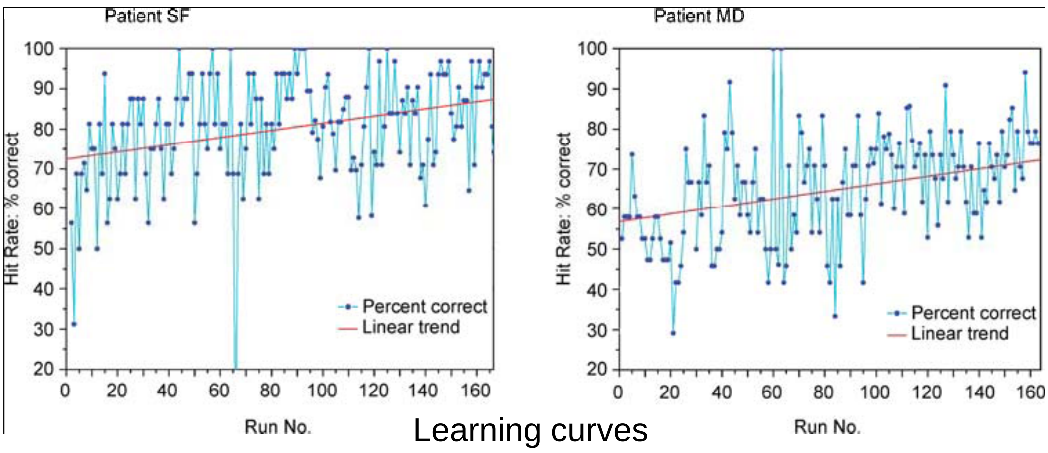
Motor deficits after stroke



Learning curves

Task : Self-modulation of sensorimotor rhythm (mental imagery)

Feedback by up-down motion of the cursor on the screen

\+ Feedback by proportional motion of the orthosis on the paralysed hand

→ *Sensory input related to motor control* → ***Speed-up plasticity***

Birbaumer, 2007

Neurofeedback challenges

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Need to target: **specific brain activities,**
in specific brain regions,
related to specific brain processes.

Requires to better understand the mechanisms of certain pathologies in terms of dysfunctioning regions, networks and interactions.

Requires to understand the potential mechanisms of neural plasticity and cortical reorganization related to certain pathologies.

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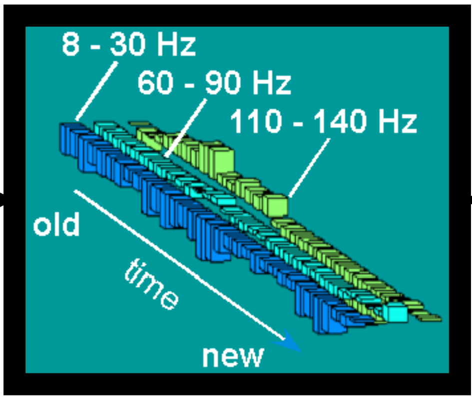
Other applications of real-time electrophysiology

Real-Time Oscillatory Brain Mapping (Epilepsy)

Real-time quantification of alpha,beta and gamma activity



BRAIN TV

Intracranial EEG Data Acquisition → Spectral Analysis → Visual Display

Lachaux et al. PLoS One, 2007

Collaboration Ph. Kahane, CHU Grenoble

Real-Time Oscillatory Brain Mapping

BRAIN TV

« Each time you play music, gamma goes up ! »

« If I sing, almost nothing .... »

No gamma when we speak

Little gamma for loud noises

Lachaux et al. PLoS One, 2007

Video-Games applications

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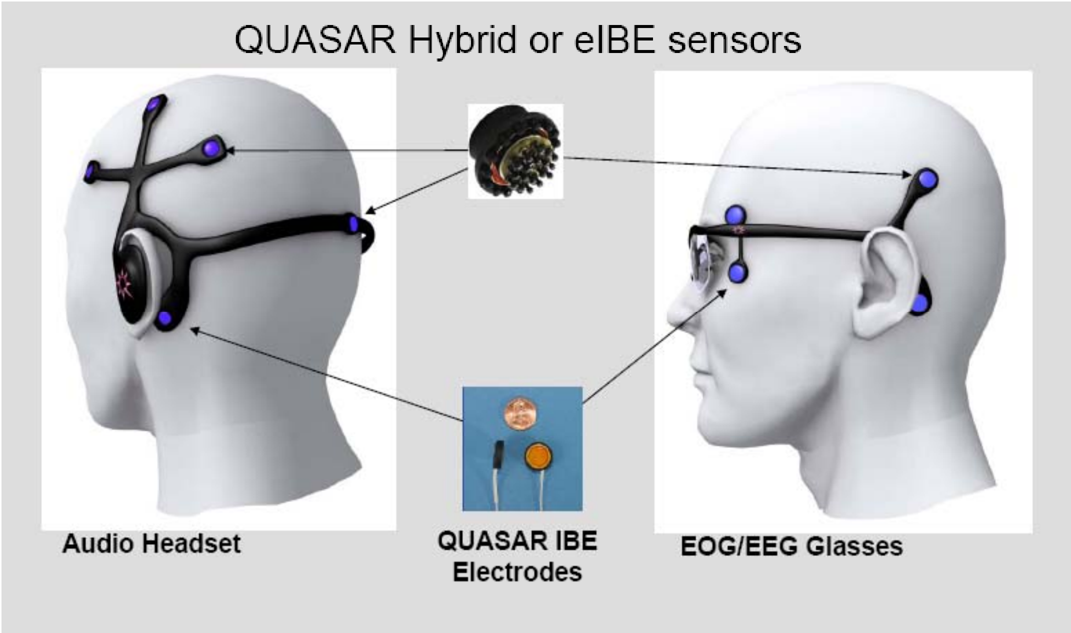
A growing field : real-time EEG for video-games
(Nintendo, Sony, …., + several small companies ….)
An opportunity for the development of new technologies.



Video-Games applications

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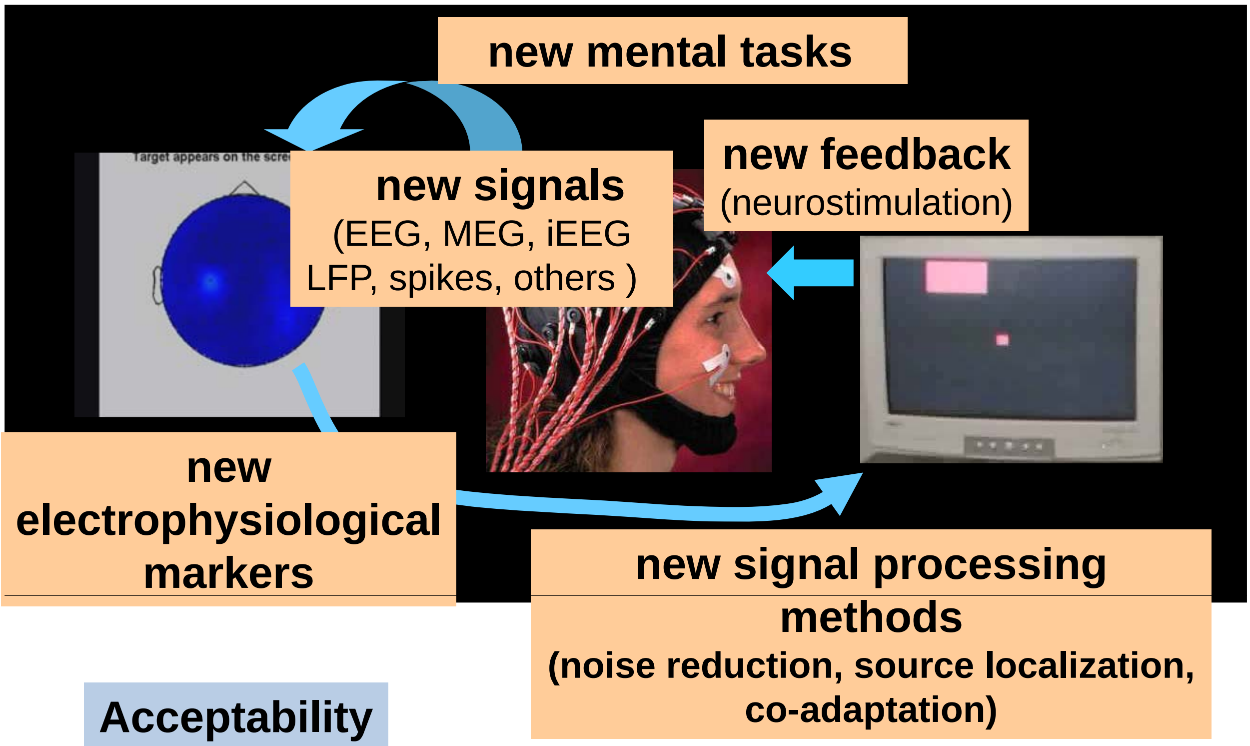
An opportunity for the development of new technologies.

Multidisciplinary challenges



**Acceptability
Ethics**