ILCB

BCI and Biofeedback Tools

Engineering Techniques,
ILCB Summer School, 01-09-2022

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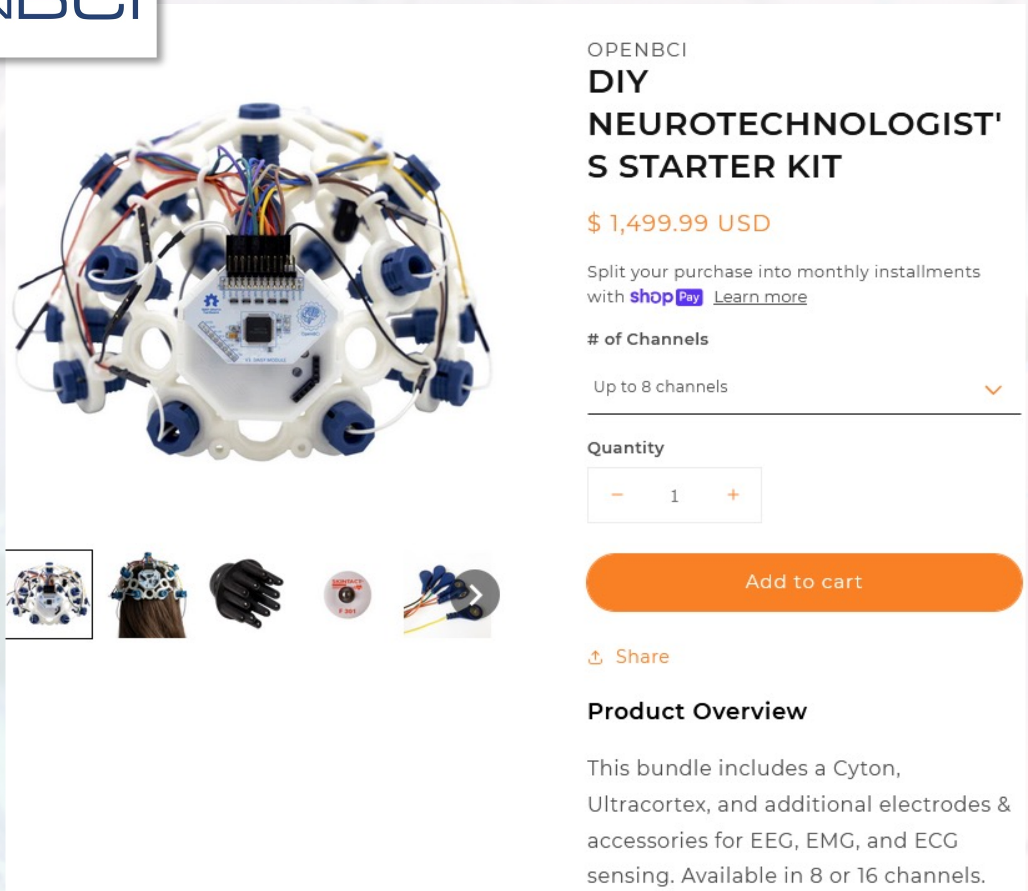
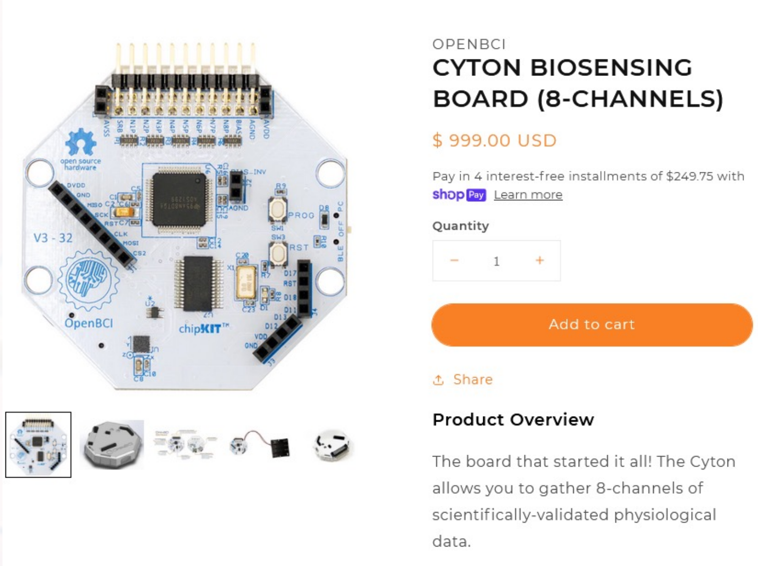
Let's start with a little demo… EEG in real time

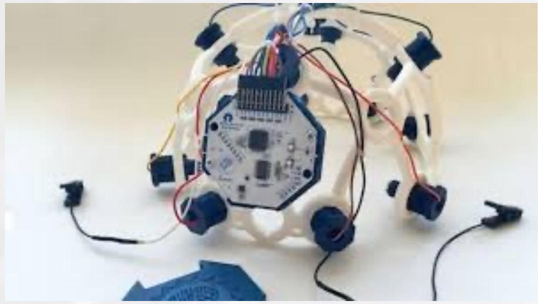
OpenBCI



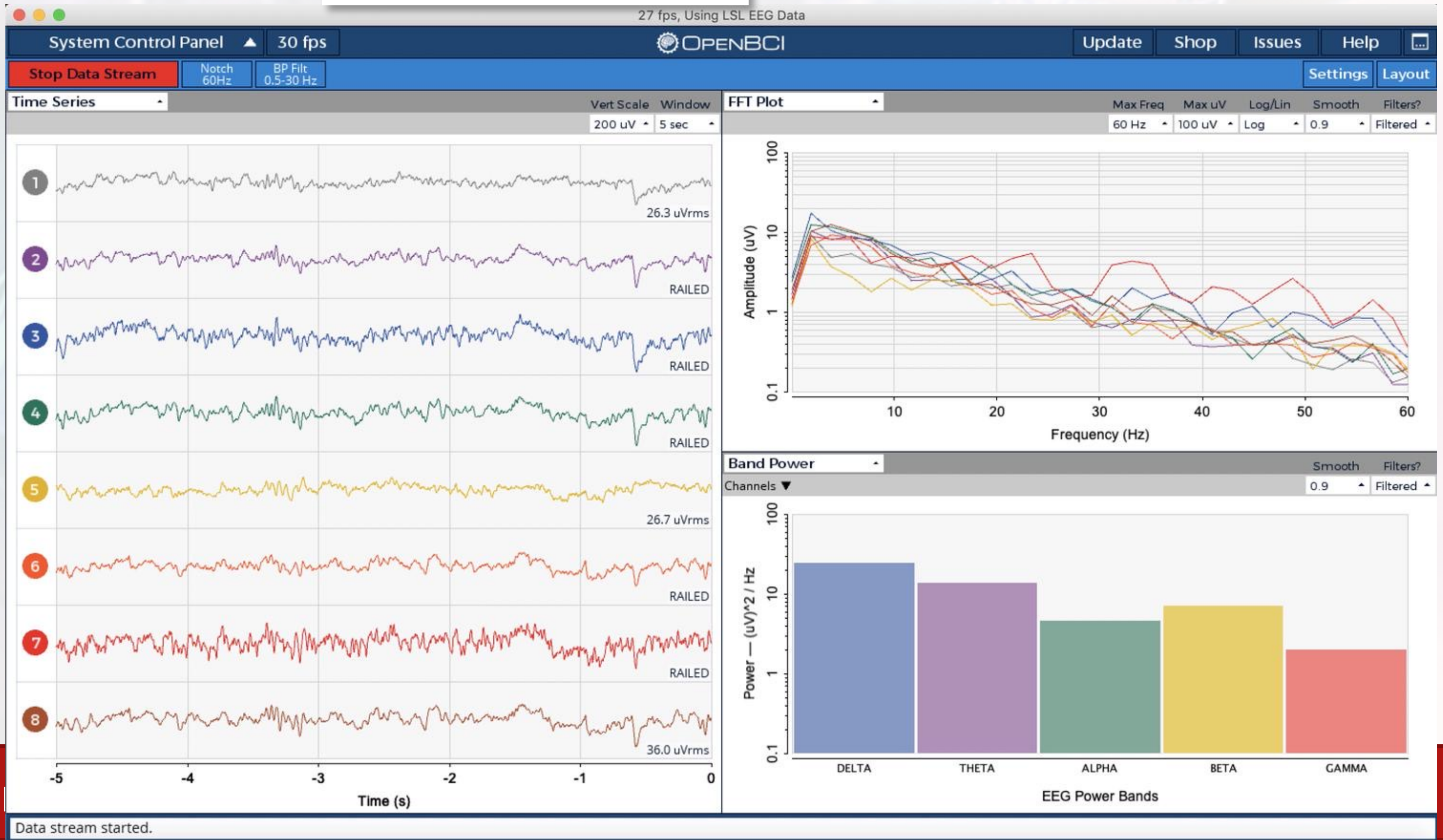


Cyton board
8-channels
Dry electrodes
250 Hz
Ultracortex Markup IV

OpenBCI



- Time series widget
- Frequency spectra
- Band power
- Networking: protocols to output data (Serial, LSL, OSC)



... Create your own widget with Processing

ARDUINO

LSL

pySerial

Applications: SSVEP-Controlled Wheelchair

« I have not failed, but I have found a 1000 ways not to make a light bulb »

Thomas Edison

Overview

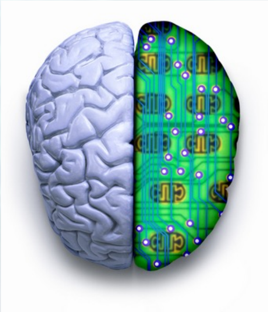
- Introduction to Brain-Computer Interface
- Motor-Imagery with almost live demonstration
- SSVEP-based BCI with (hopefully) live demonstration
- Discussion (yes, we expect you to talk too!)
- Concluding remarks.

Brain-Computer Interface (BCI): Introduction

BCI

Communication by thought

©MindAffect



Wolpaw, 2002: tools of communication and control that allow users to interact with their environment by means of their cerebral activity alone

- To consciously act and communicate without using our muscles
- give the brain a new communication channel that is independent of conventional channels

Brain-Computer Interface (BCI): Introduction

Historical Events

* **1960s** Joe Kamiya (Pr. of psychology, Berkeley) – **1st neurofeedback paradigm**, training of participant to enter the alpha state

~~~ 1970 – development of computer sciences, simple app using neurofeedback ~~~

Some attempts by music composers to produce music in real time from brain activity

* **1973** Pr. Jacques Vidal (computer science, Los Angeles) – **1st description of the concept of BCI** in "Towards direct brain-computer communication"

~~~ 90's - First real-time BCI designs ~~~

J. R. Wolpaw et al., 1991, "An EEG-based brain-computer interface for cursor control"

Brain-Computer Interface (BCI): Introduction

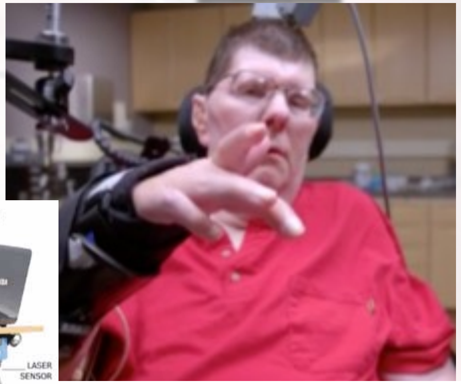
BCI Usage

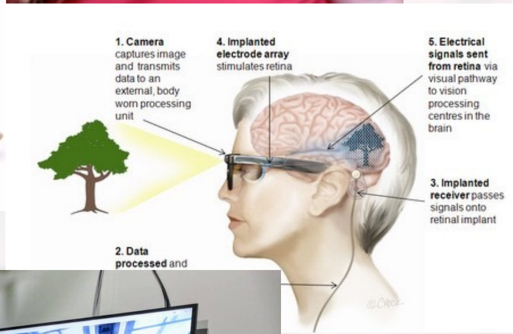
- **Replacement** of lost bodily functions
  - Communication (Speller P300, SSVEP)
  - Environment control (Prosthesis)
  - Locomotion (Wheelchair)

- **Restoration** of lost brain-limb connection
  - Neuroprosthesis (motor-imagery task)

- **Improvement** of impaired motor control after a stroke
  - Exercises with various feedbacks (virtual limb, robotised arm)

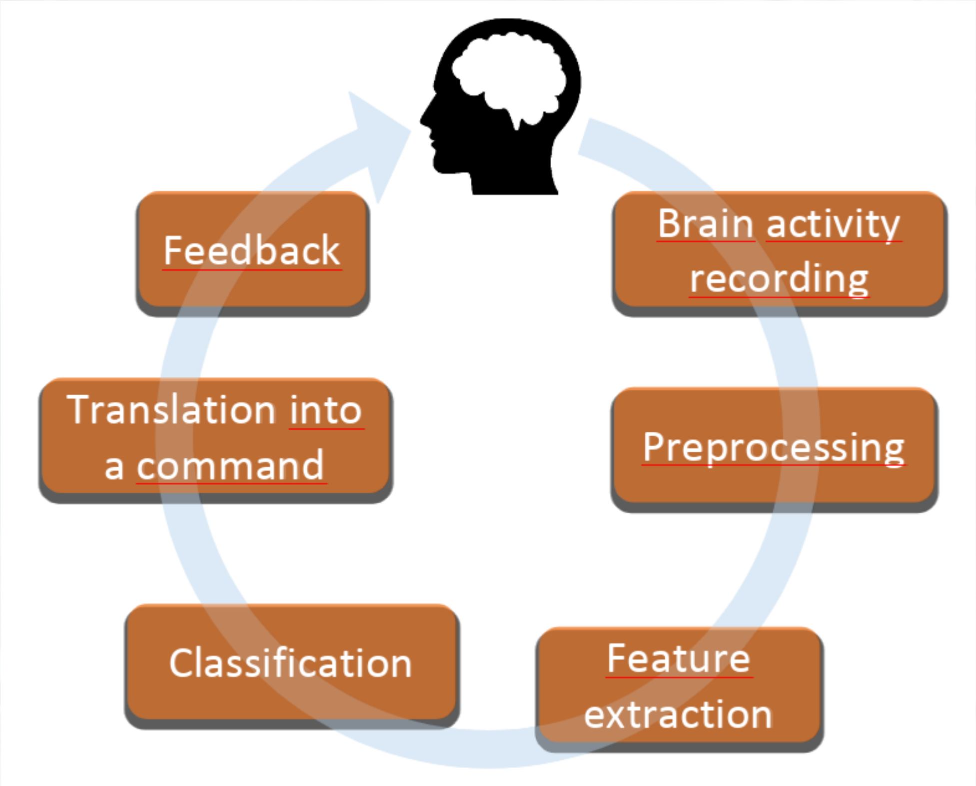
- **Enhancement**
  - Mental state monitoring (passive BCIs)
  - Home automation
  - Gaming and Virtual reality





BCI Architecture

- Closed loop system with usually 6 main stages

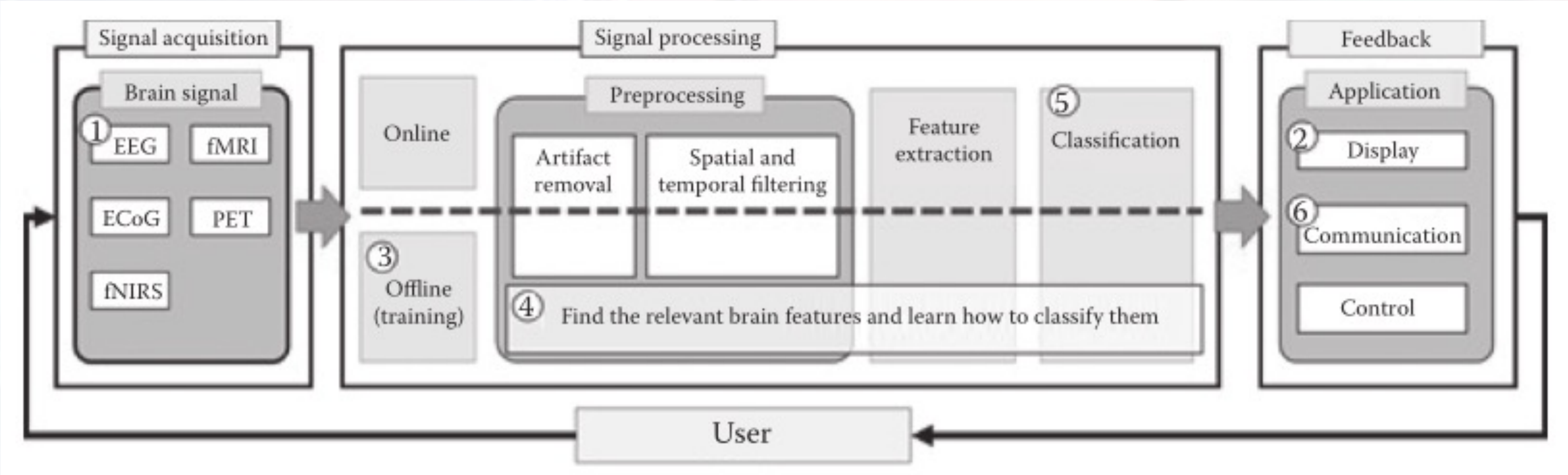


adapted from Clerc, M., Bougrain, L., & Lotte, F. (Eds.). (2016). Brain-computer Interfaces: Foundations and Methods. ISTE Limited.

BCI Architecture

Most BCIs require **two stages**:

- **offline calibration** stage: determine system's settings (costly in time)
- **online operational** stage: system recognizes brain activity patterns, translates them into application commands

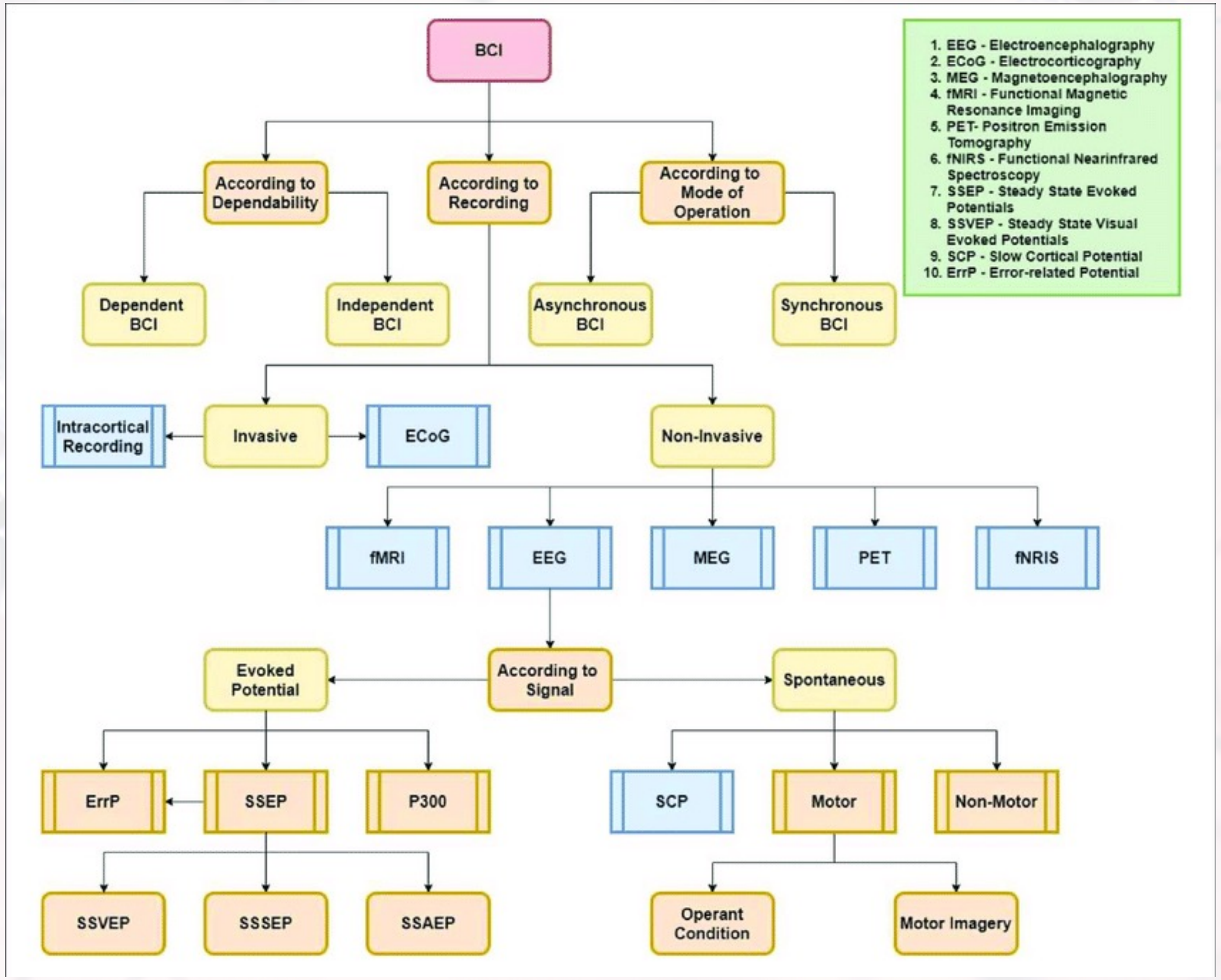


Clerc, M., Bougrain, L., & Lotte, F. (Eds.). (2016). Brain-computer Interfaces: Foundations and Methods. ISTE Limited.

Brain-Computer Interface (BCI): Introduction

BCI System Classification

- **dependent** versus **independent**
- **invasive** versus **non-invasive**
- **synchronous** versus **asynchronous**
- **active** (mental task) versus **reactive** (evoked potentials) versus **passive** (mental state, cerebral rhythms)
- Hybrid

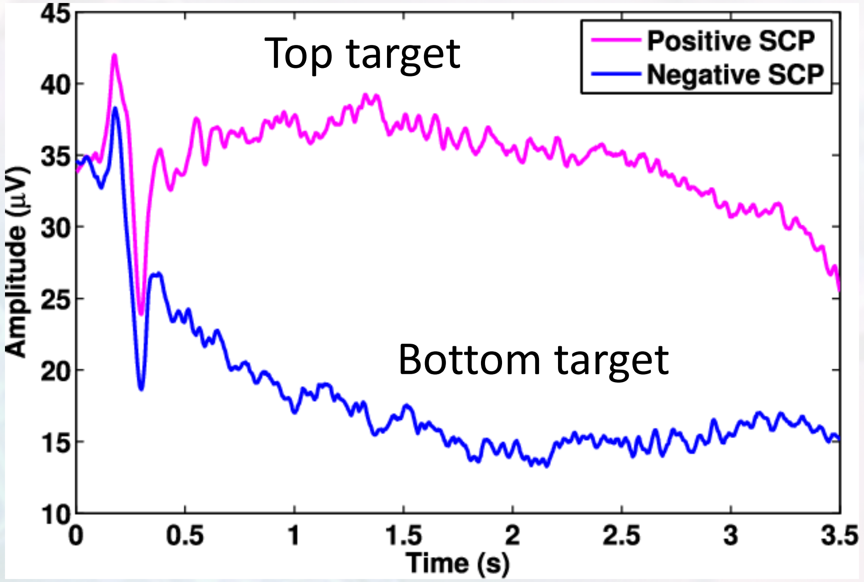


Rashid, et al. (2020)

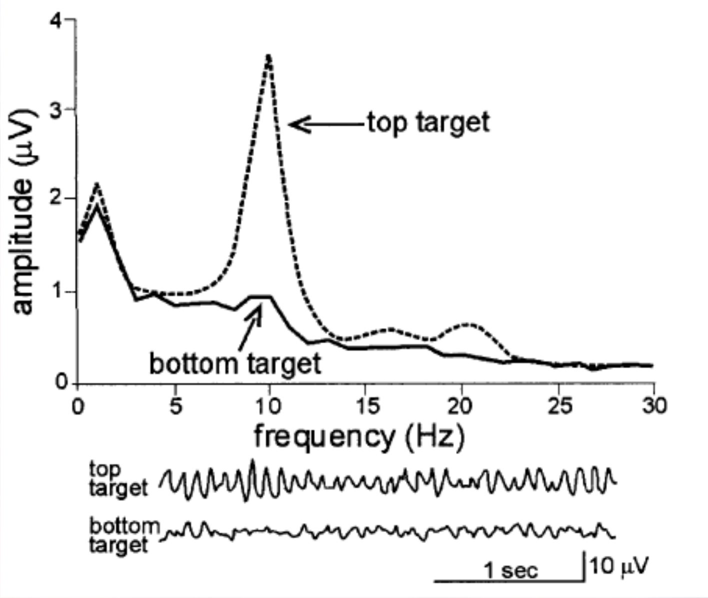
Brain-Computer Interface (BCI): Introduction

BCI Examples: Active BCIs

Slow cortical potentials



Sensorimotor rhythms (mu and beta)

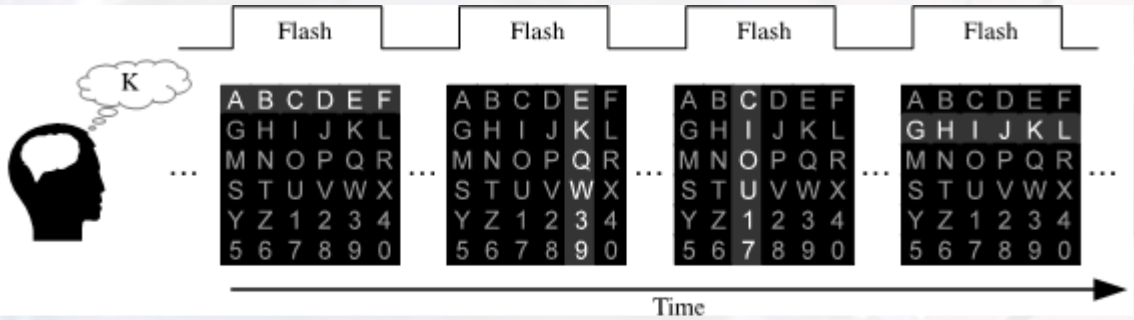


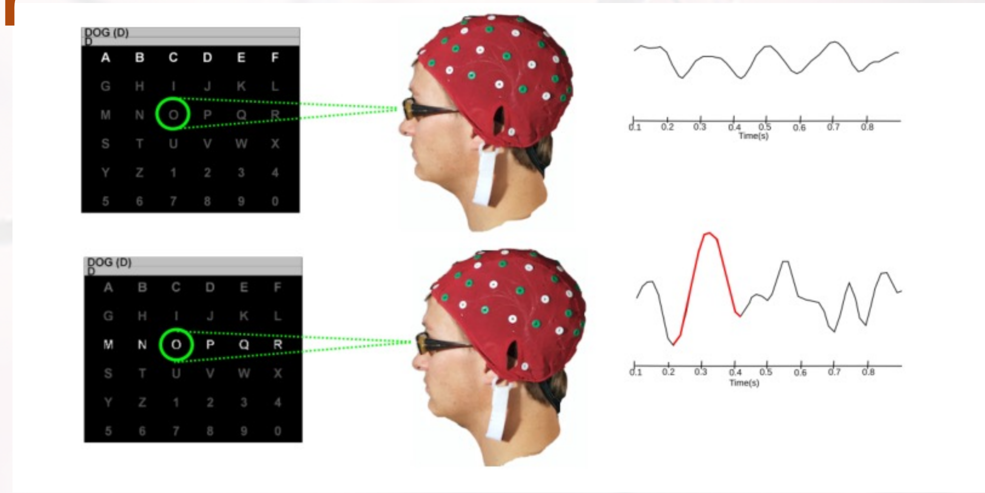
- Voluntary variations of slow cortical potentials
- Cognitive ERP: 300ms to several seconds
- Extensive training (~3 months)

- scalp EEG recorded over sensorimotor cortex
- Users control the amplitude of a 8–12 Hz mu rhythm (or a 18–26 Hz beta rhythm)

Brain-Computer Interface (BCI): Introduction

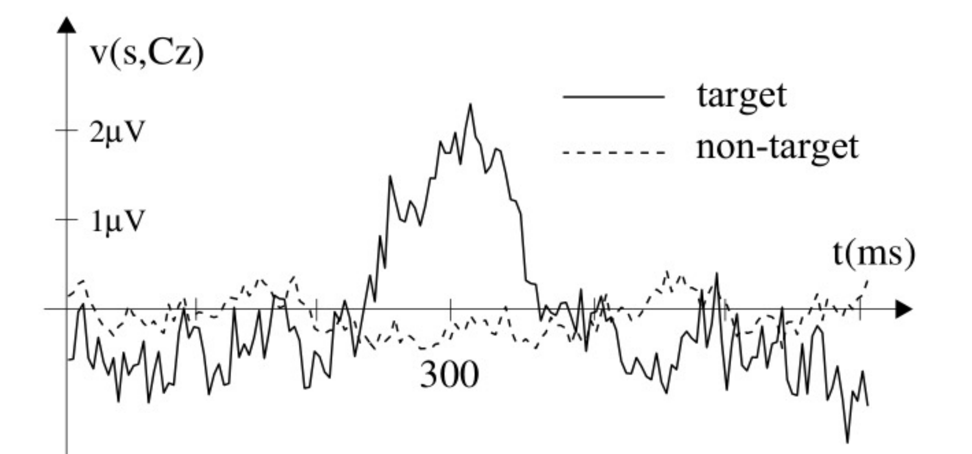
BCI Examples: Reactive BCIs - P300 Speller





- Positive cortical potential ~300 ms after occurrence of a rare, expected event (ERP) [parietal lobe]
- little training, reliable

- but:
  - computational time (integration over several several stimuli)
  - high attentional demands prevent use in complex situations (navigation, control)

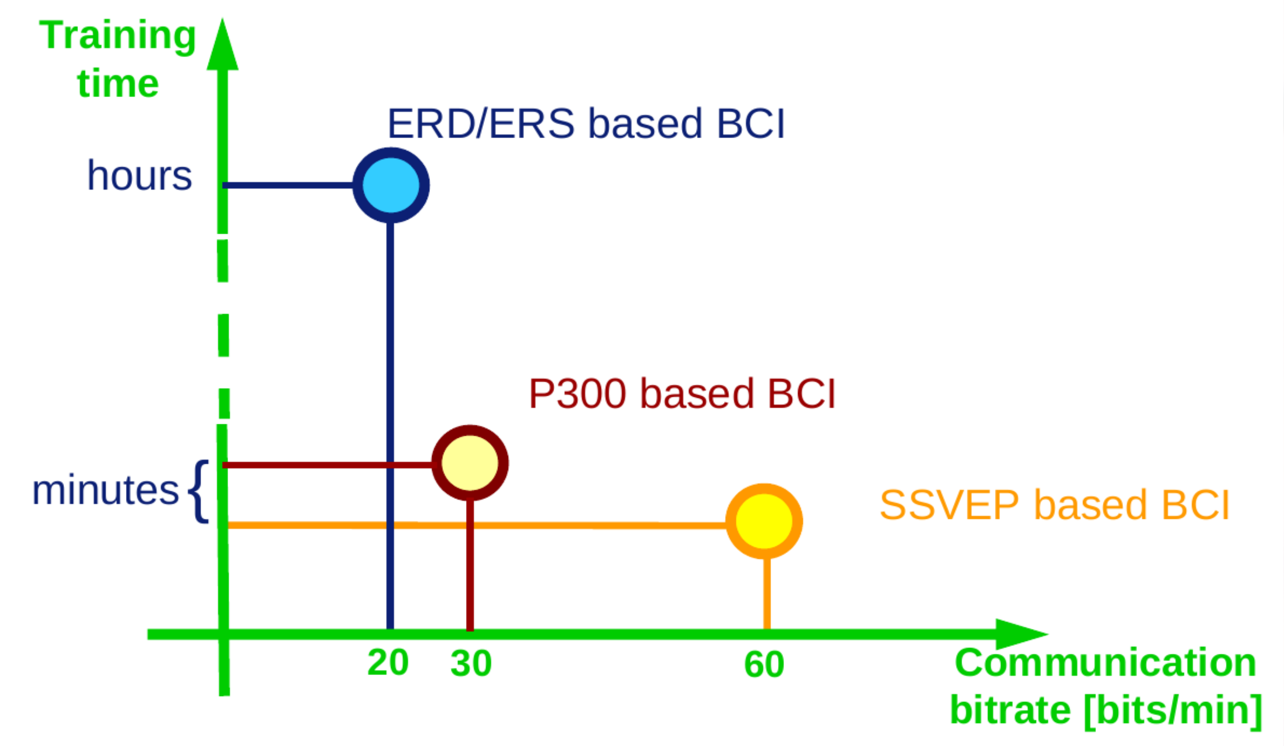


Lotte et al. (2015(

Brain-Computer Interface : P300 Speller

BCI Examples

- Mental-Imagery task - > Demo
- Evoked-Potentials (SSVEP, SSSEP, ASSEP) -> Demo



Garcia (2022)

BCI Software

Table 1: Comparison of Software for use in BCI research

	Primary Language	Python Bindings	BCI focused	Primary BCI Modules	Contributions within last year
BciPy	Python	yes	yes	yes	yes
BCI2000	C++	yes	yes	yes	no
OpenVibe	C++	yes	partial	yes	yes
PsychoPy	Python	yes	no	no	yes
Psychtoolbox	Matlab	yes	no	no	yes
PyFF	Python	yes	no	no	no
BCILAB	Matlab	yes	yes	no	yes

Table 1 Comparison of Software for use in BCI research. A breakdown of the primary programming language, python compatibility, focus on BCI, presence of all modules needed for BCI operation, and contributions within the last year. Many of these systems can operate on most modern operating systems, however maintaining compatibility with older systems is not guaranteed and acquisition devices may not provide drivers for all operating systems.

Memmott et al. (2021)

Motor Imagery – based BCI

Active BCI: Mental imagery

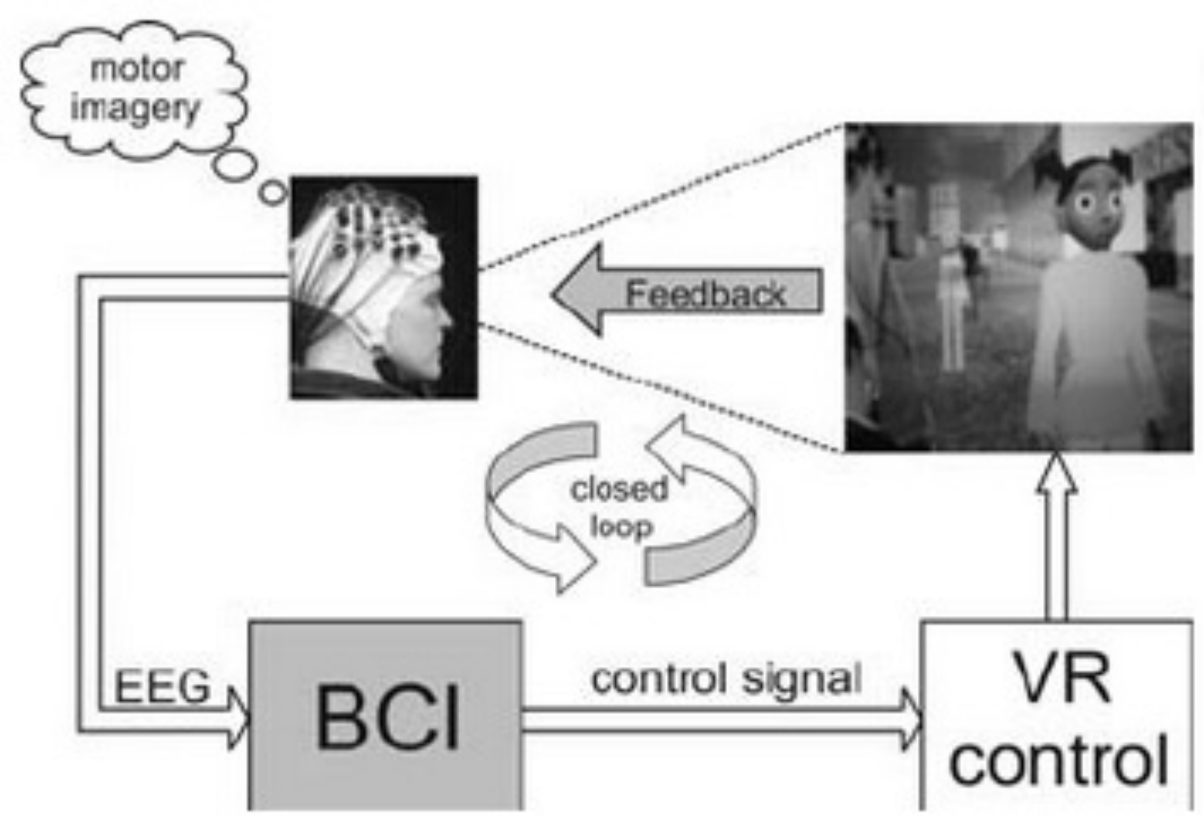
- Mental tasks: motor-imagery of the limb, mental calculation or navigation

- **Active BCI** that employs the user's **endogenous** brain activity in the absence of any external stimulus *(Pfürtscheller & Da Silva, 1999)*

- Initially: communication for paralyzed people (yes/no)

- Today: **neurorehabilitation** of stroke patients – MI neurofeedback effective in reestablishing motor movements immediately after a stroke *(Mattia 2016, Pichiorri 2015)*

Active BCI: Mental imagery



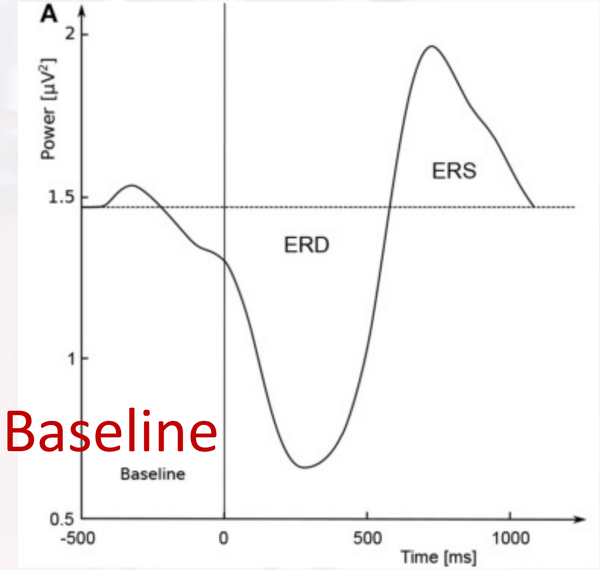
(Pfürtscheller et al 2011)

Active BCI: Mental imagery

- Mental task will induce in specific cortical regions and in specific frequency bands:

1°) Event-Related Desynchronisation (ERD – while being performed)

2°) Event-Related Synchronisation (ERS – once the user has stopped)

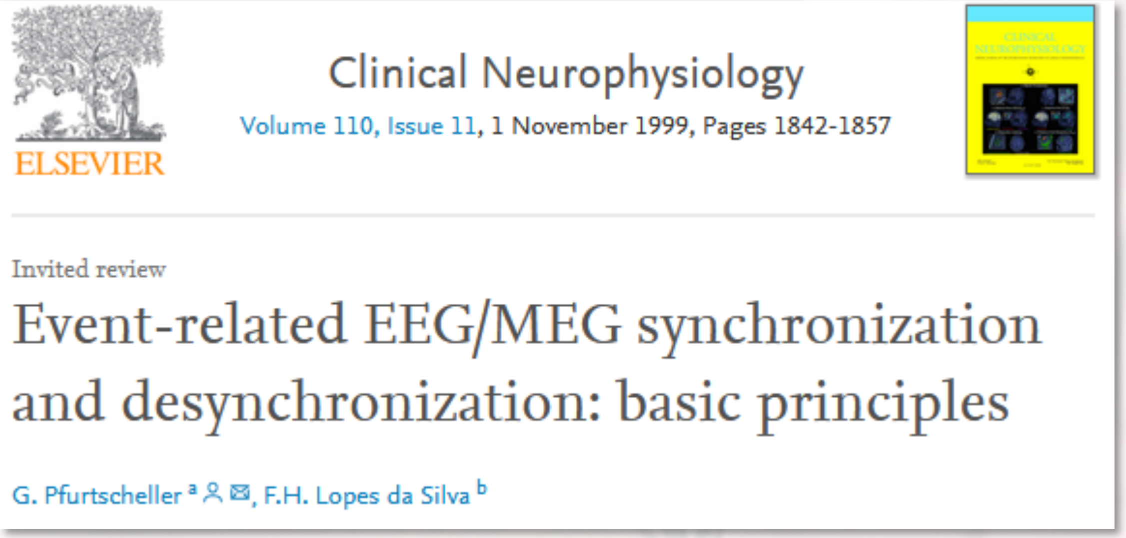


t=0 s start of the imagery movement

(adapted from Lemm et al., 2009)

Event-Related Desync/Synchronization

- Decrease or increase in synchrony of the underlying neuronal populations reflecting cortical activation and deactivation *(Pfurstcheller & Da Silva, 1999)*



Clinical Neurophysiology

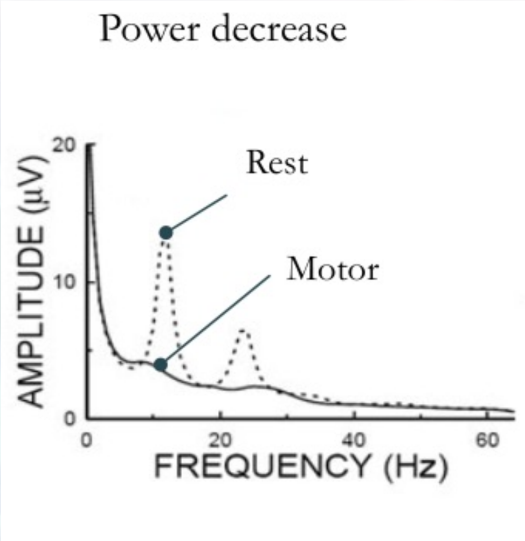
Volume 110, Issue 11, 1 November 1999, Pages 1842-1857

ELSEVIER

Invited review

Event-related EEG/MEG synchronization and desynchronization: basic principles

G. Pfurtscheller [a], F.H. Lopes da Silva [b]

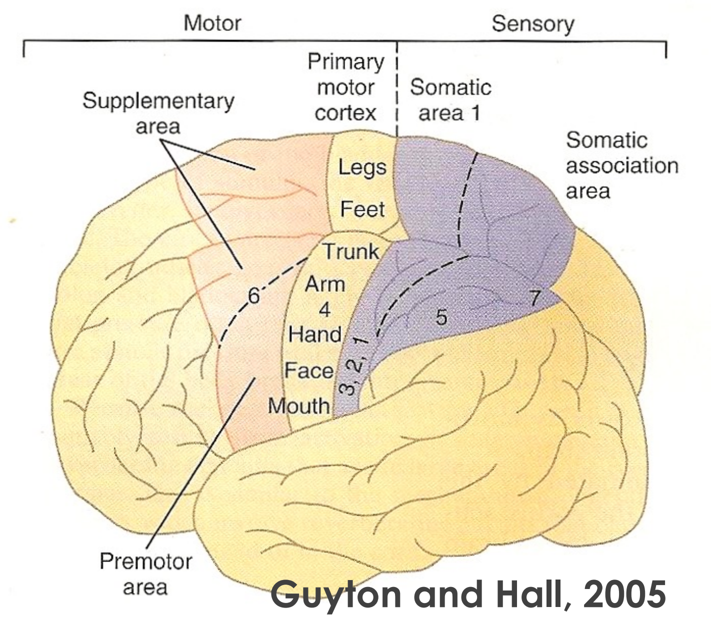


Desynchronization effect
(Pfurtscheller et al, 1999)

Rest vs Motor

Neuronal networks become asynchronous during mental activity;
ERD – correlated with mental **activity**;
ERS – correlated with mental **inactivity**

Motor-imagery



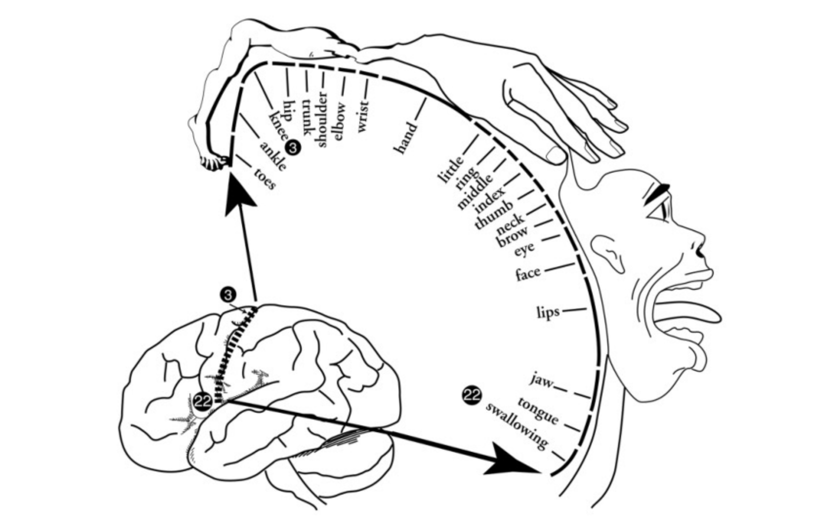


Figure 2.2: The Wilder Penfield Homunculus: the drawing of the limbs along the M1 region shows the regions responsible for generating a motor control signal to different parts of the body.[Adapted from [19]]

- The Primary Motor Cortex (PMC) is responsible for planning and executing movements
- Correspondence between the PMC areas and the various muscle groups

Motor-imagery

- Movements tasks induce changes to brain activity (ERS/ERD)

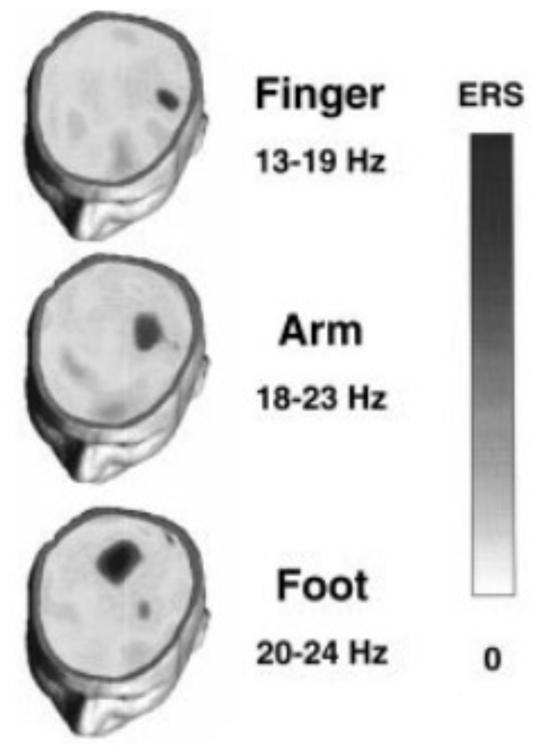
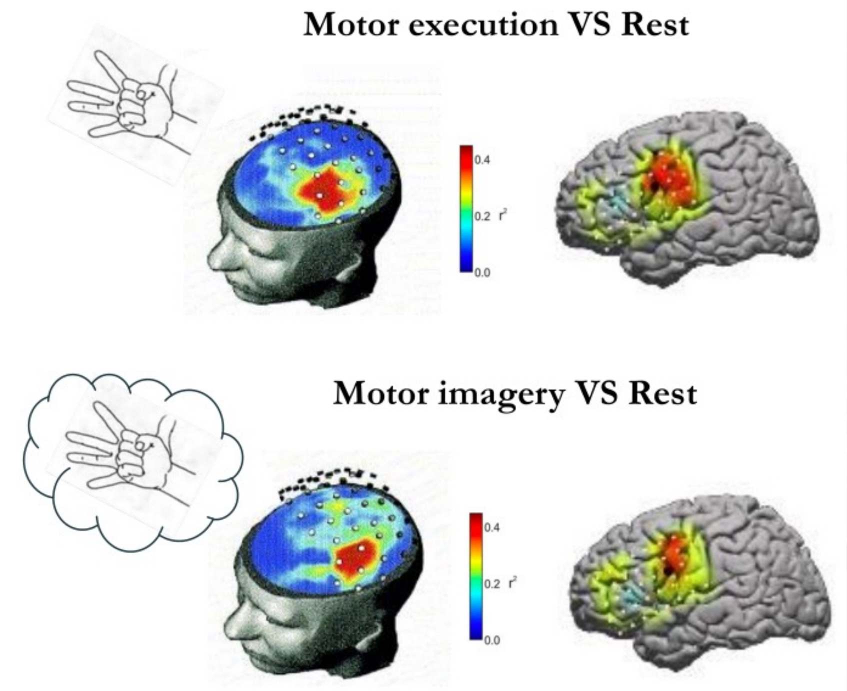
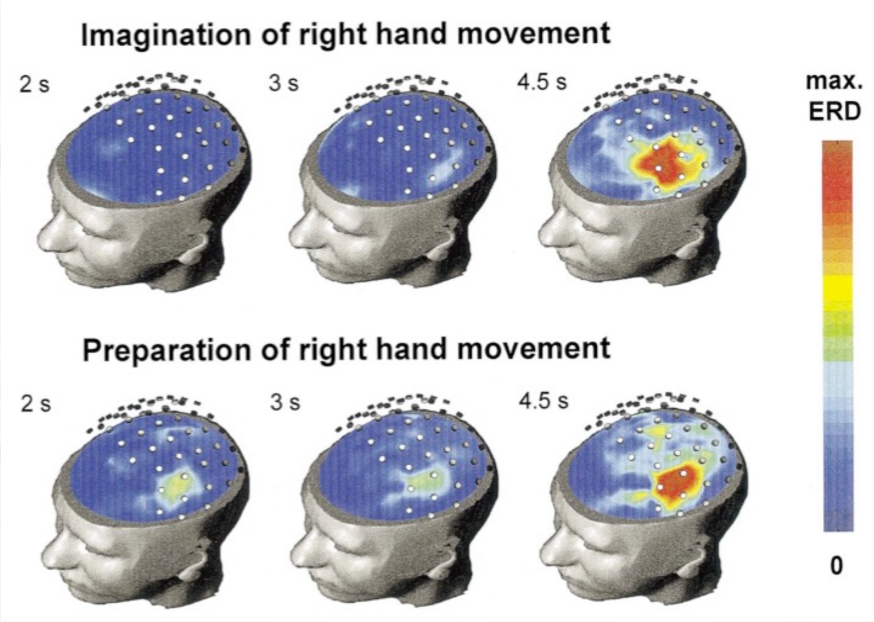


Fig. 10. Movement-specific location of the beta ERS in one subject displaying a somatotopic organization of the beta oscillations after finger, arm and foot movement. Note the different subject-specific frequency bands lowest with finger and highest with arm and foot movement, respectively. 'Black' indicates location of maximal ERS.

Pfurstcheller & Da Silva, 1999

Motor-imagery





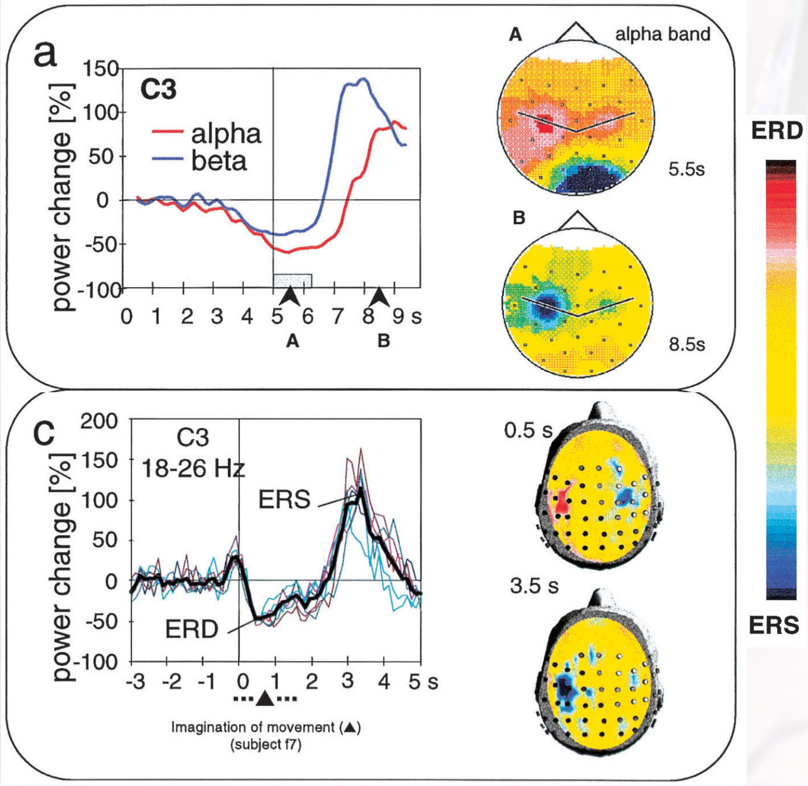
- Synchro and Desynchronisation of brain waves at motor cortex areas, whether by preparing the movement of the body or by imagining it

Motor-imagery

- Movements tasks induce changes to brain activity visible in the EEG

α/μ
8-12 Hz

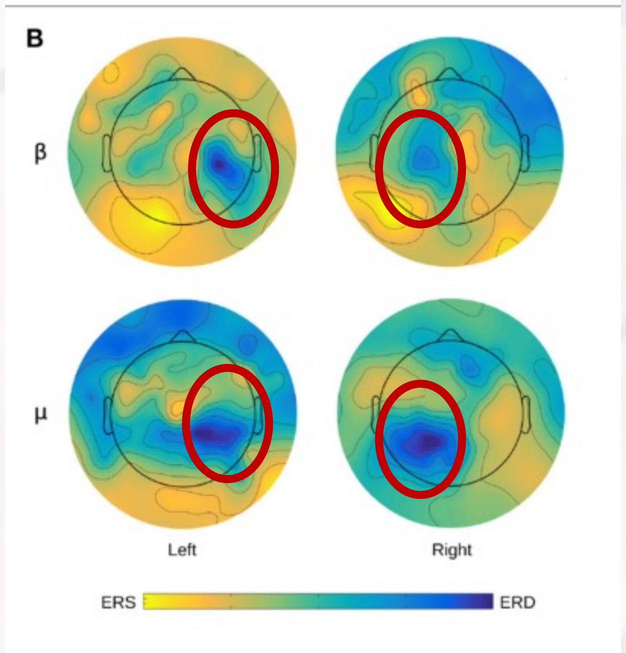
β
18-26 Hz



Right hand

Pfurstcheller & Da Silva, 1999

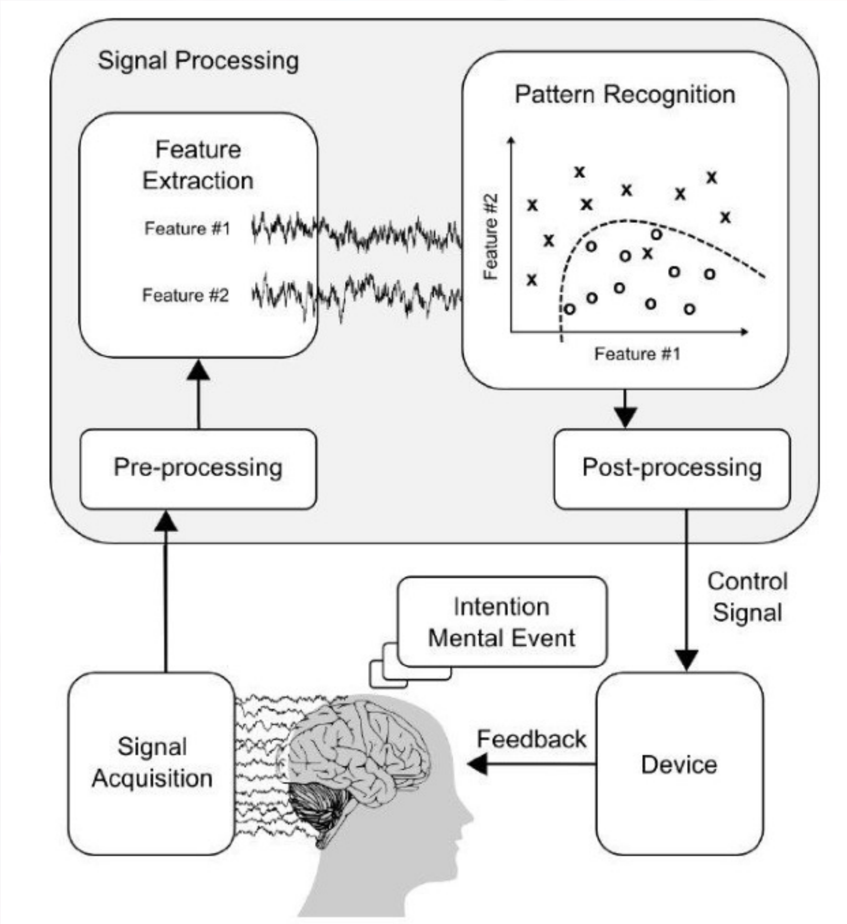
Topographic map



Left hand Right hand

Features to be captured in BCI

Motor imagery



Hoffmann et al., 2006 : "A good feature extraction method should reduce the dimension of the input data as much as possible while keeping all the information necessary for classification."

Motor imagery: Graz protocol

I- training the system

Series of MI-task (ex. Left/Right)

[feature extraction to train a classifier]

II- training the user

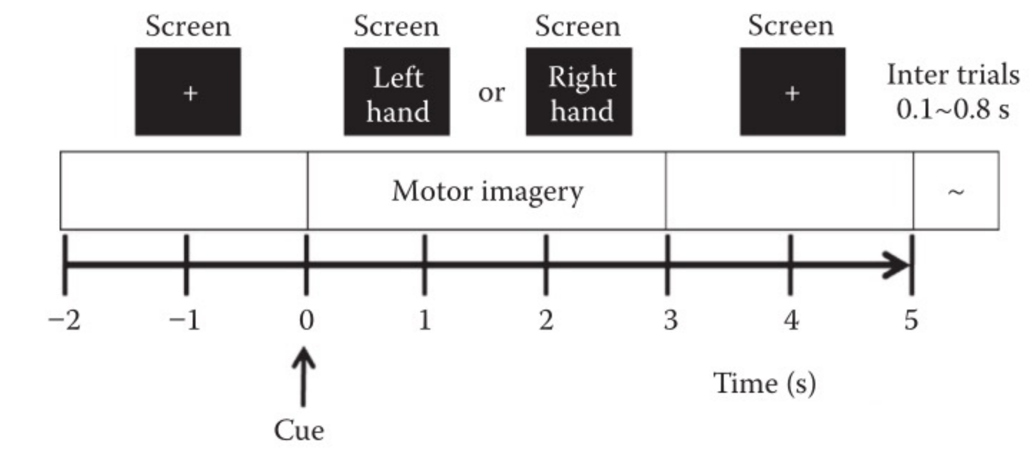
MI-task with feedback.

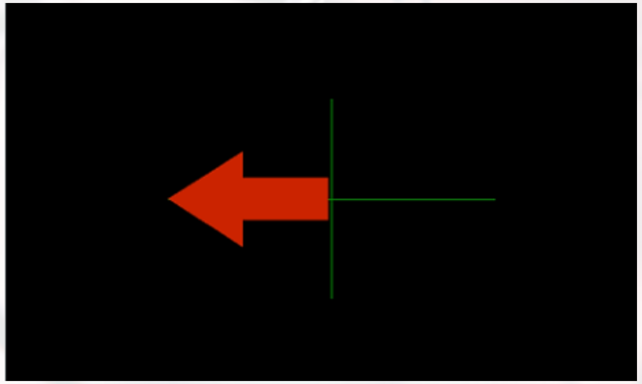
User goal: to develope effective strategies to increase system performance

Pfurtscheller & Neuper, "Motor Imagery and Direct Brain-Computer Communication", 2001

Graz protocol

Offline





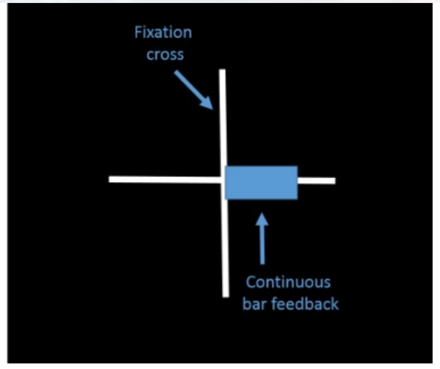
Indication of which MI task is to perform

Multiple sessions, each of which multiple sequences (4-6 runs - fatigue>6)

One run:

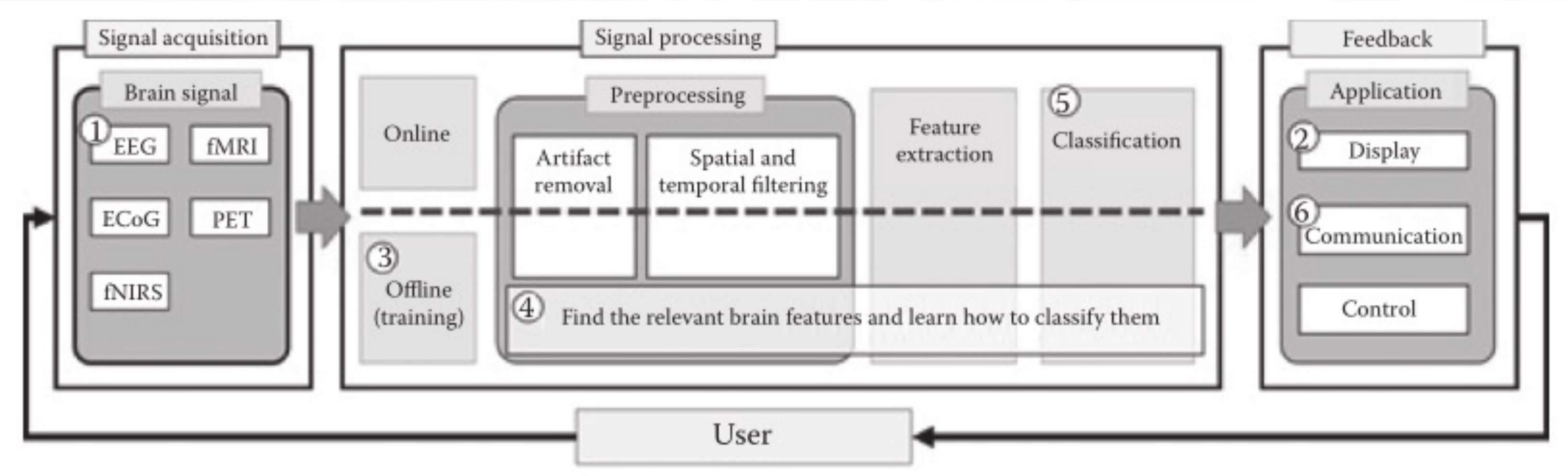
- 10-20 trials per class (Left/Right)
- ~ 7 min

Online



Feedback

Motor imagery



(1) an offline calibration stage, during which the system's settings are determined

(2) an online operational stage, during which the system recognizes the user's brain activity patterns and translates them into application commands

BCI research community is currently searching for solutions to help avoid the costly offline calibration stage

OpenVibe

openvibe.inria.fr

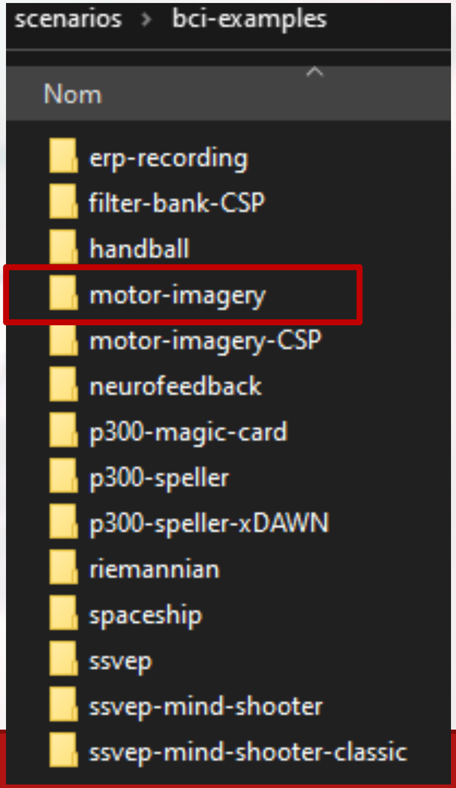
An open-source software platform
- Design, test and use BCIs
- Real-time EEG acquisition, processing and visualization
- Offline or batch analysis of large datasets

Wide EEG device compatibility (EGI, Brainamp, Biosemi,… C++ driver)

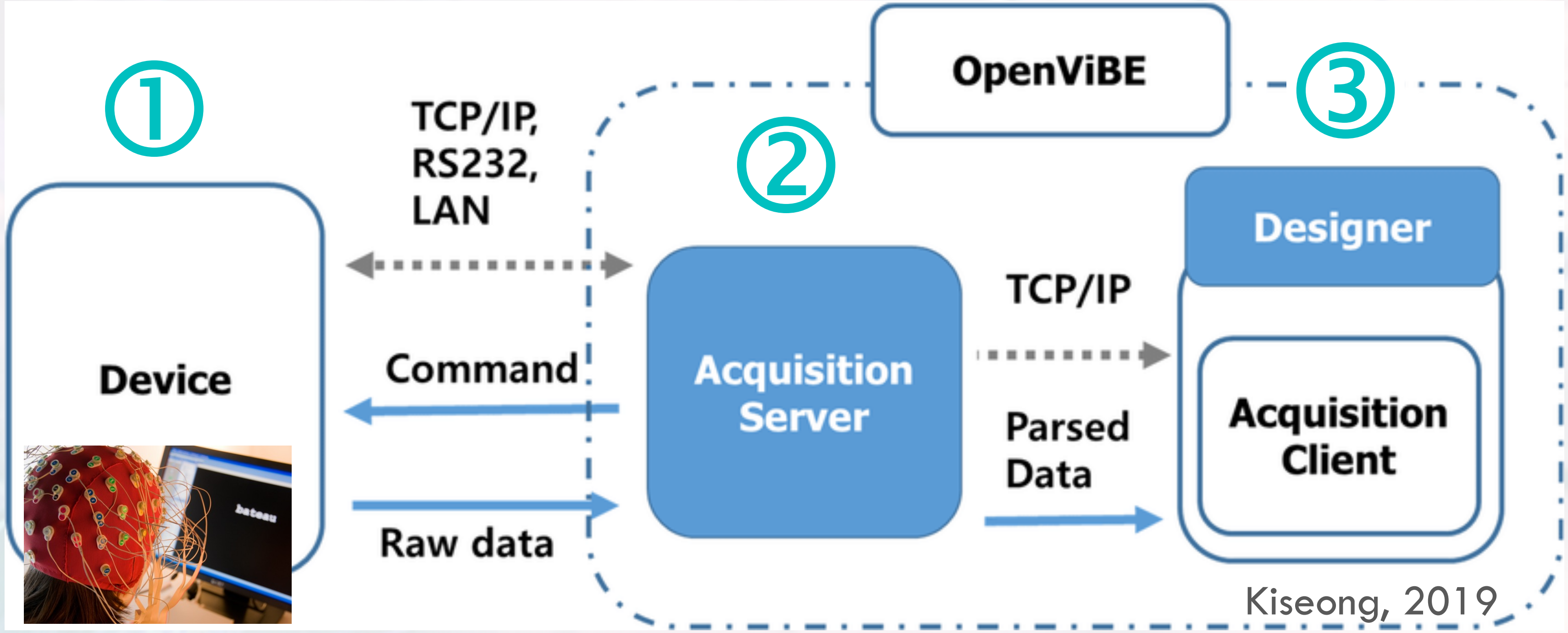
Compatibility with &

BCI paradigm demos available + tutorials

Visual programmation (GUI boxes) + own plugin development in C++



OpenVibe working flow

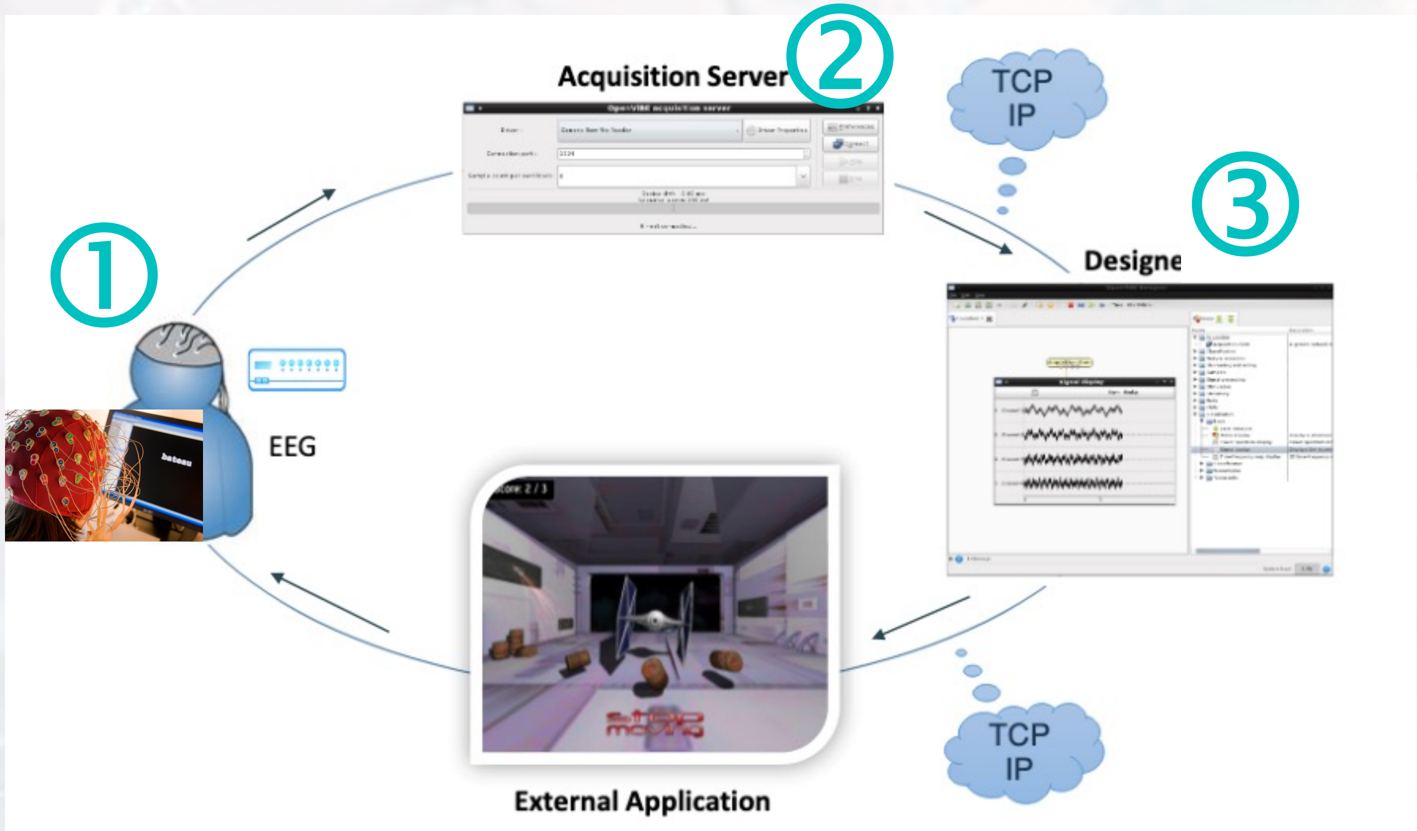


Dotted gray: communication protocol, solid blue: data flow, and colored boxes represent processes.

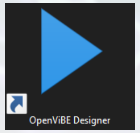
Acquisition server: Configuration to receive raw data depending on the device system

Designer: Define and Launch stimulation, online and offline data processing

OpenVibe working flow



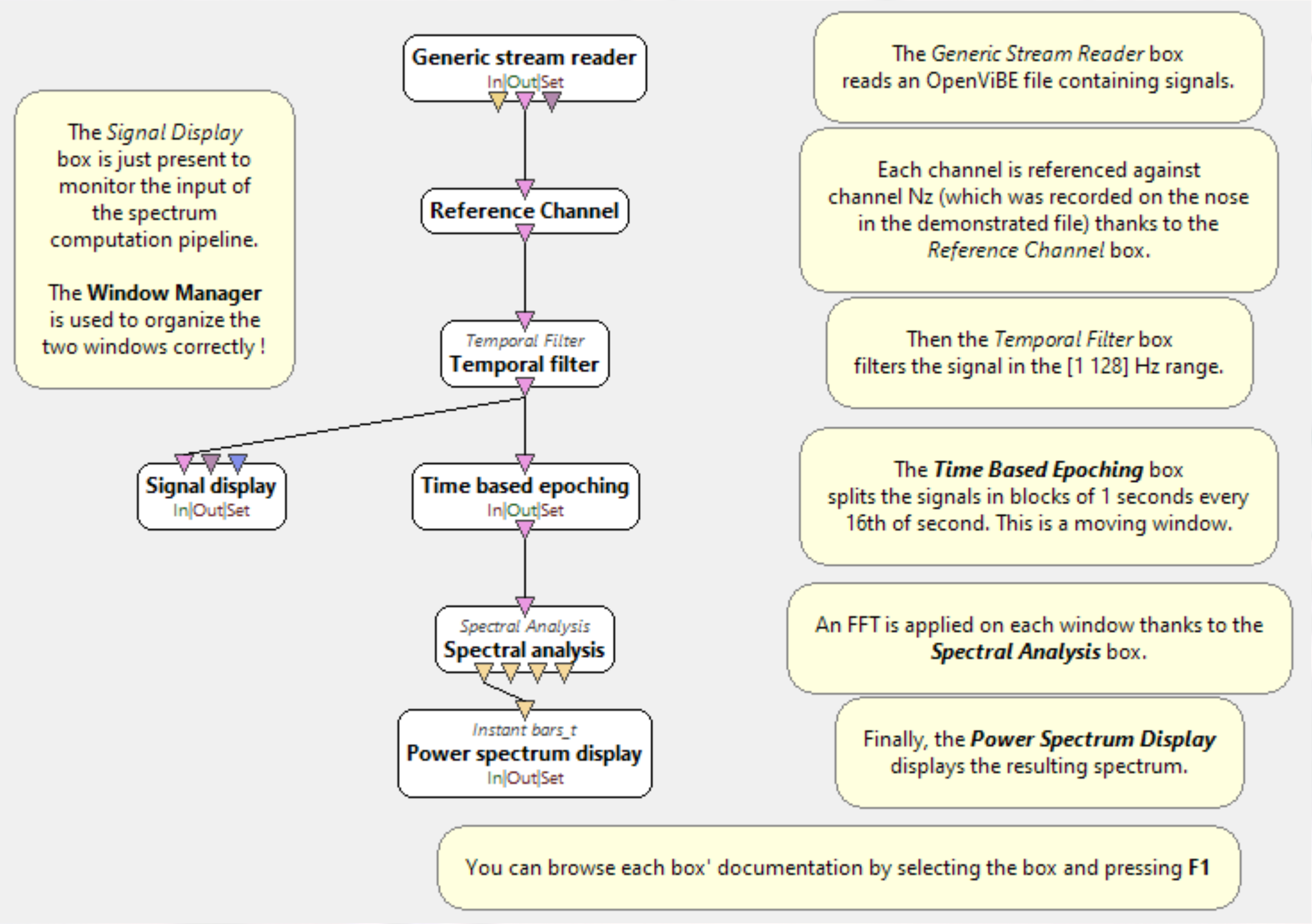
Acquisition server: Configuration to receive raw data depending on the device system



Designer: Define and Launch stimulation, online and offline data processing

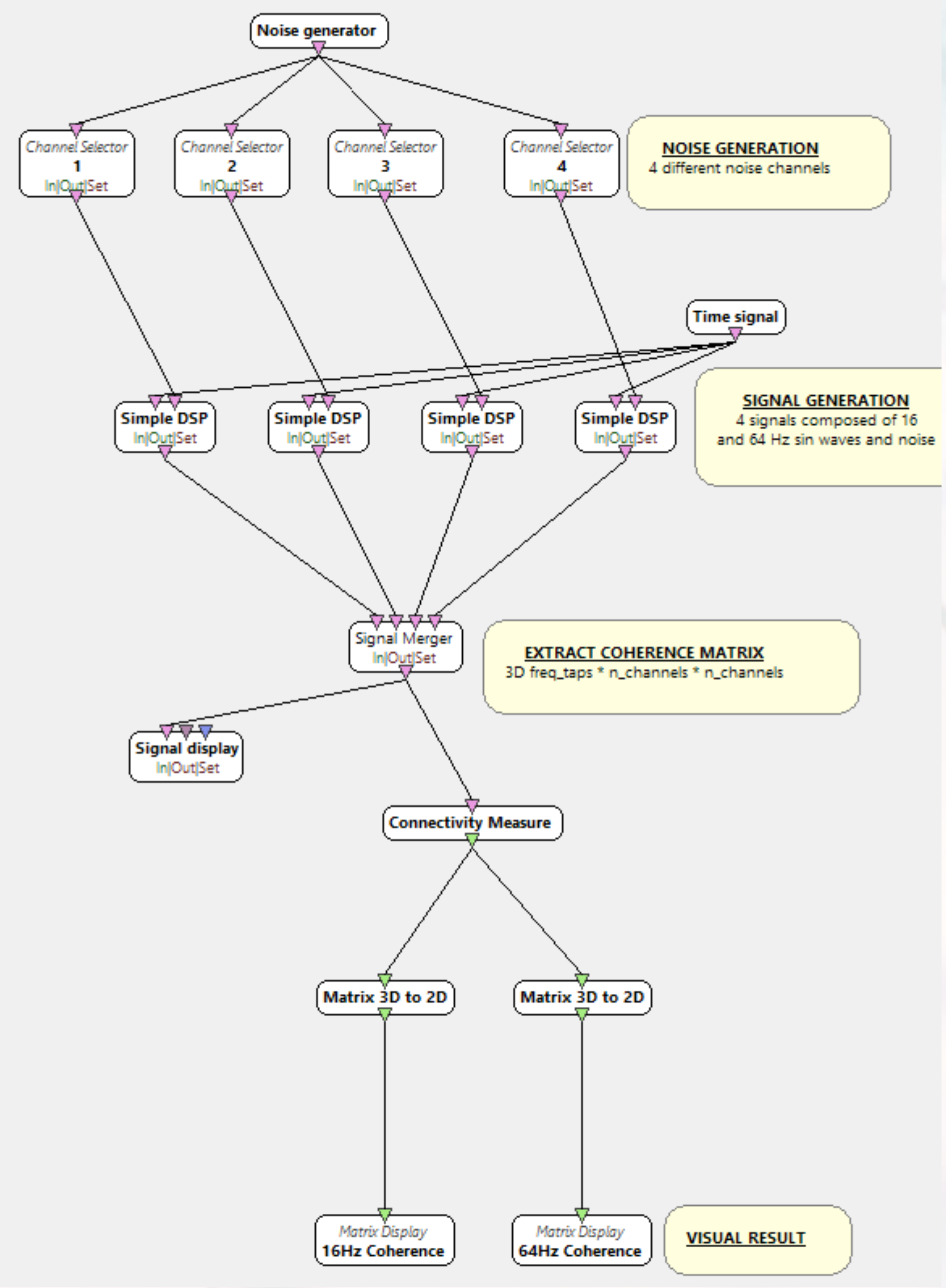
Openvibe – Box tutorials

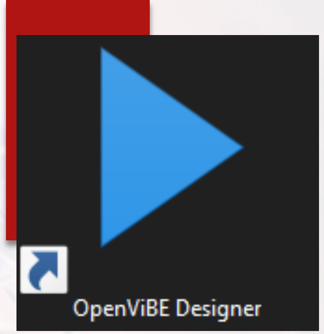
power-spectrum.xml



Openvibe – |

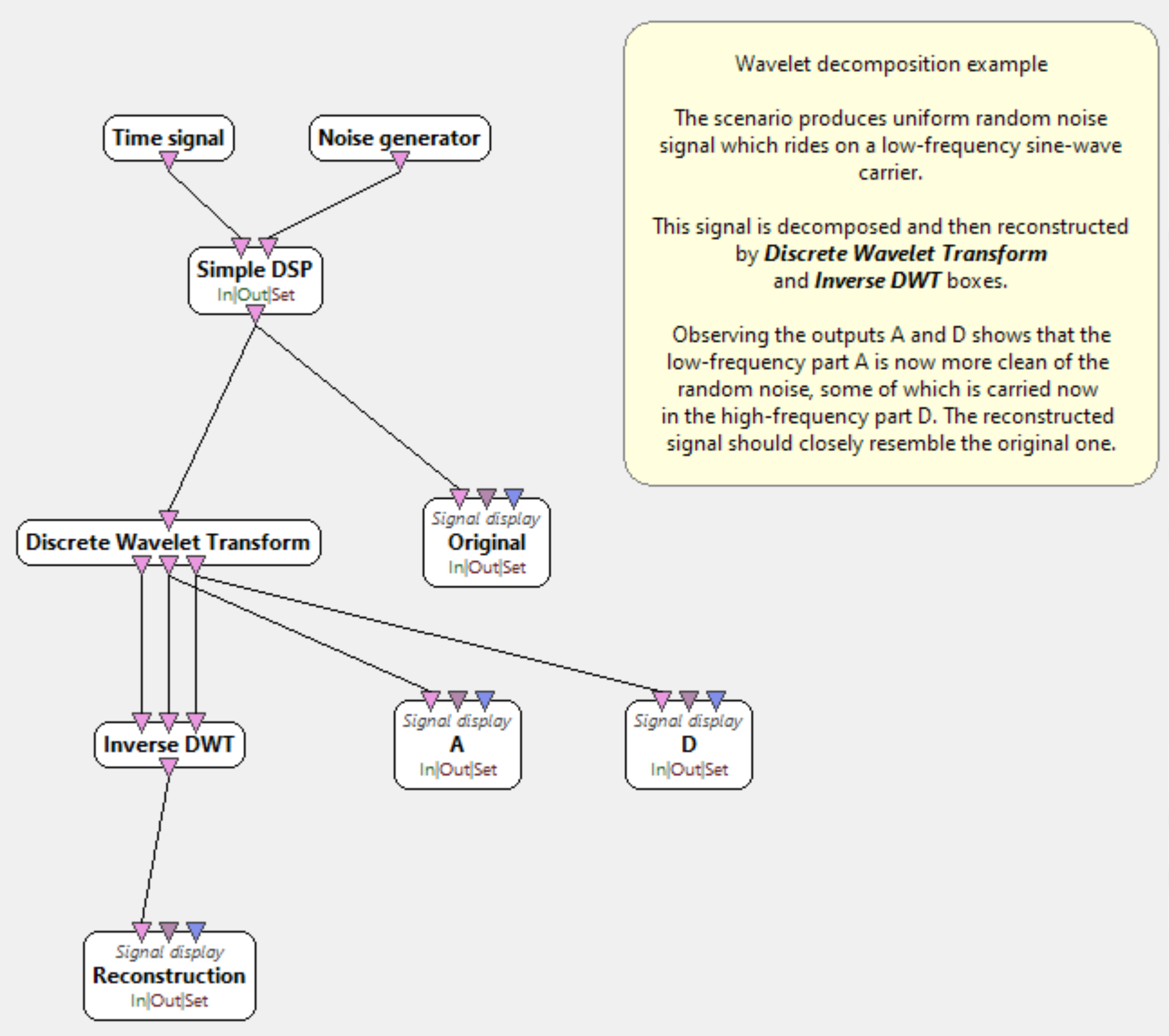
connectivity_measure

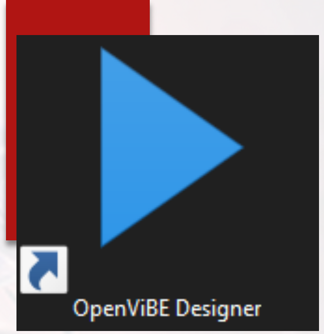




Openvibe – Box tutorials

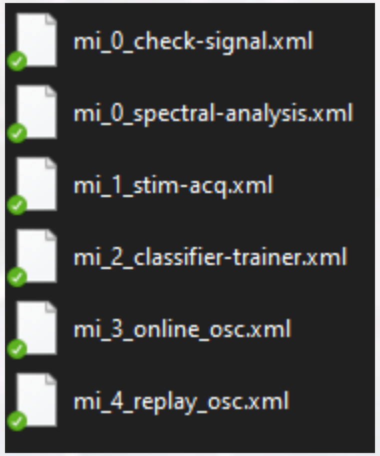
wavelet-decomposition

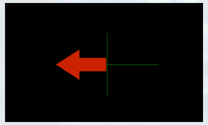




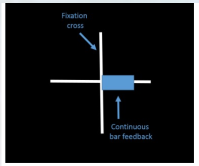
Artifact removal, PCA, Machine learning…

Openvibe: Graz protocol + OpenBCI

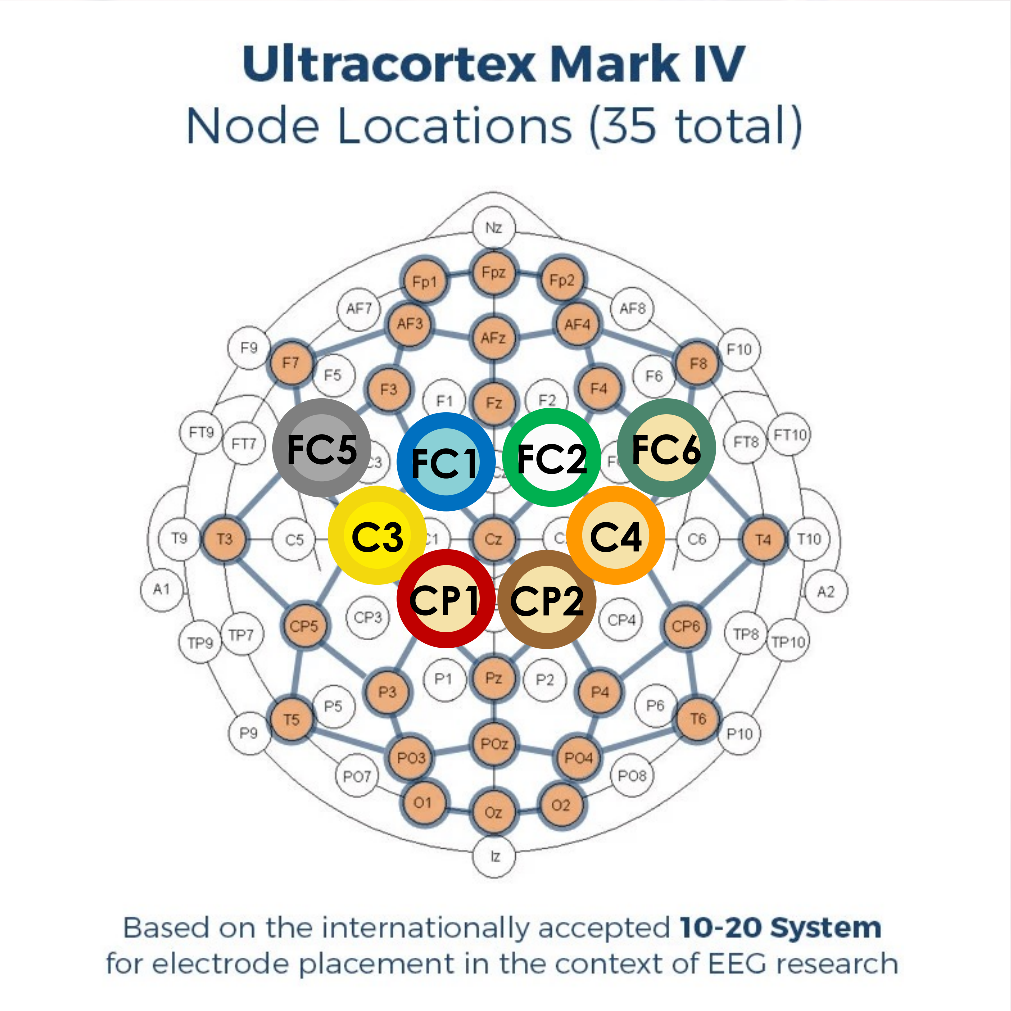




- mi_1_stim-acq: stimulation (L/R) while recording the training data set
- mi_2_classifier-trainer: classifier parameters estimate
- mi_3_online_osc: classification in real time with feedback



+ send command by OSC to a [web app]



Motor imagery: data processing pipeline

Spatial filter
Surface Laplacian

↓

Temporal filter
Band-pass 8–24 Hz

↓ ↓

Stimulation based epoching Left MI task *0.5 to 4.5 s*	Stimulation based epoching Right MI task *0.5 to 4.5 s*
Mean power *$log(1 + x^2)$*	Mean power *$log(1 + x^2)$*

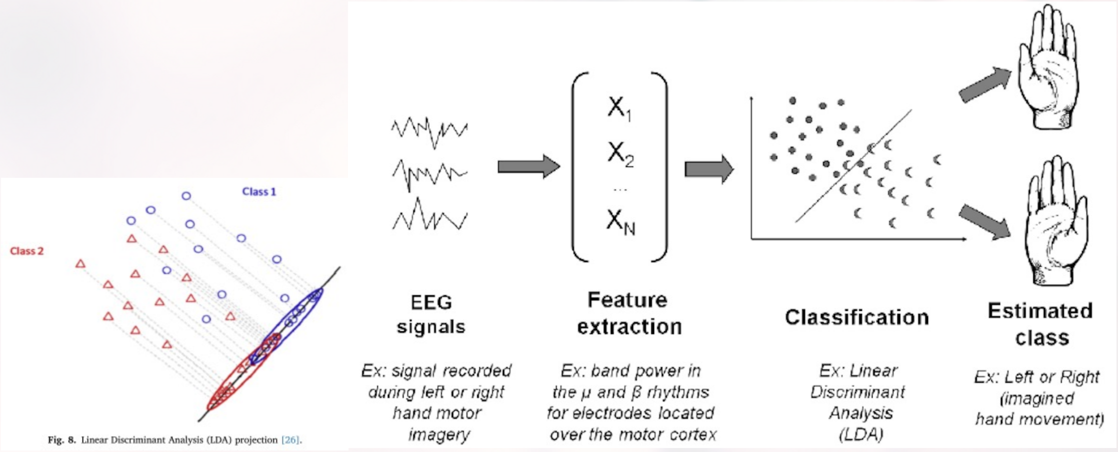
↓ ↓

Classifier trainer
Linear Discriminant Analysis

2 output channels:

- **Left side:** 3*C3 – (FC5 + FC1 + CP1)
- **Right side:** 3*C4 – (FC6 + FC2 + CP2)

α/μ: 8-12 Hz
β: 18-26 Hz



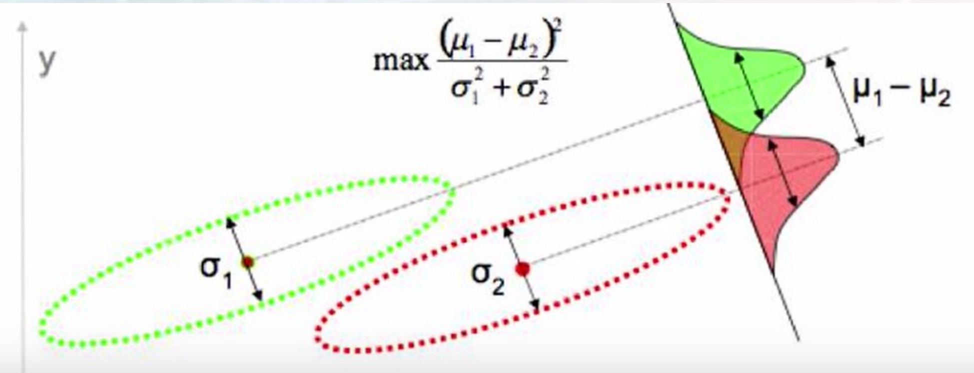
- find a linear discrimination of the two features

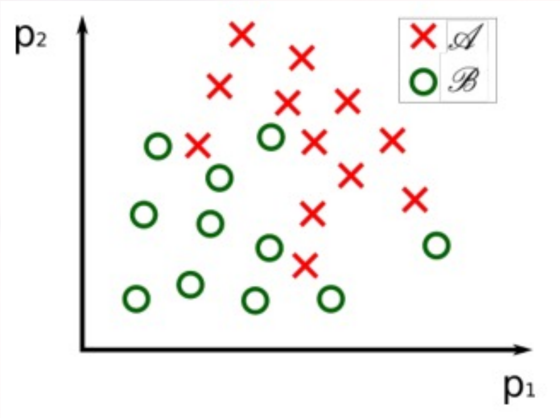
Linear discriminant Analysis

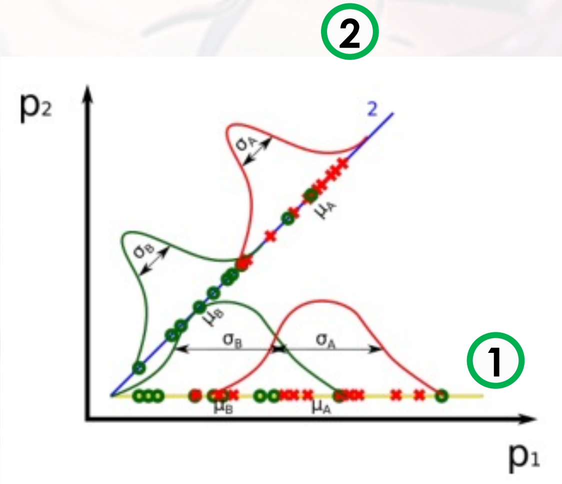
- Find the projector line that gives:

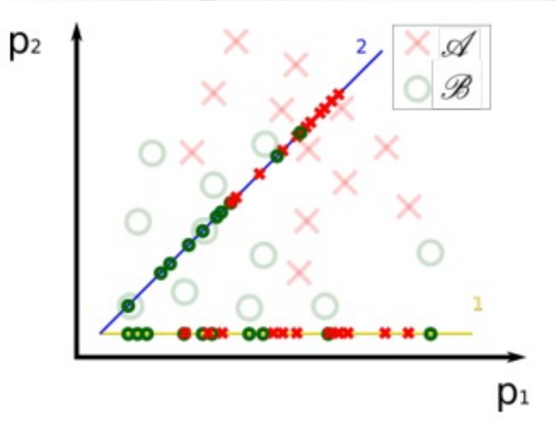
- maximum separation between means of projected classes
- minimum variance within each projected class

- Solution: eigenvectors based on between-class and within-class covariance matrices









Example - Projector 2: best discriminant

Openvibe: Graz protocol + OpenBCI

- Multiple sessions with Franziska

- Low classification accuracy by imagining the movement (60% with the Left class being better discriminated)

```
Cross-validation test accuracy is 55.836040% (sigma = 5.424622%)
  Cls vs cls       1      2
  Target  1:    58.5  41.5 %, 1020 examples
  Target  2:    46.9  53.1 %, 1020 examples
Training set accuracy is 60.441176% (optimistic)
  Cls vs cls       1      2
  Target  1:    63.4  36.6 %, 1020 examples
  Target  2:    42.5  57.5 %, 1020 examples
```

- By actually doing the movement: good accuracy (92%!) – classification based on the mu-beta features is very reliable

```
Classifier trainer> Cross-validation test accuracy is 92.354288% (sigma = 7.365529%)
Classifier trainer>   Cls vs cls       1      2
Classifier trainer>   Target  1:    97.1   2.9 %, 1020 examples
Classifier trainer>   Target  2:    12.4  87.6 %, 1020 examples
Classifier trainer> Training set accuracy is 92.156863% (optimistic)
Classifier trainer>   Cls vs cls       1      2
Classifier trainer>   Target  1:    96.9   3.1 %, 1020 examples
Classifier trainer>   Target  2:    12.5  87.5 %, 1020 examples
```

Motor imagery

- Co-adaptation user/machine - substantial training to find the correct imagination strategy that leads to the most distinct ERD/ERS

- Currently it can only be used with a maximum of 3 or 4 different MI tasks to ensure maximal performances (classification accuracy)

BCIs improvement

« Illiterate users »

Most current systems do not properly establish this mutual understanding

- 10 to 30 % of users unable to control a BCI: “BCI illiteracy” or “BCI deficiency” phenomenon
- MI-BCI : even for not “illeterate”, performance rather low
  - 75% of classification accuracy for 2 class MI-BCIs
  - 20% reach 80 to 100%
- 2 main factors

  (1) Signal processing (Stage I) – many studies over the last years
  (2) The user-training role: mostly neglected – inefficient training protocol (instructions, training tasks, feedback and training environment)
- Controlling an BCI requires acquisition of specific skills = to generate stable and distinct brain activity patterns while performing the tasks
- Understand how the humain learn and how to adapt training process

BCIs improvement

Summary guidelines for designing more effective training protocols (C. Jeunet)

Training task

Progression (increasing difficulty), adaptative user-specific
Self-paced and asynchronous sessions
Preparatory training tasks (meditation)

Feedback

Visual with emotional connotations (smileys) – tactile is promising (channel much less saturated in interactive situations) / increase the quantity and quality of information (topography of cerebral activity…)

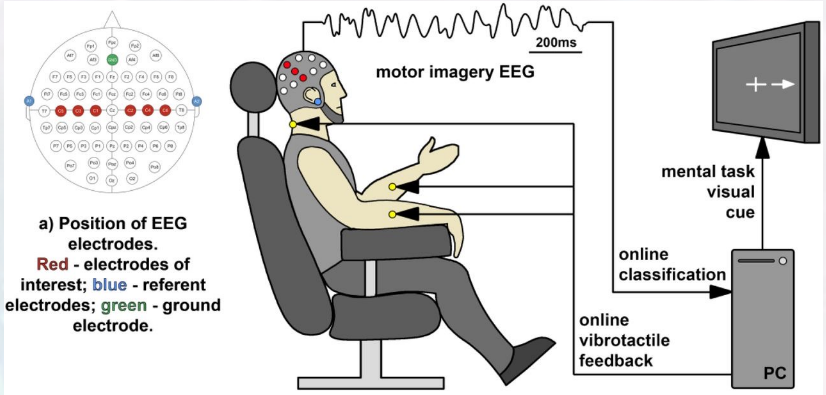
Training environment

Improvement of user motivation & experience: gamified protocols (ex. ball-basket paradigm, spaceship that must avoid asteroids)
Integration of virtual reality. Ex "Use the force" – allows users to levitate a spaceship by imagining moving their feet

MI-based BCIs improvement

Continuous Tactile Feedback for Motor-Imagery based Brain-Computer Interaction in a Multitasking Context

Camille Jeunet, Chi Vi, Daniel Spelmezan, Bernard N'Kaoua, Fabien Lotte, Sriram Subramanian



b) Experimental setup of BCI training.
Red dots - electrodes of interest; blue dot - referent electrode; yellow dots - vibrotactile actuators.

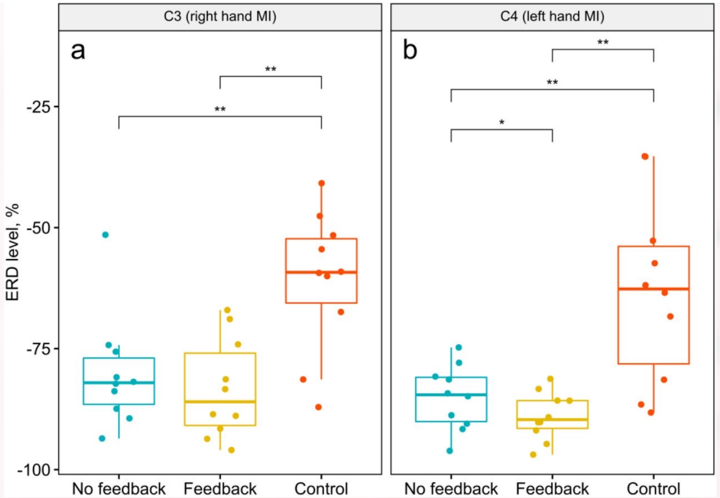
New Results | Follow this preprint

A BCI-based vibrotactile neurofeedback training improves motor cortical excitability during motor imagery

N. Grigorev, A. Savosenkov, M. Lukoyanov, A. Udoratina, N. Shusharina, A. Kaplan, A. Hramov, V. Kazantsev, S. Gordleeva

doi: https://doi.org/10.1101/2021.02.28.433220

Now published in *IEEE Transactions on Neural Systems and Rehabilitation Engineering* doi: 10.1109/tnsre.2021.3102304



"Vibrotactile feedback during MI training induced significant enhancement of ERD activity only for non-dominant, left hand over contralateral motor cortex area measured in C4 electrode"

Steady-State Visually Evoked Potentials (SSVEP)

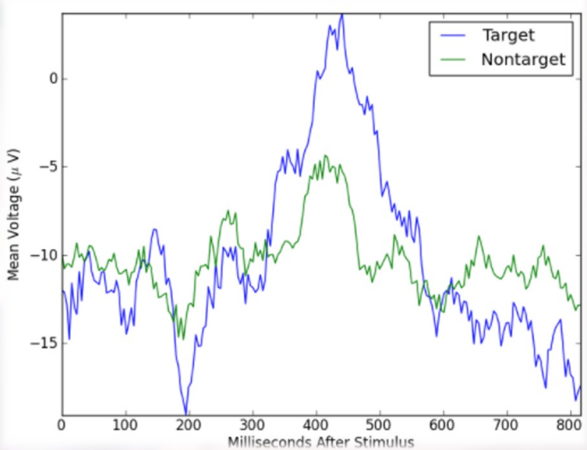
Evoked Potentials Brain Computer Interface

Evoked potentials: electrical potentials elicited when a stimulus is presented. They can be…

- **Visual**: visually evoked potentials (**VEP**) & steady-state evoked potentials (**SSVEP**)
- **Auditory**: auditory steady-state response (**ASSR**)
- **Haptic**: steady-state somatosensory evoked potentials (**SSSEP**)

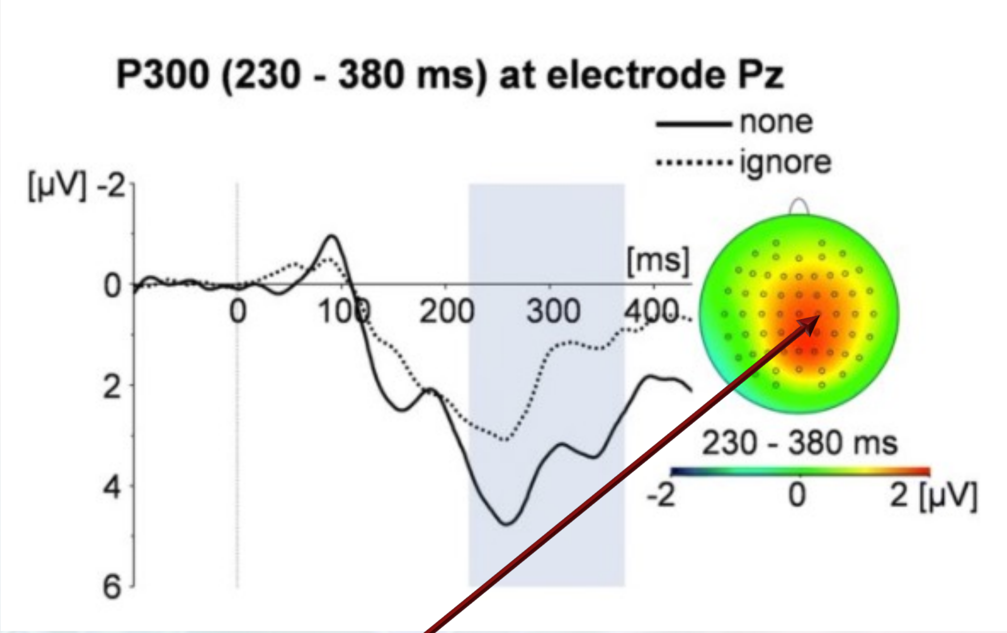
Event-Related Potential (ERP) based BCI:

- Electrophysiological response triggered by a specific event or stimulation.
- Response is time delayed in relation to the event → ERP Latency
- Response has a direction or polarity → positive or negative



P300 : Positive deflection that (generally) peaks 300ms after event onset.

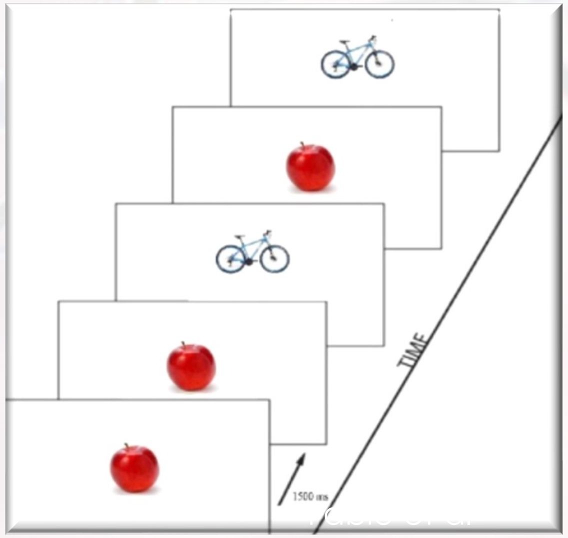
Evoked Potentials Brain Computer Interface



Central-Parietal regions

- Linked to attentional and memory processes
- Usually generated by the **oddball paradigm.**

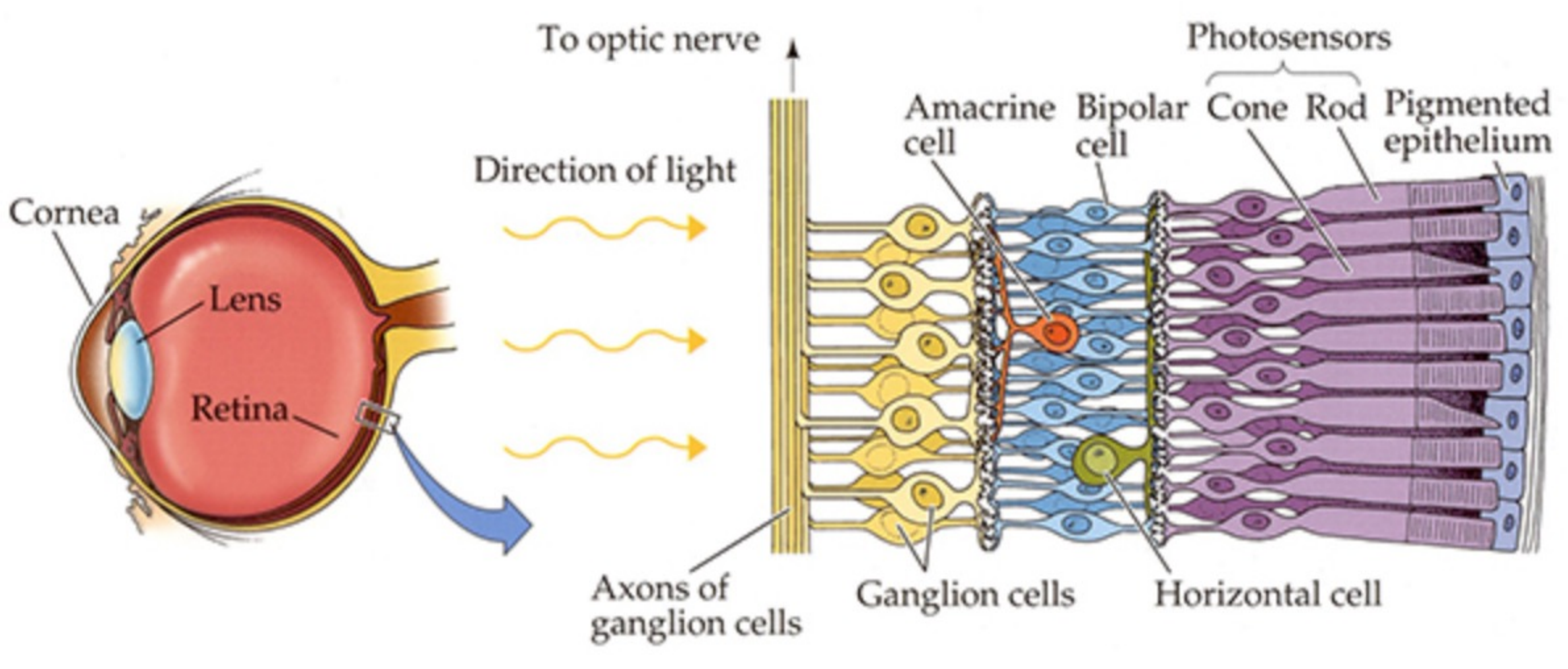
Visual oddball



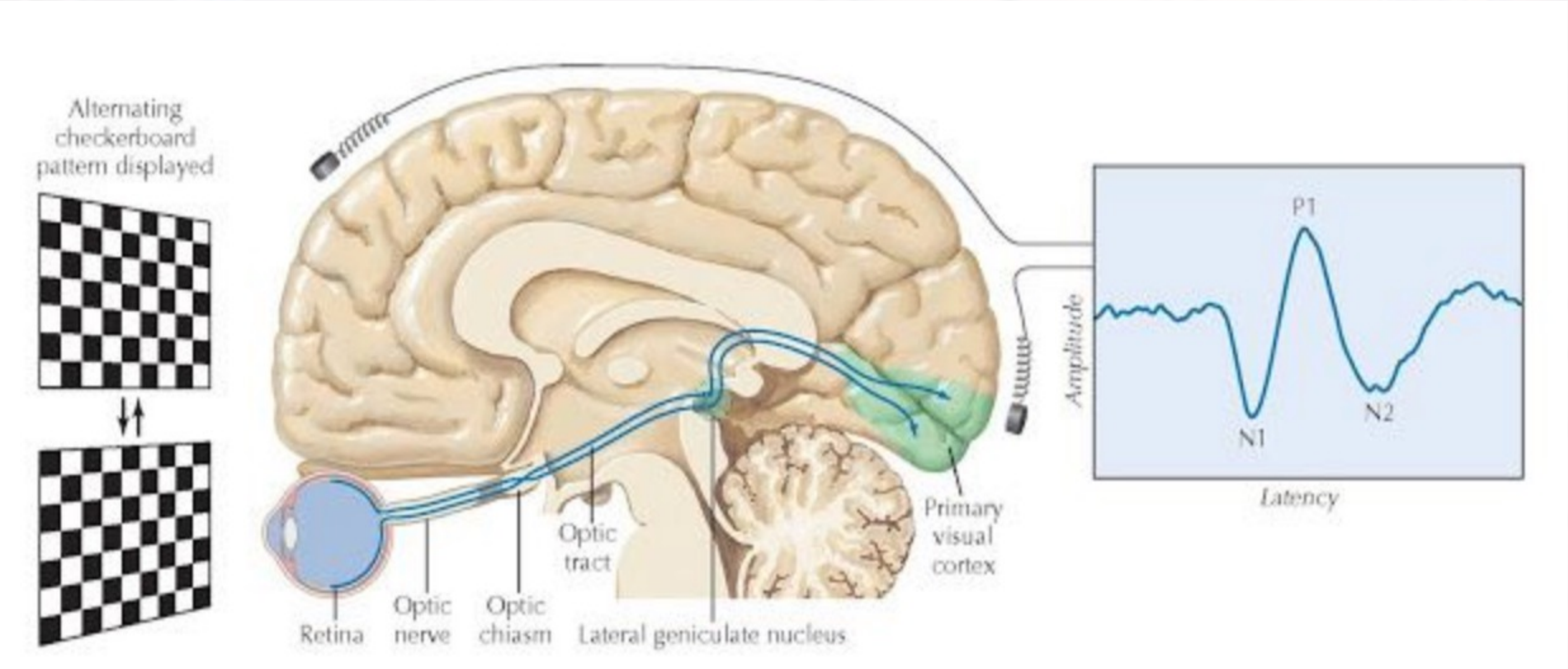
Auditory oddball

P300 component widely used in BCI applications as it is relatively easy to generate.

Visually-Evoked Potentials (VEPs)



Visually-Evoked Potentials (VEPs)



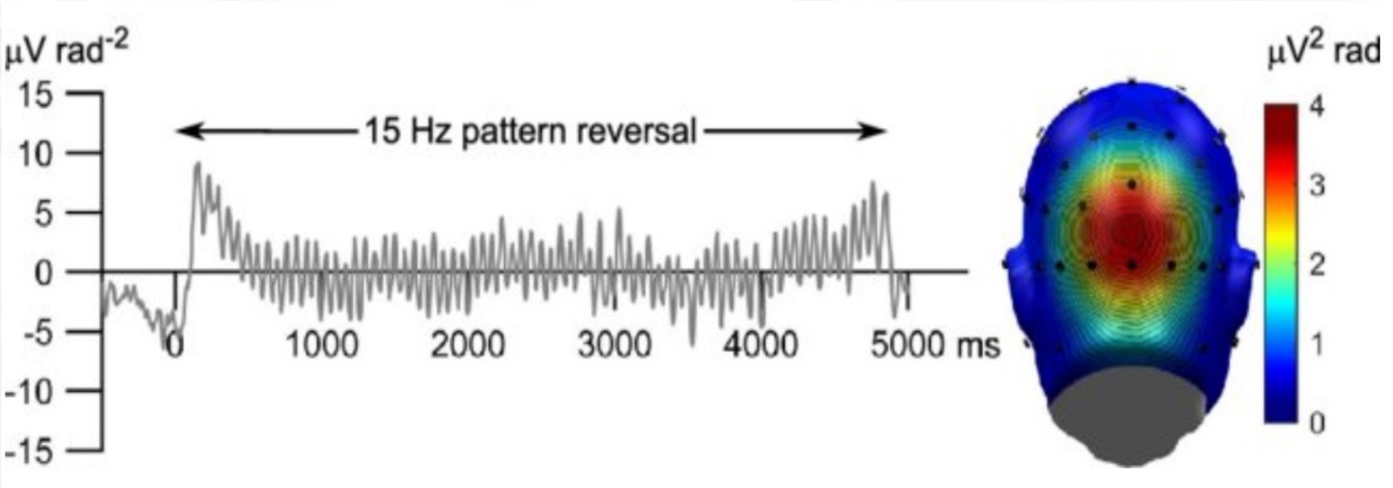
Steady-state Visually Evoked Potential (SSVEP)

SSVEPs are generated when a user focuses attention on a visual flicker at a certain frequency from 6Hz to 75Hz.

The continuous visual stimulation **evokes** a synchronised steady-state brain activity, whose frequency spectrum depends on the flicker frequency of the visual stimulus.

A **resonance phenomenon**.

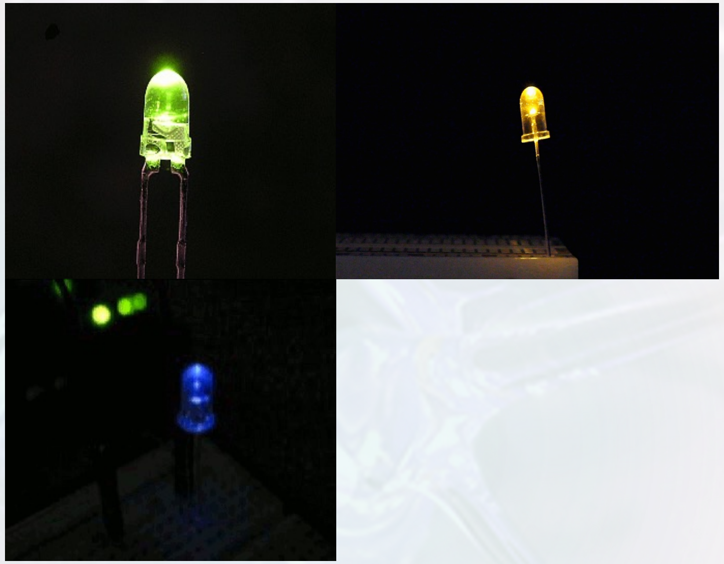
Time & **phase-locked** to the driving stimulus.



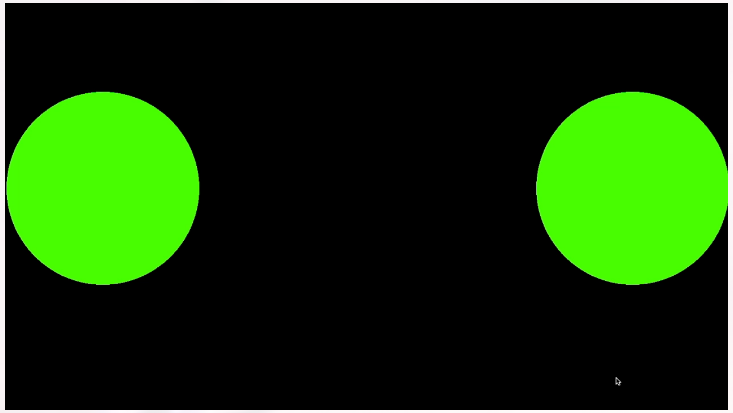
Antov, M.I., Plog, E., Bierwirth, P. *et al.* Visuocortical tuning to a threat-related feature persists after extinction and consolidation of conditioned fear. *Sci Rep* **10**, 3926 (2020)

SSVEP: Repetitive Visual Stimuli (RVS)

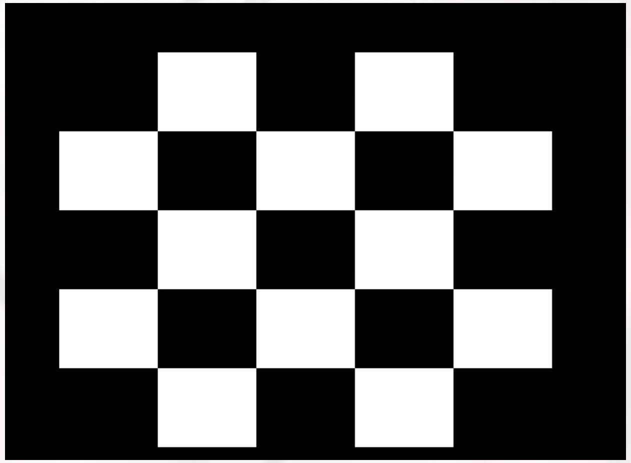
Light stimuli i.e. LEDs

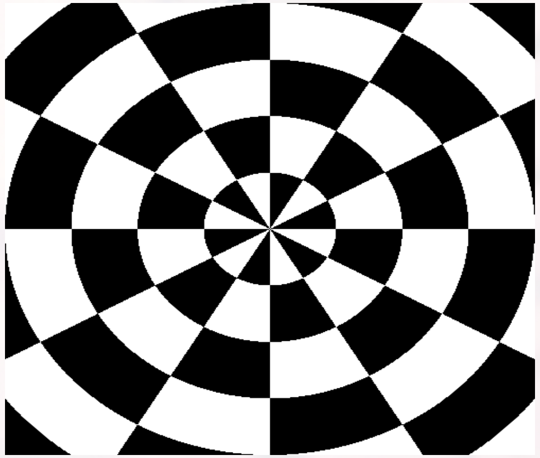


Single Graphics Stimuli



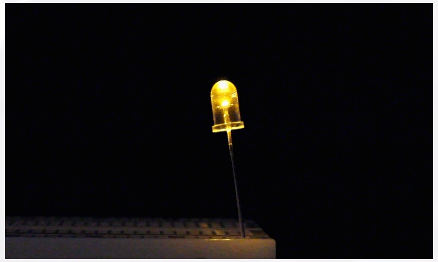
Pattern Reversal

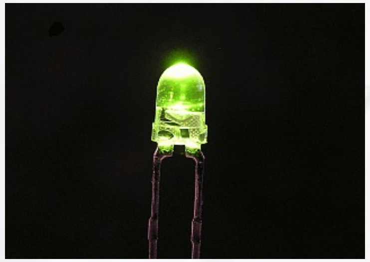




SSVEP: Repetitive visual stimuli (RVS) Types

Light stimuli i.e. LEDs





Modulation depth to quantify the strength of the stimulus

$$(l_{max}-l_{min}) / (l_{max}+l_{min})$$

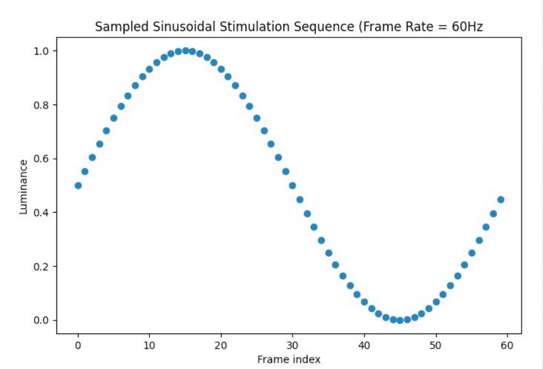
where *l* is the luminance *(measure of intensity)*

Single Graphics Stimuli:

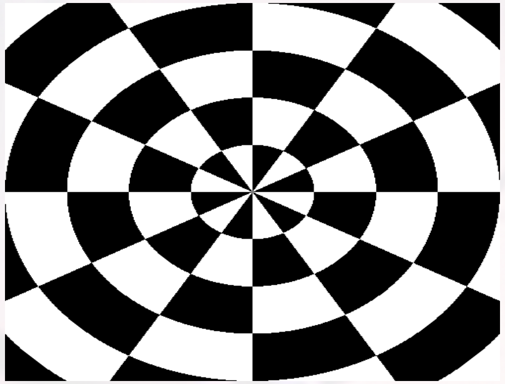
$$s(f,i)= \frac{1}{2}\{1 + sin[2\pi f(i/Refresh\ rate]\}$$

Sampled sinusoidal stimulation.

- Stimulation frequency as the number of full cycles per second.
- The colour contrast.



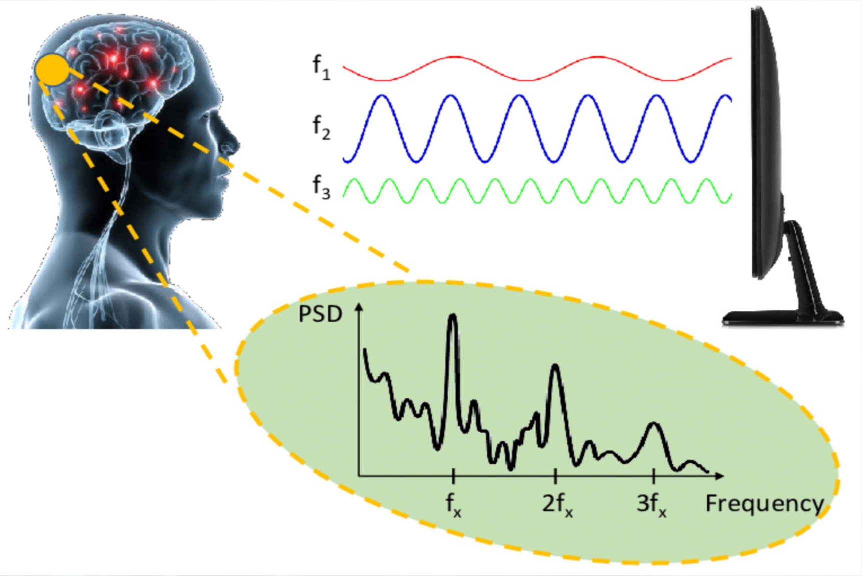
Pattern Reversal :



Oscillatory alternation of two patterns. Patterns are alternated at a certain number of alternations per second.

- Number of reversals per second
- Subtended visual angle of each tile.
- The pattern contrast.

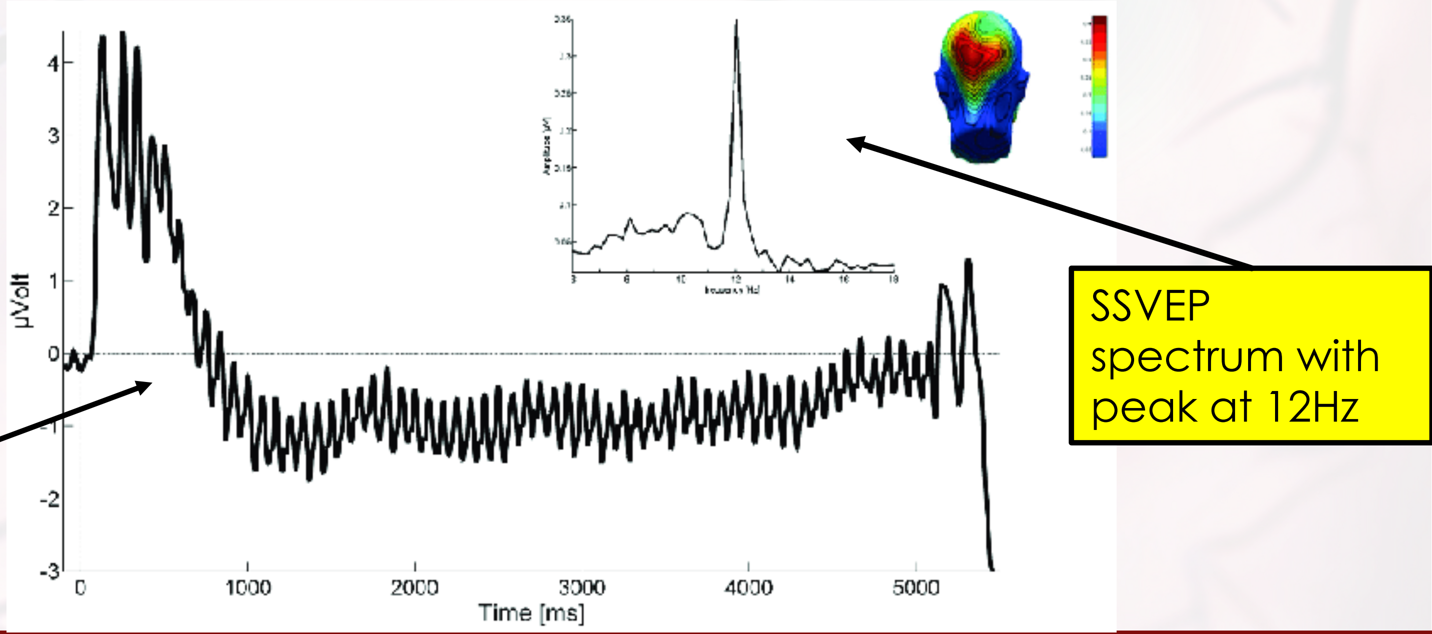
Steady-state Visually Evoked Potential (SSVEP)



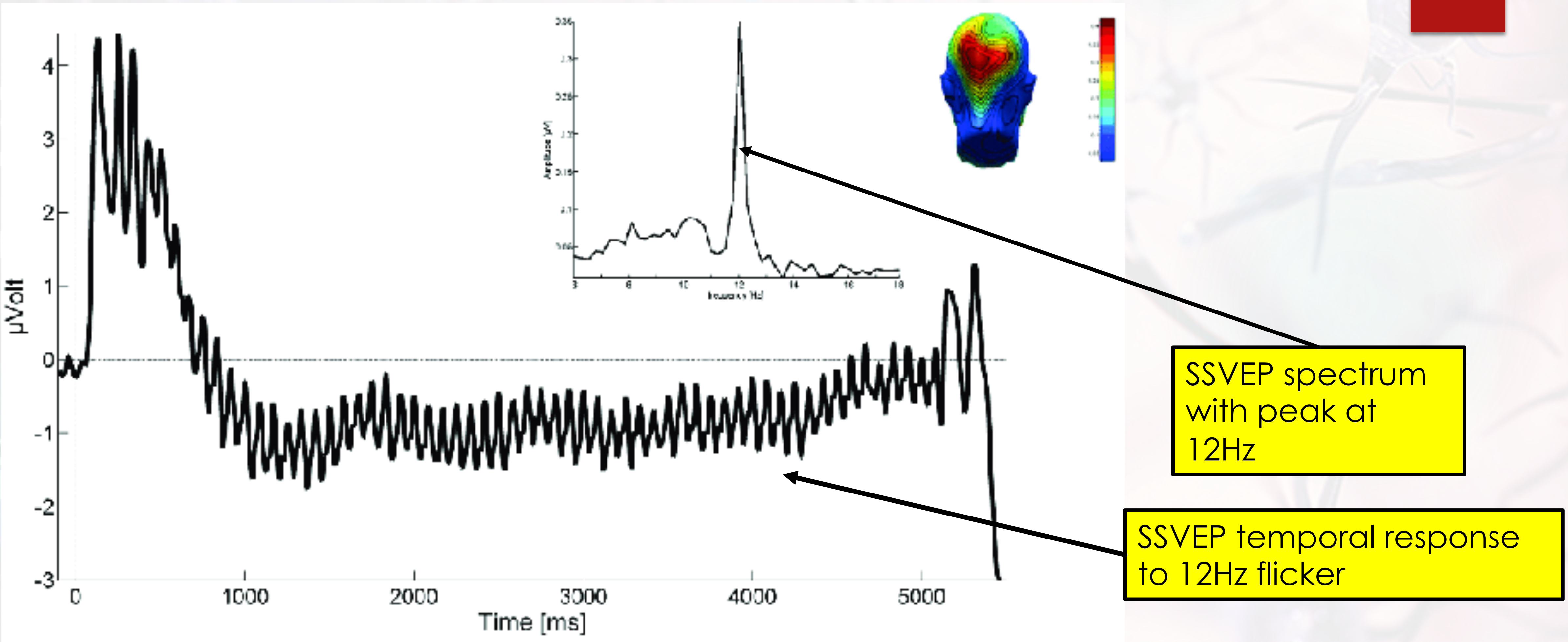
SSVEPs are generated over the occipital region when the retina of the eye is excited with visual stimulus that flickers at fixed frequencies exceeding 4Hz.

Activity in the occipital region of the brain entrains to the rhythmic flickering of the visual stimulus.

Evoked SSVEP is in phase with the flickering visual stimulus.



Steady-state Visually Evoked Potential (SSVEP)



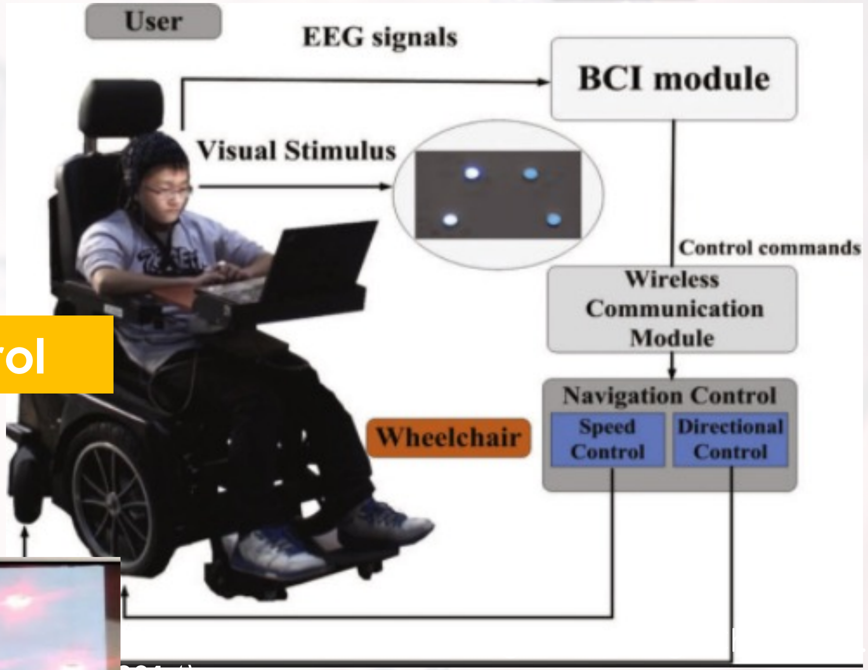
The freqency of the stimulus repetition and its harmonics can be detected in the spectrum of the SSVEP.

SSVEP-Based Brain-Computer Interface

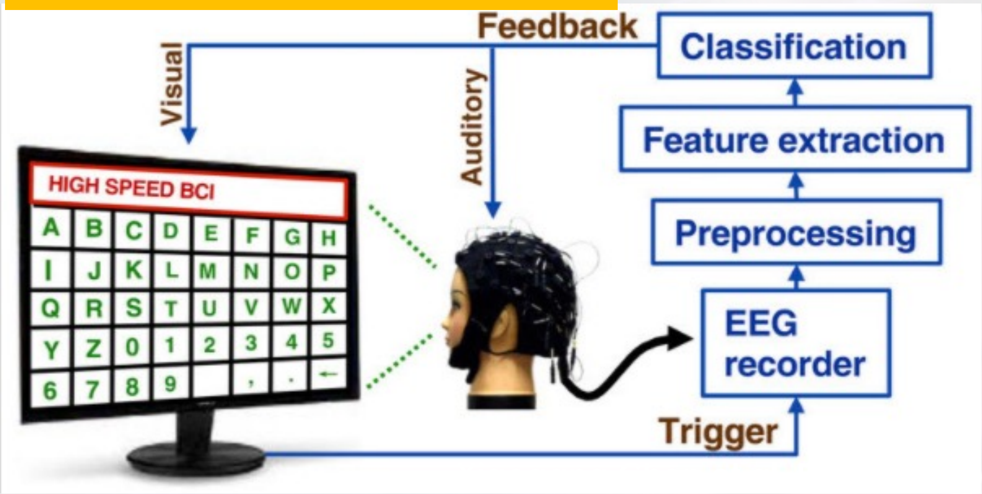
SSVEPs are very popular in the field of BCI due to their:

- Reliability (high accuracy).
- High information transfer rate.
- The protocol is relatively easy to set up.
- It requires little to no training.
- SSVEPs are robust to artifacts.

Wheelchair control

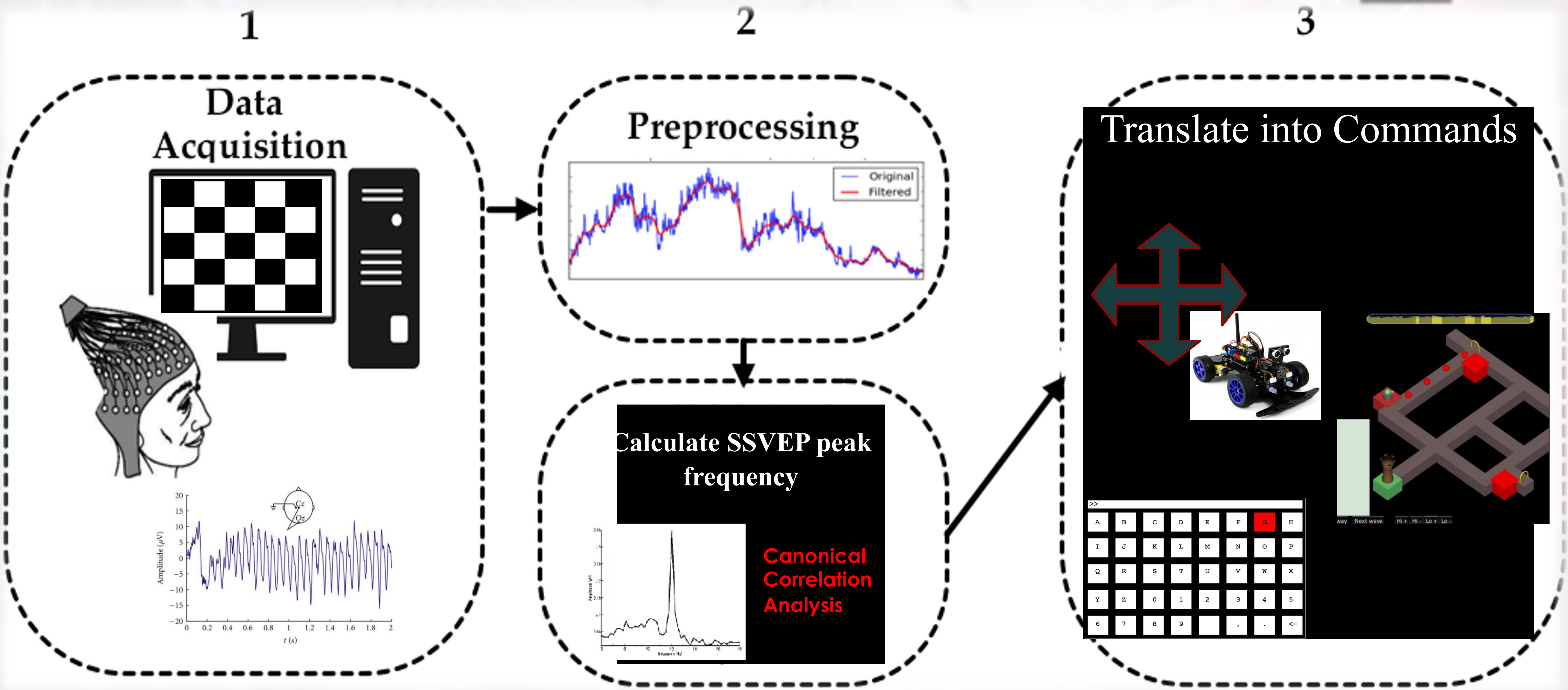


SSVEP-based Speller

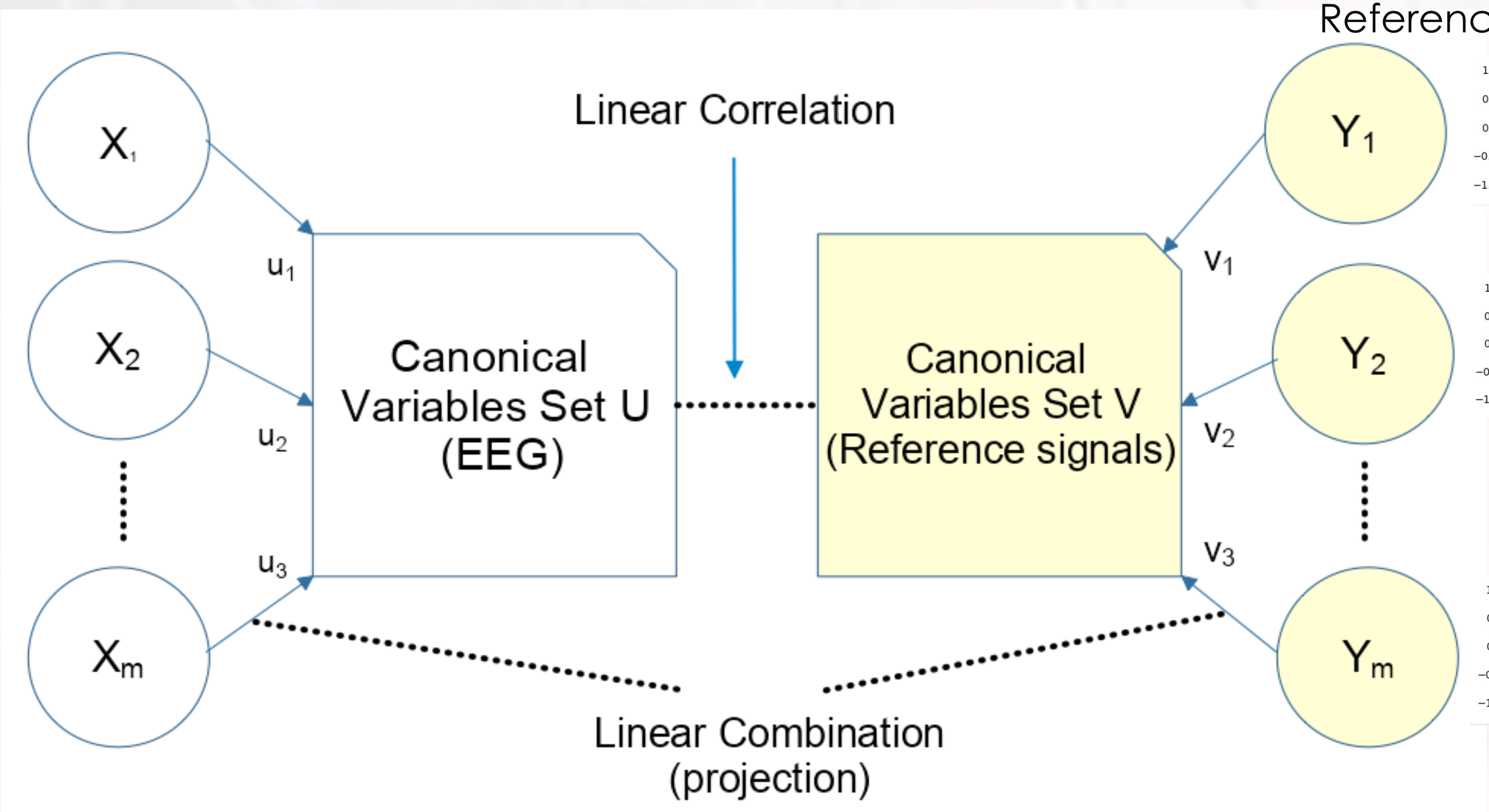


Exoskeleton control

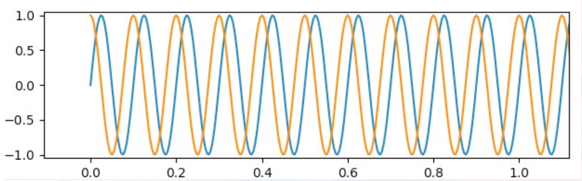
SSVEP: OVERVIEW OF SSVEP-BASED BCI PIPELINE

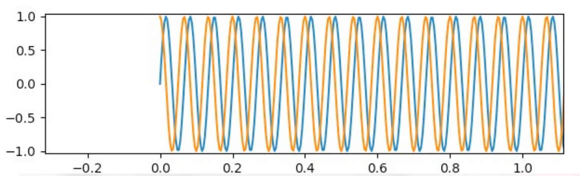


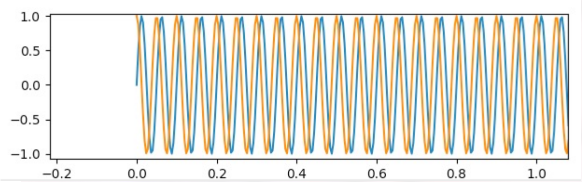
SSVEP DETECTION: CANONICAL CORRELATION ANALYSIS



Reference signals







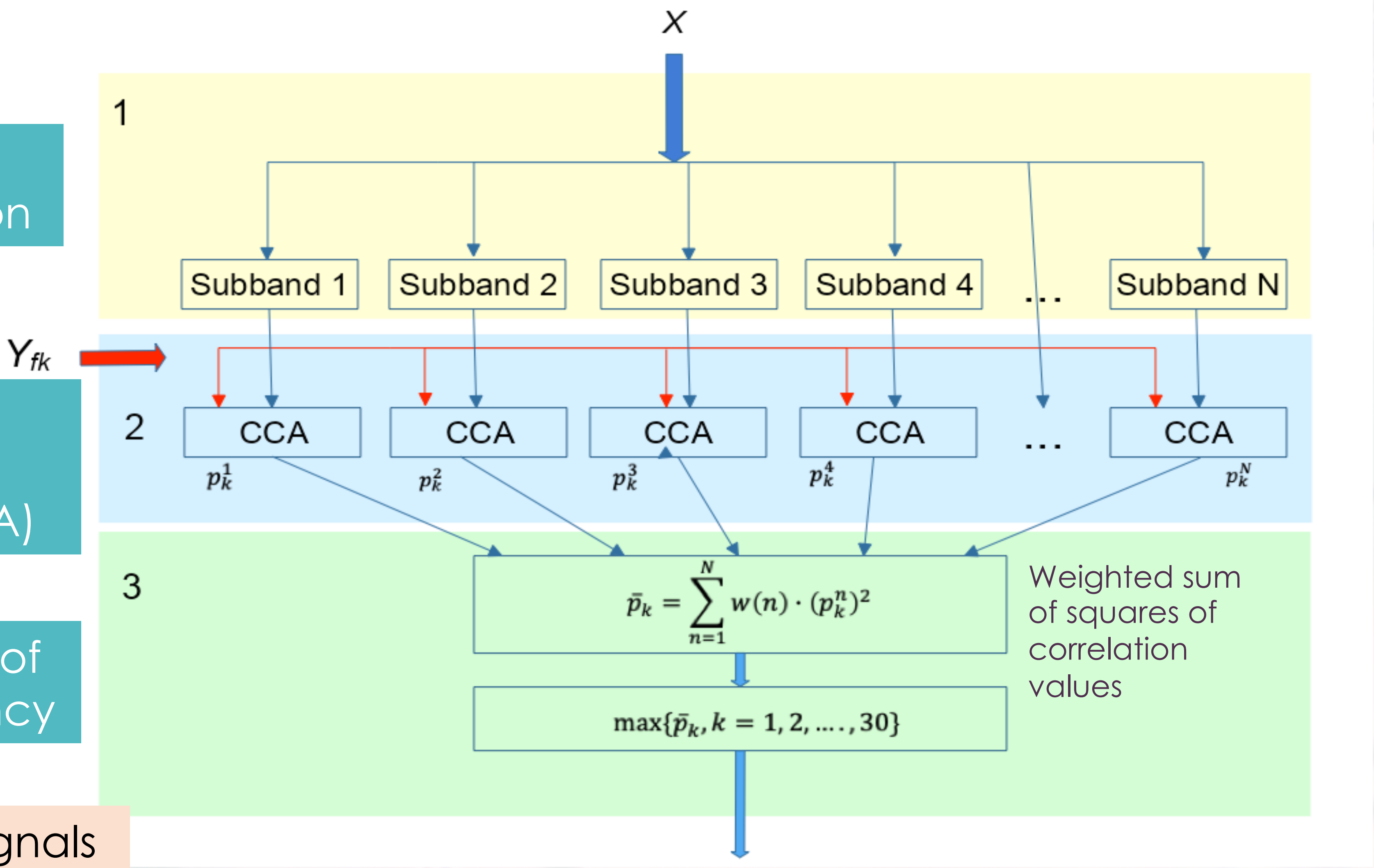
Spatial filtering method that finds the linear combination of two datasets that maximizes the linear correlation.

SSVEP Detection: Filter-bank CCA

Sub-band decomposition

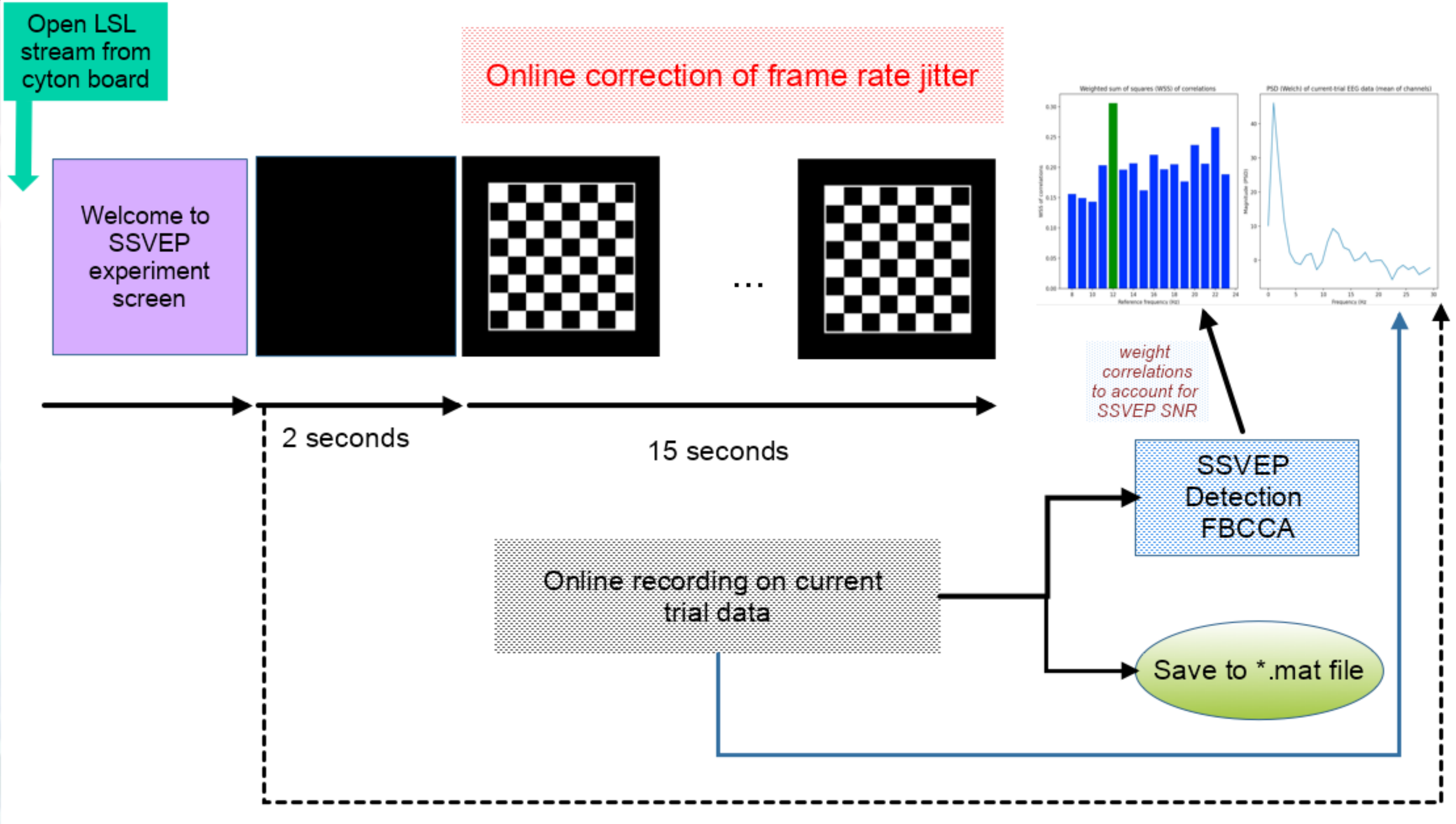
Canonical Correlation Analysis (CCA)

Identification of target frequency



Y_{fk} = reference signals

Simple SSVEP-Based BCI



Single Trial

Terminal - geringswald@Q: ~/tools/OpenBCI_GUI

File Edit View Terminal Tabs Help

Terminal - geringswald@Q: ~/projects/CREx/summer_school/2022/cours_bci/SummerSchool_2022_BCI/BCI_SSVEP-main

File Edit View Terminal Tabs Help

geringswald@Q: ~/projects/CREx/summer_school/2022/cours_bci/SummerSc... | geringswald@Q: ~/projects/CREx/summer_school/2022/cours_bci/SummerSc...

```
geringswald@Q:~/projects/CREx/summer_school/2022/cours_bci/SummerSchool_2022_BCI/BCI_SSVEP-main$
```

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openBCI_GUI:
[DEFAULT]: D
[ERROR]: Fai
OpenBCI_GUI:

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ControlPanel
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ControlPanel
[WARN]: Foun
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Successfully
[DEFAULT]: A
initButtonPr
OpenBCI_GUI:


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||
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OpenBCI_GUI:
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X11Util: Open[1]: NamedX11Display[:0.0, 0x7f936c019d20, refCount 1, unCloseable false]
geringswald@Q:~/tools/OpenBCI_GUI$
```

IPython: home/

BCI/BCI_SSVEP-main/record_data.py - Mousep

utilsSSVEP.py | Untitled 7

```
p.argmax(scores)]) + "Hz")
```

installation_notes | Videos

Type	Date Modified
folder	Fri 26 Aug 2022 20:01:21 CEST
folder	Fri 26 Aug 2022 19:56:19 CEST
folder	Mon 01 Aug 2022 12:44:22 CEST
folder	Mon 01 Aug 2022 11:19:31 CEST
folder	Mon 01 Aug 2022 10:49:19 CEST
folder	Mon 01 Aug 2022 03:10:01 CEST
folder	Fri 29 Jul 2022 14:37:28 CEST
folder	Fri 29 Jul 2022 12:11:35 CEST
folder	Thu 28 Jul 2022 18:57:59 CEST
folder	Thu 28 Jul 2022 18:50:57 CEST
folder	Thu 28 Jul 2022 18:31:11 CEST
folder	Thu 28 Jul 2022 18:25:06 CEST
folder	Thu 28 Jul 2022 17:11:14 CEST
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folder	Thu 28 Jul 2022 12:36:28 CEST
folder	Thu 28 Jul 2022 12:32:28 CEST
folder	Thu 28 Jul 2022 12:29:32 CEST
folder	Thu 28 Jul 2022 12:16:10 CEST
plain text document	Sun 28 Aug 2022 15:32:28 CEST
MPEG-4 video	Sun 28 Aug 2022 15:31:03 CEST

ice Impress

graphical object
nd. (b) In pattern
ted at a specified

110%

Filetype: Python | UTF-8 | Line: 325 Column: 31 Selection: 2 | OVR

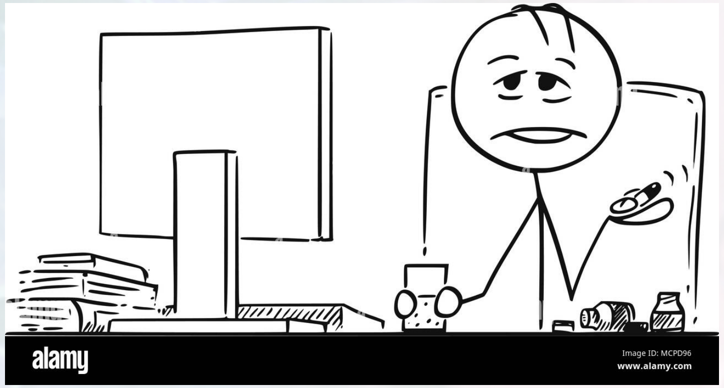
Navigate to Dining Room, turn on the Lamp, and retu
of commands is R-R-R-R-D-R-R-D-U-L- L-L-L.

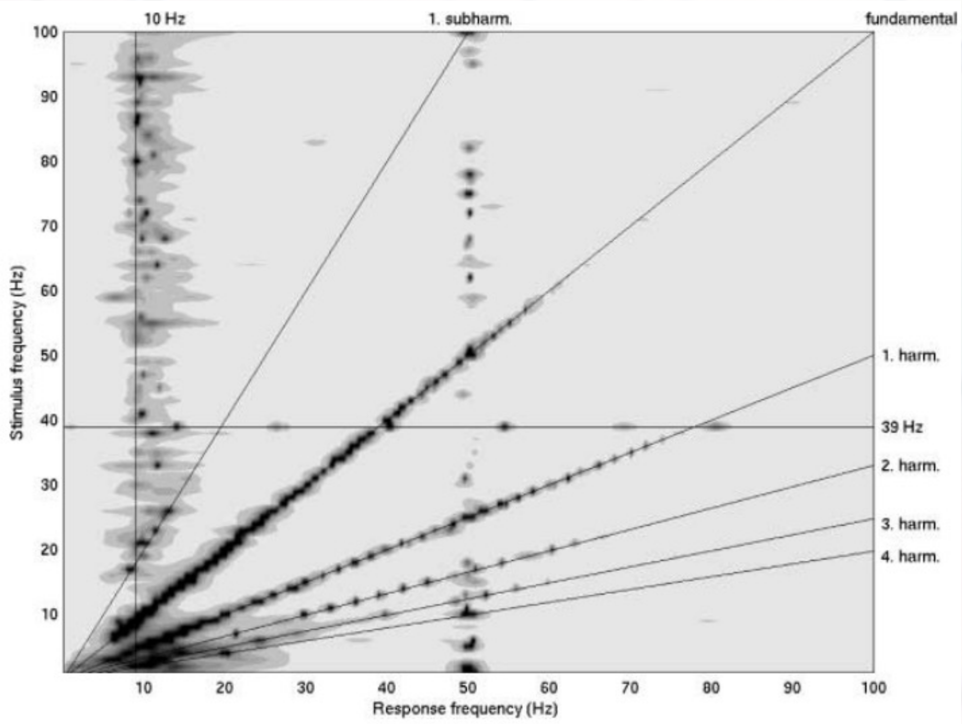
accuracies of

Page 24 of 24 | 7,490 words, 46,487 characters | Default Page Style | 120%

Steady-state Visually Evoked Potential (SSVEP) Discussion

- What are limiting factors of the SSVEP-BCI?
  - Stimulus presentation
    - Hardware
    - User
  - Feature Selection (EEG Signal)
    - Frequency





Herrmann (2001)

Q. Is SSVEP-based BCI « dependent » or « independent » BCI …Why?

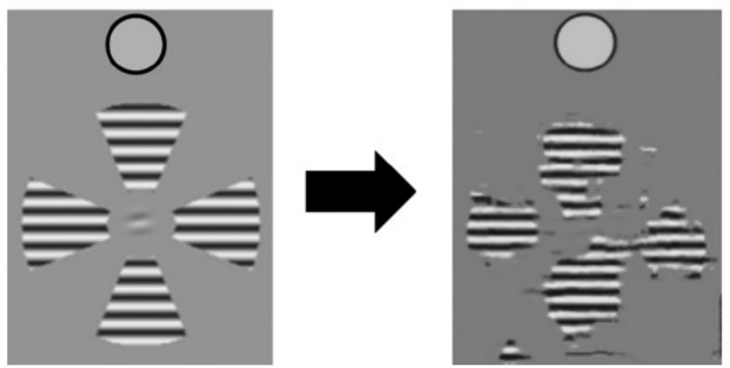
A. It is dependent.

The participant uses their eye muscles to focus on the target stimulus gaze control.

Steady-state Visually Evoked Potential (SSVEP) Discussion

- SSVEP-BCIs: visual stimuli
  - the human visual field
  - the role of eye movements
  - dependent versus independent BCI
  - covert versus overt attention

Marmor & Marmor (2010)

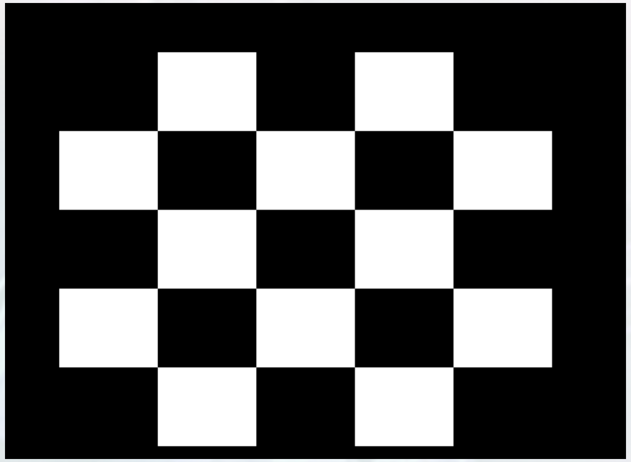


Rosenholtz et al. (2019)

Rosenholtz et al. (2012)

Steady-state Visually Evoked Potential (SSVEP) Discussion

- SSVEP-BCIs: visual stimuli
  - adapted stimuli (scaling according to eccentricity)
  - spatially overlapping stimuli



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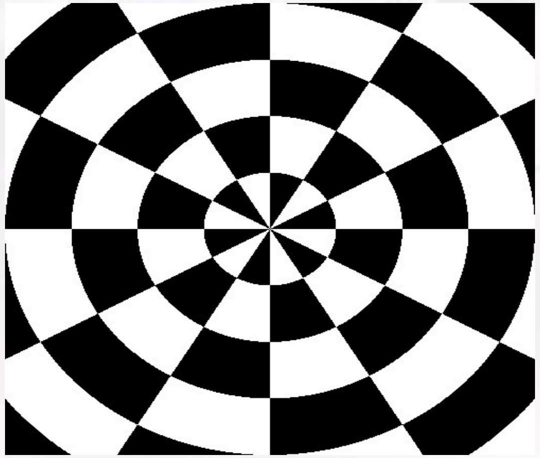


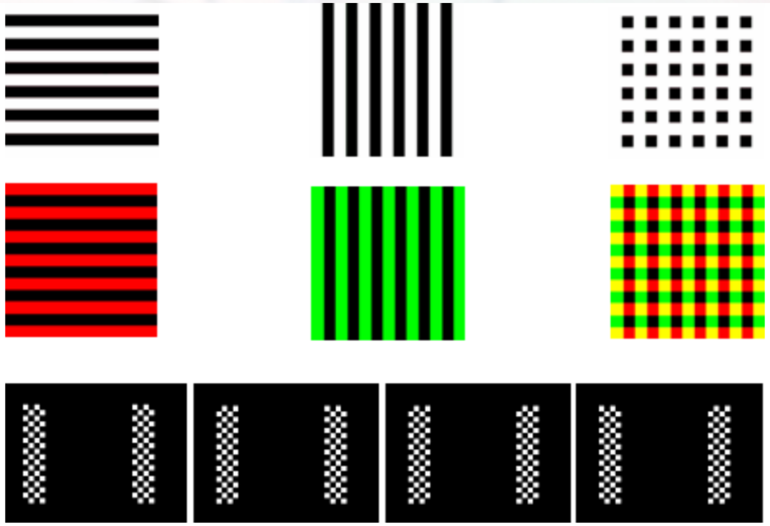


Figure 1.
The top row presents the three images used in the BW linebox condition, and the middle row contains three images used in the color linebox condition. The four images used in the BW checkerbox condition are on the bottom row.

Allison et al. (2008)

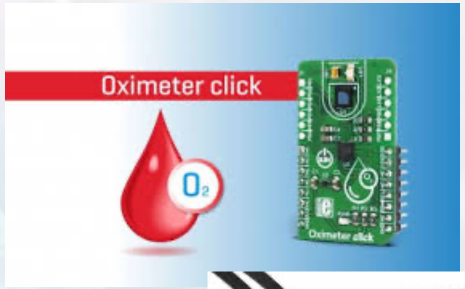
CONCLUSION

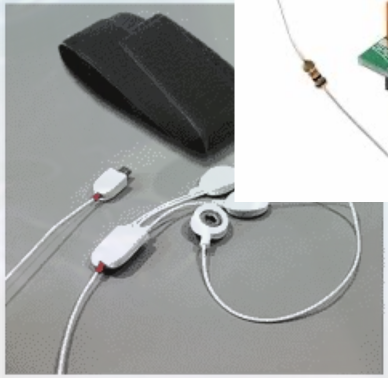
Brain-Computer Interface (BCI): Conclusion

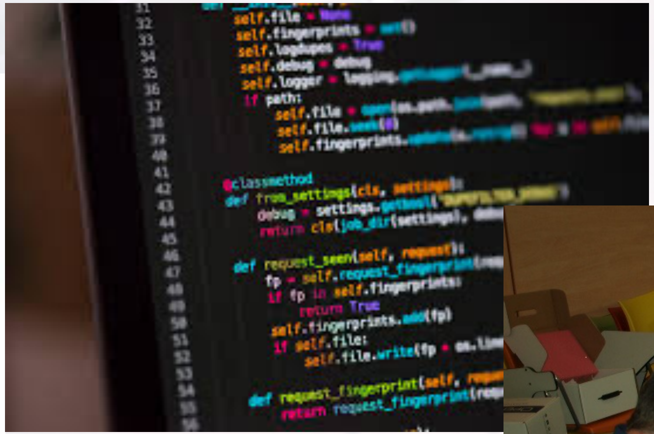
BCI

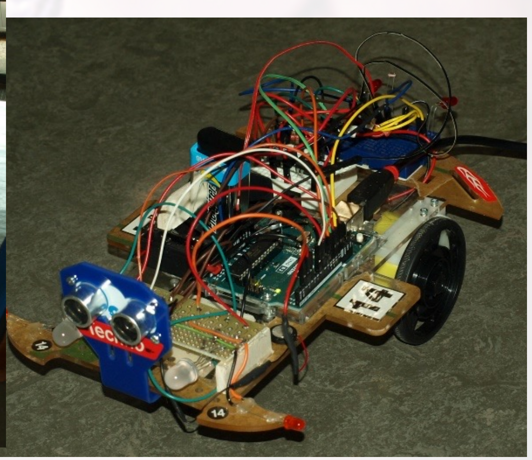
- Designing a BCI is a complex and difficult task that requires knowledge of several disciplines (computer science, electrical engineering, signal processing, neuroscience, psychology)
- Many ongoing challenges
    - Illiteracy (using an interactive, co-learning approach)
    - Long-term use of BCIs: health implications or change in brain functionality?
    - Ethical standards: liability in case of accidents, appropriate use of bio-signal data, privacy (marketing, political agendas)#
- Open community (software, hardware)

For more of this fun…UE Ingénierie Cognitive







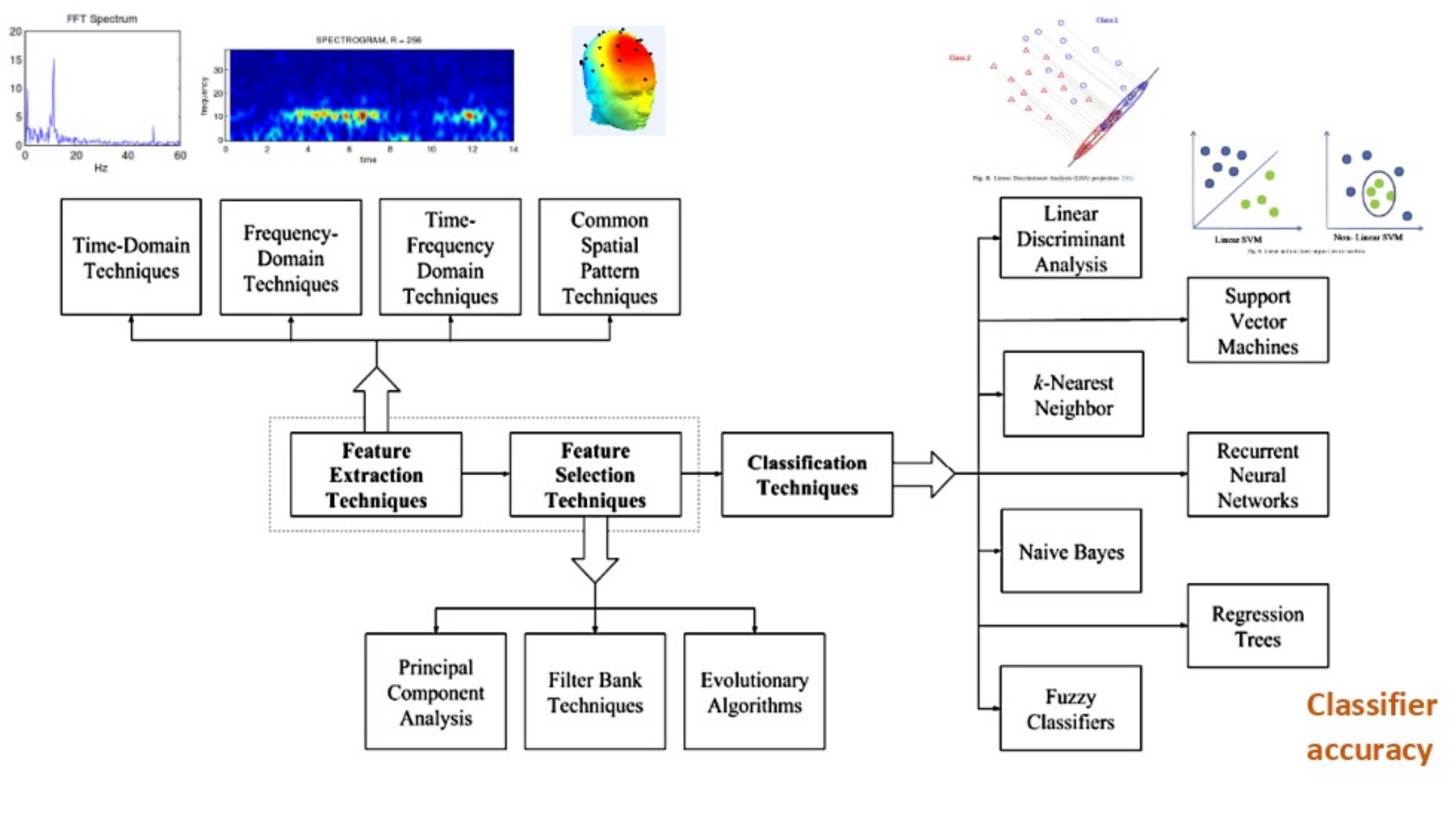


ILCB

Thank you for your attention in this...

Brains-CREx Interface!

BCI architecture: Signal Processing



Deep learning: single signal processing block (group together the feature extraction, feature selection and classification tasks)

adapted from Padfield et al. (2019)