Introduction to Brain Computer Interfaces

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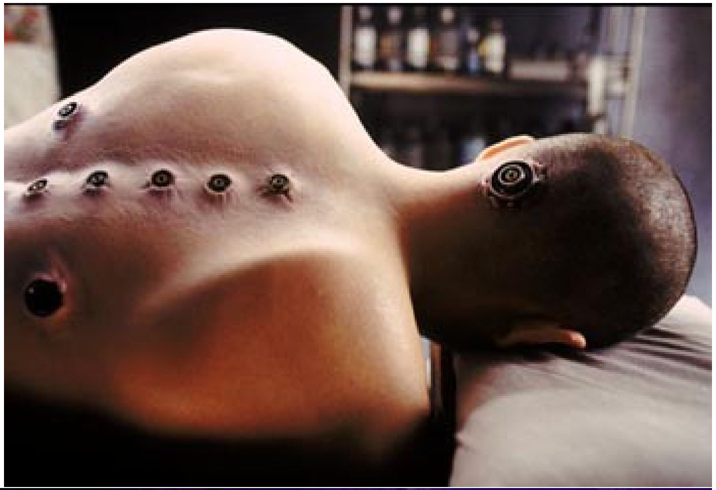
- What is a BCI?
- BCI Overview
  - How does a BCI work?
  - Why is BCI so hard?
- Summary
- How do we build a BCI?

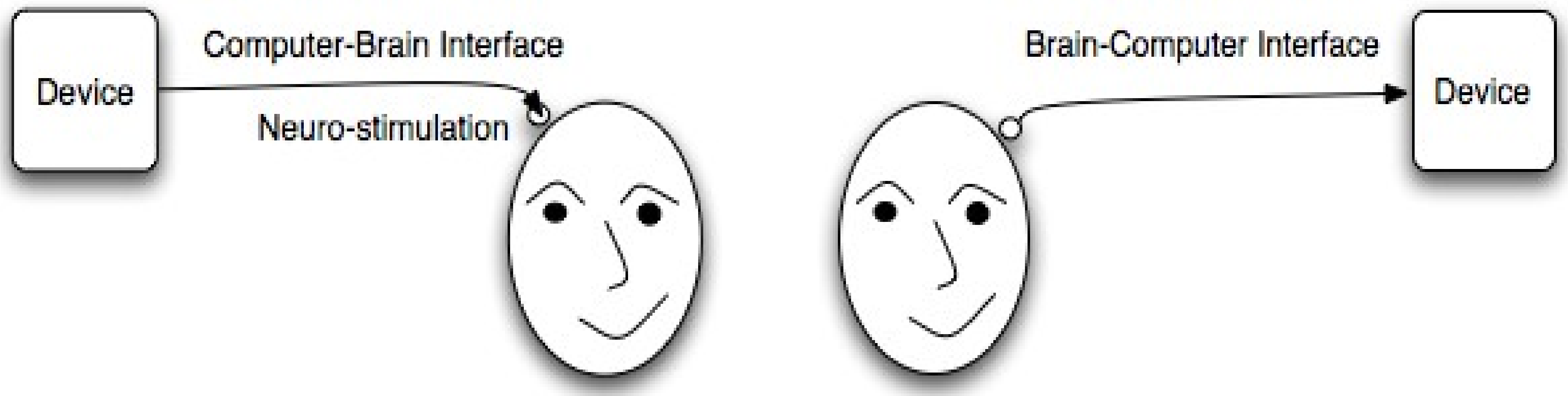
BCI in sci-fi : The hope/hype/future?



What are the distinguishing characteristics of a sci-fi BCI?

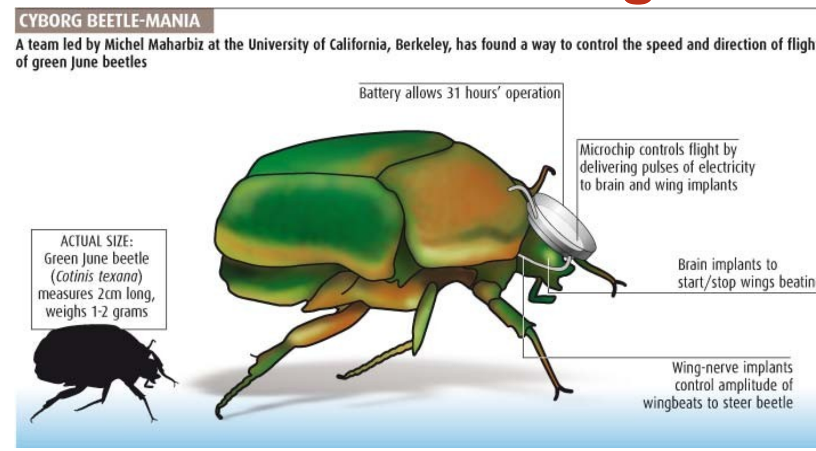
- Brain, computer, connection, control, thought
- Fast, accurate
- Psychic, natural, **intuitive** – thought directly turned into action
- Feedback, immersive, virtual-reality
- Physical connection to the CNS
- Better than natural/human?
- 2-way communication

BCI vs. CBI

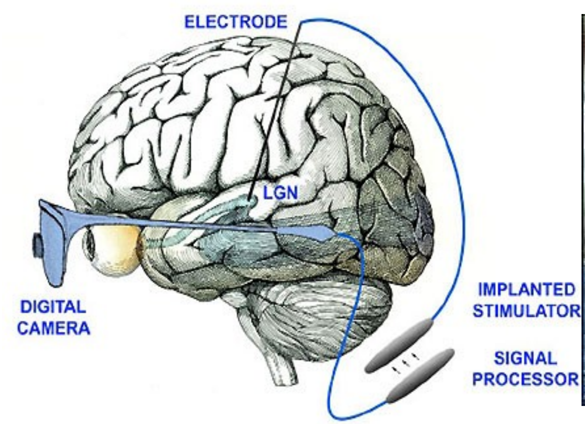


- Computer → Brain (CBI)
  - Computer puts information into the brain
- Brain → Computer (BCI)
  - Brain puts information into the computer

The reality : Computer Brain Interfacing



- Remote Controlled Animals
- Bionic Eyes
- Deep Brain Stimulation
  - For Parkinson's
  - For Depression



Note:
No generation of (rich) virtual sensory signals (… yet?)

The Reality : Brain Computer Interfacing

- BrainGate – 2d cursor control
- Graz. Univ. Austria –
  - grasp control
  - VR Navigation
  - P300 visual speller
- Emotiv – game system

Compare the hype to reality

- Much less fine-grained control
- Restricted to a small set of options
- Slow, inaccurate – <<1char/sec
- Non-intuitive

These differences are mostly due to the low signal-to-noise ratio of brain signals

- What is a BCI?
  - The current state-of-the-art
- BCI Overview
  - How does a BCI work?
  - Why is BCI so hard?
- Summary
- BCI Demo

So what is a Brain computer interface?

Commonly used definition:

A system which allows someone to communication information about their mental state without the use of the peripheral nervous system.

Note the emphasis:

- Without the use of the peripheral nervous system
- … this means signal must come directly from the brain
- That is, no muscles, no eyes, no motor neurons, nothing outside the skull

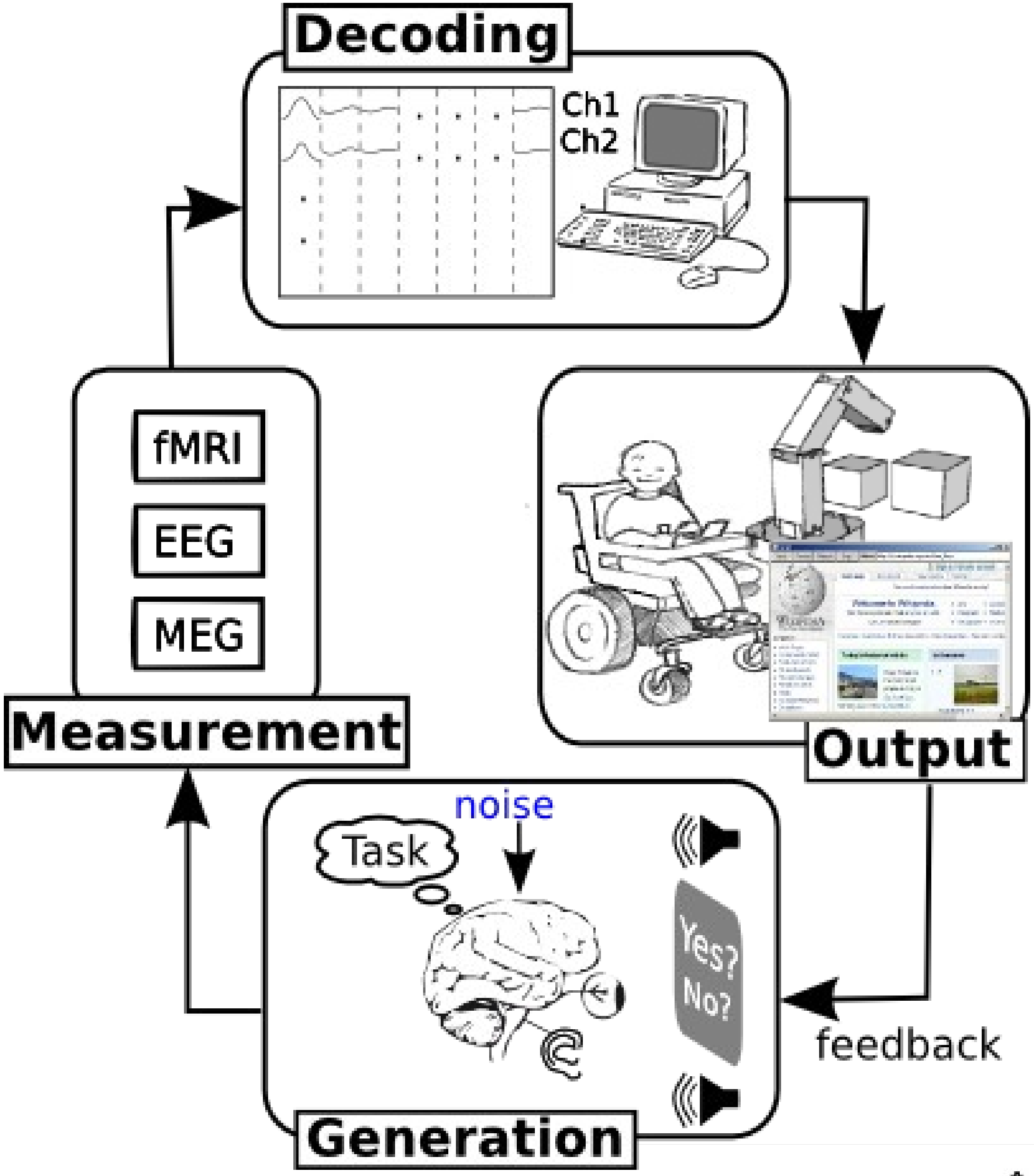
Question:

Is the Emotiv system really a BCI?

How does a BCI work?

Fundamentally, BCI is a simple(?) engineering problem;

1) Generation: Get the person to produce a strong brain signal, either by performing an explicit mental-task, or through normal mental processes
2) Measurement: Build a machine able to measure the properties of their brain, e.g. EEG, MEG, fMRI
3) Decoding: Build a machine able to decode the measurements to deduce the users mental state
4) Output: Communicate the mental-state to the outside world.



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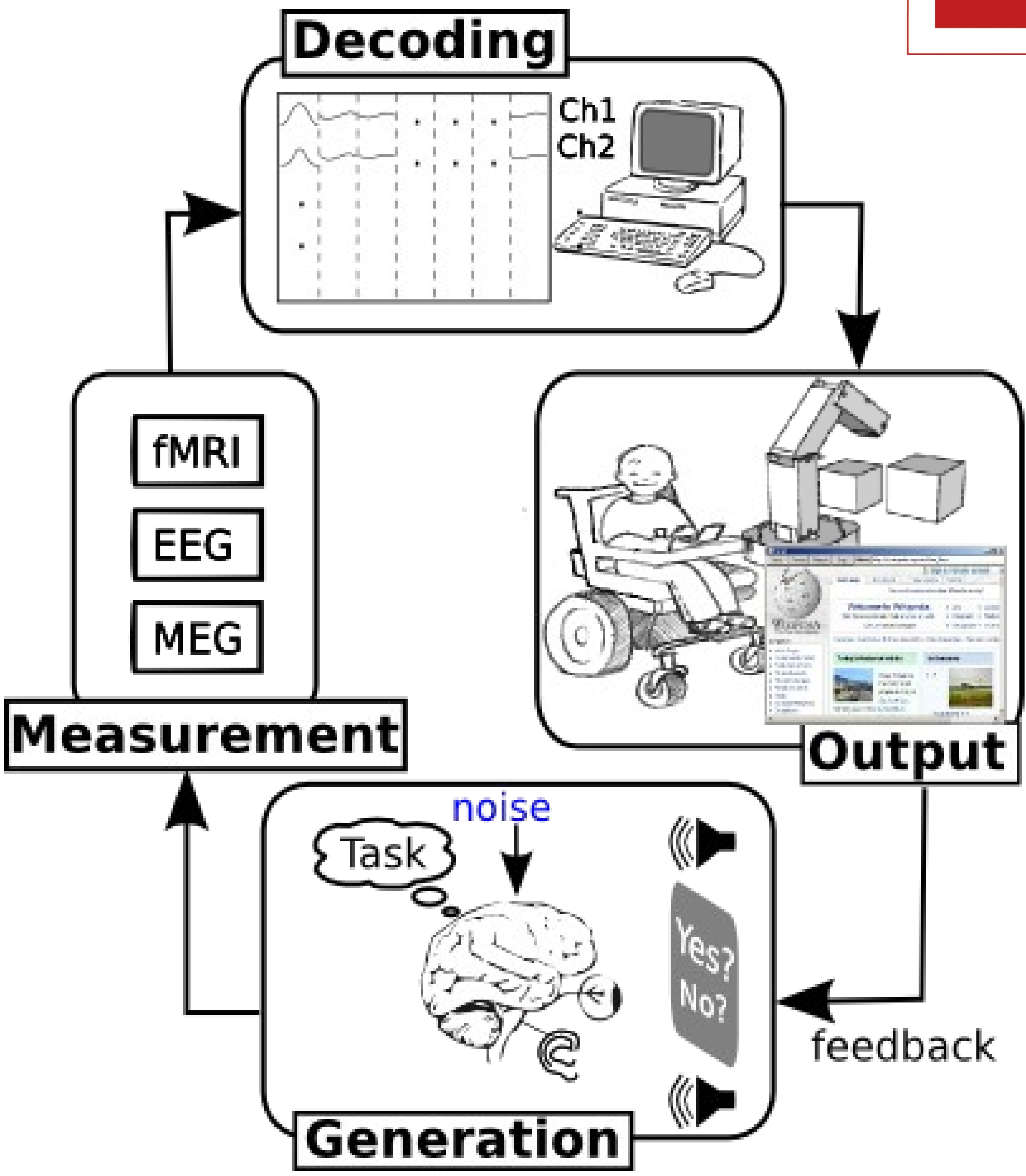
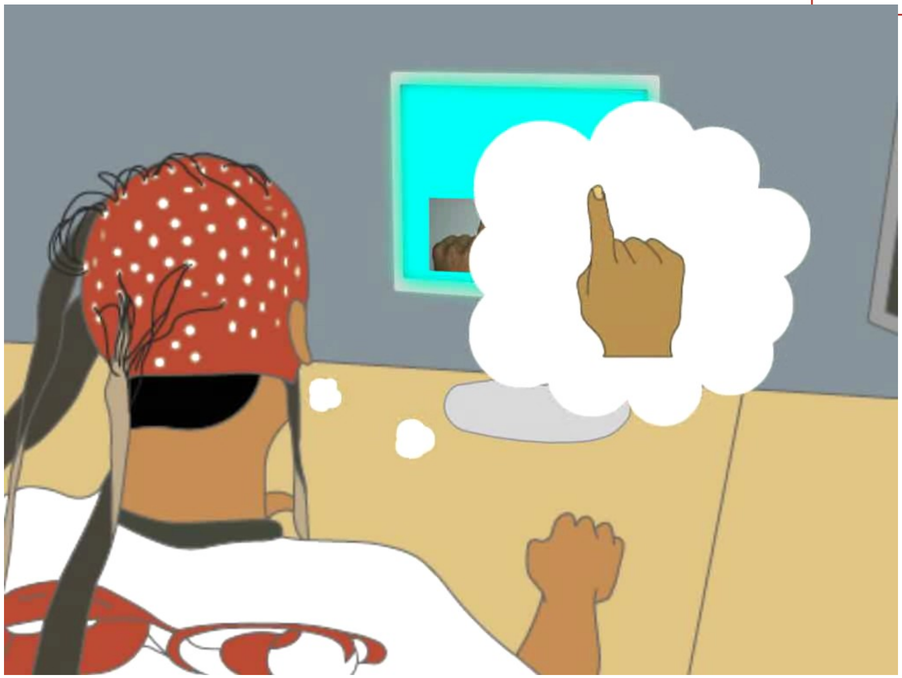
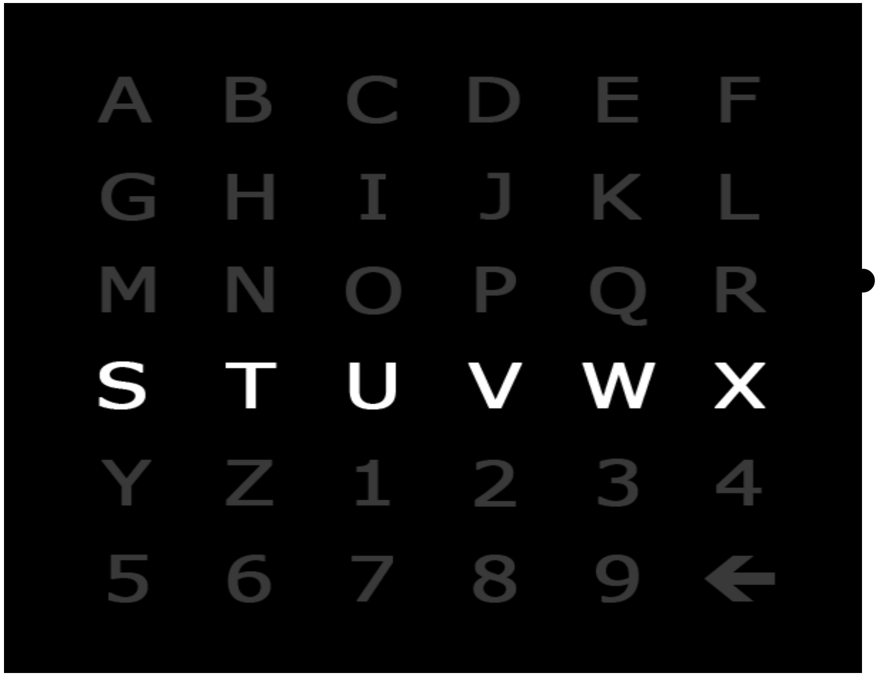


Generation: Common Mental Tasks

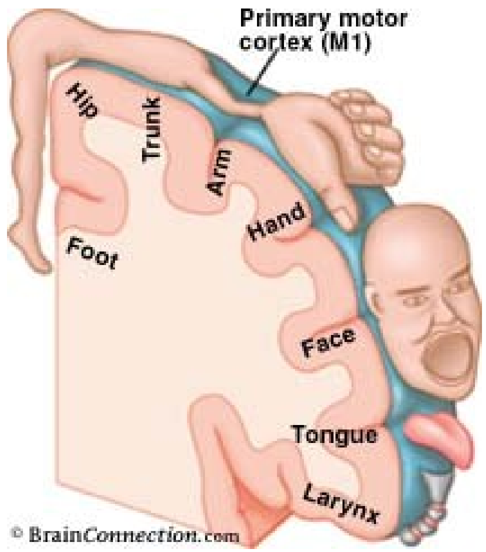


- Imagined Movement BCI
  - Stimulus independent
  - Induced Response

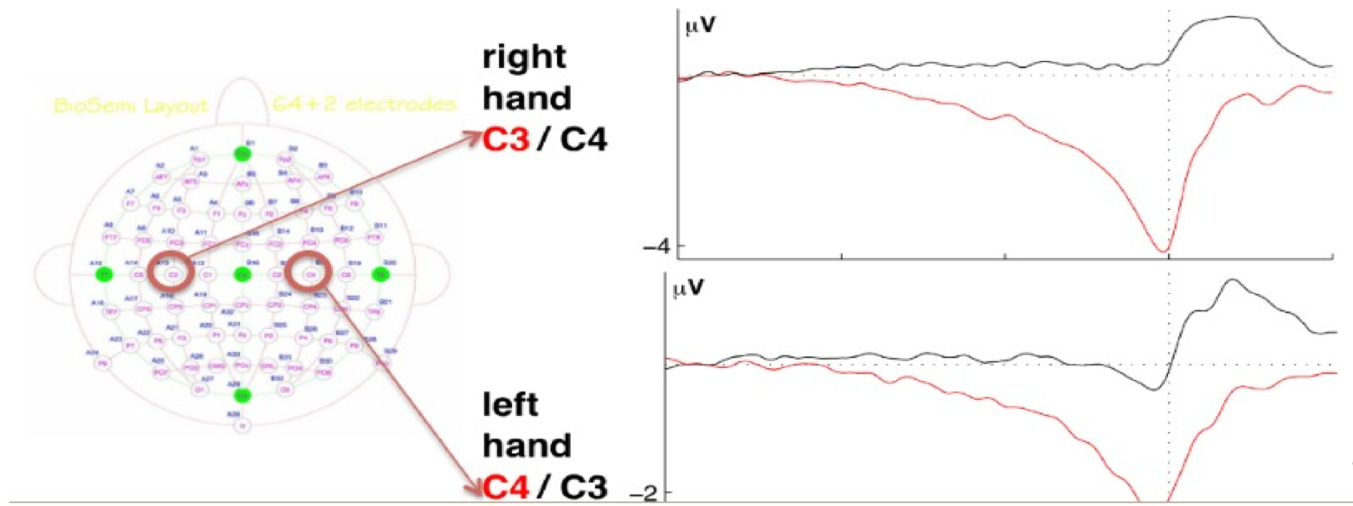


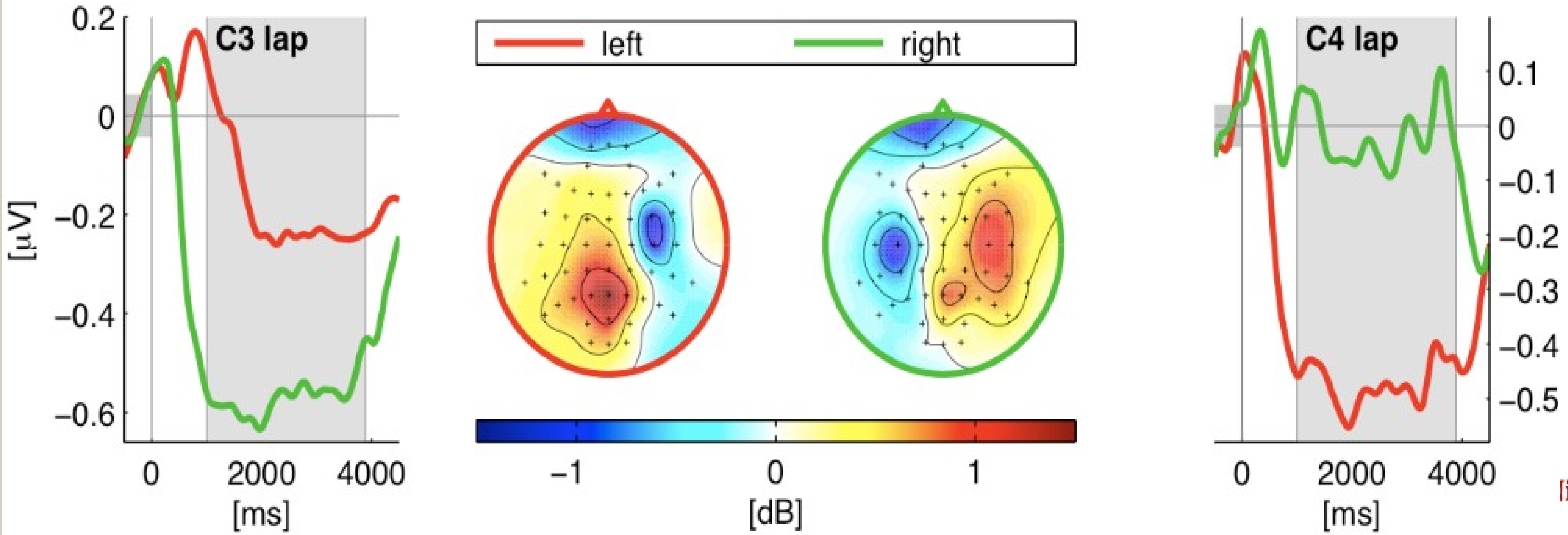
- Matrix Speller BCI
  - Stimulus dependent
  - Evoked Response

6-Movement Based BCIs



Lateralised Readiness Potential (LRP)





ERD/
ERS

Evoked BCIs

- ERP – time-locked signal generated in response to stimulus
- Can depend on more than raw stimulus properties, e.g.

Syntatic processing, semantic processing, semantic updating, error-processing, surprise, etc.

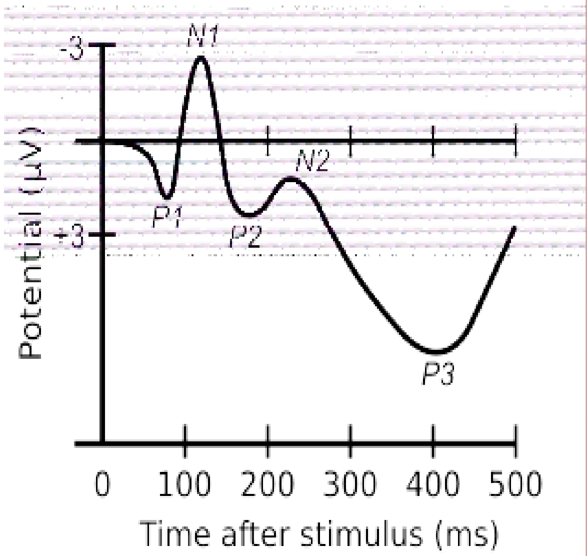
- P300 – 'oddball' response

Evoked by: unusual stimulus or absence of stimulus

Influenced by: uncertainty resolved by event, importance (salience) of the stimulus

P300a – stimulus response

P300b – cognitive response



- P300 - ERP applications

Cortically Coupled Computer Vision (CCCV/RSVP), Brain-fingerprinting

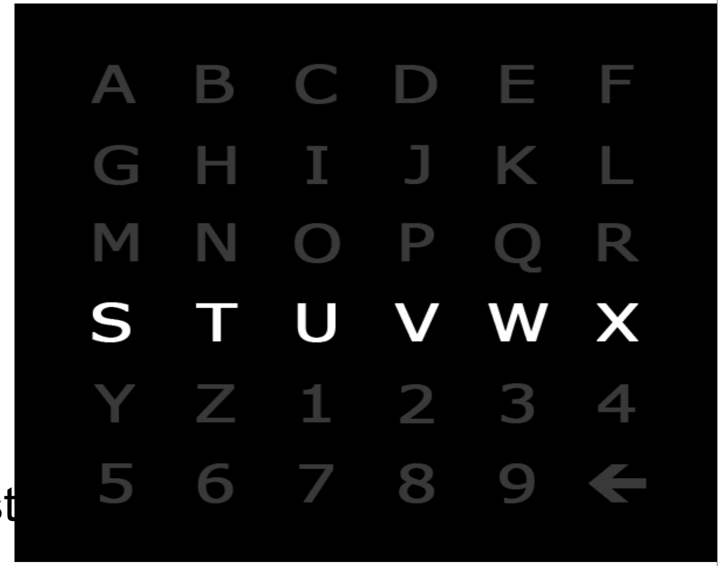
- BCI spelling (Farwell&Donchin) matrix speller

Parallel selective attention task

Each symbol has unique sequence of 'odd-ball' events

- Overt vs. covert attention

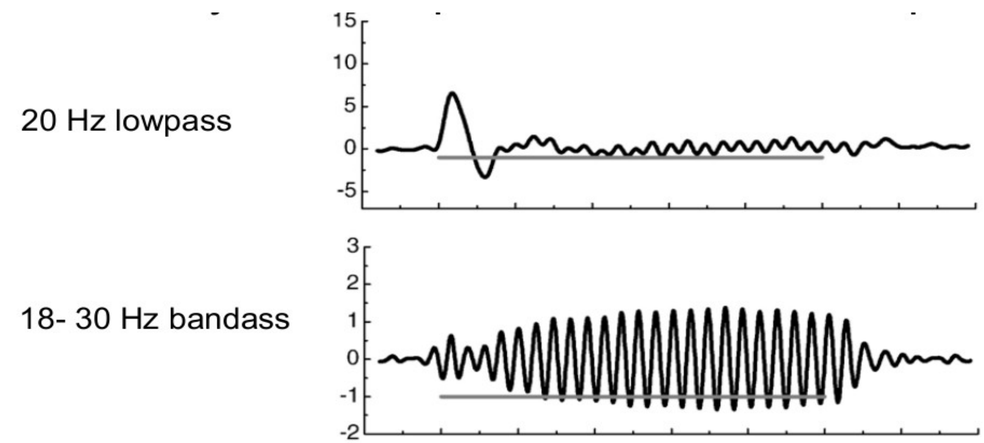
Most matrix speller performance based on eye-pointing **but st** works without it..



7-Evoked BCIs - SSEPs

- Steady State Response

response to long-term periodic stimulus



- Modality dependent optimal frequency

Visual (VSSEP)– 16-20Hz, occiptial cortex

Auditory (ASSR) – AM modulation ~40Hz, auditory cortex

Tactile (SSSEP) – AM ~21Hz, contralatorial somatosensory cortex

Used to diagonise correct operation of the sensory system

- Response amplitude influenced by selective attention

Used for parallel/serial selective attention BCI

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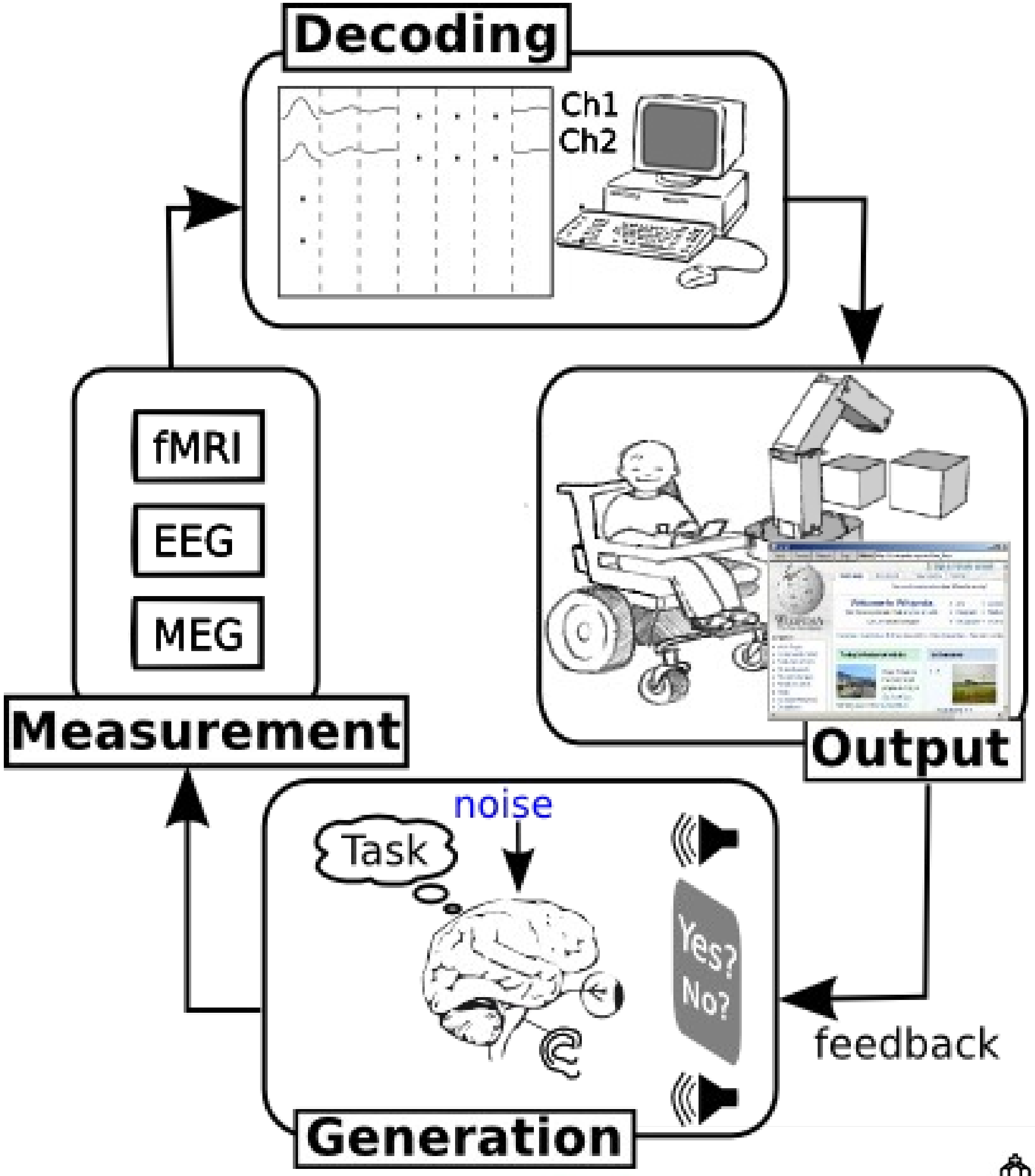
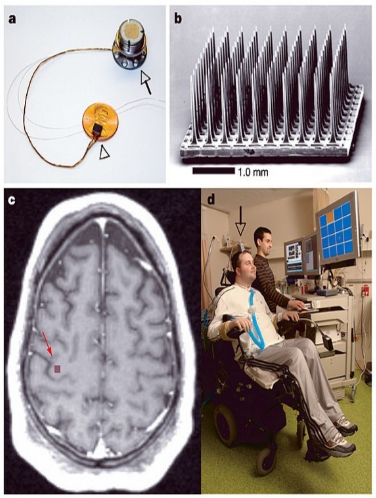


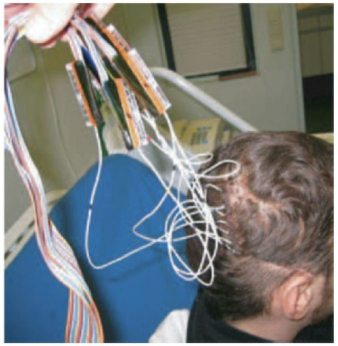
Measurement : Types of Devices

Invasive

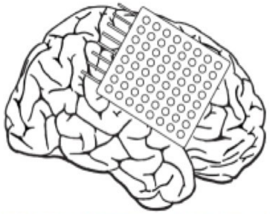


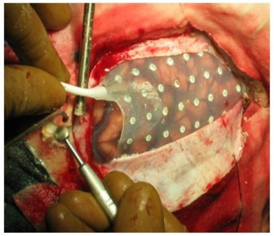
Implanted microelectrode array (Cyberkinetics, Inc)

Figure from Hochberg et al. Nature, July 2006.



Department of Epileptology, University of Bonn, 2004





Electrocorticography (ECoG)

Non-Portable

Magnetoencephalography (MEG)

Functional Magnetic Resonance Imaging (fMRI)

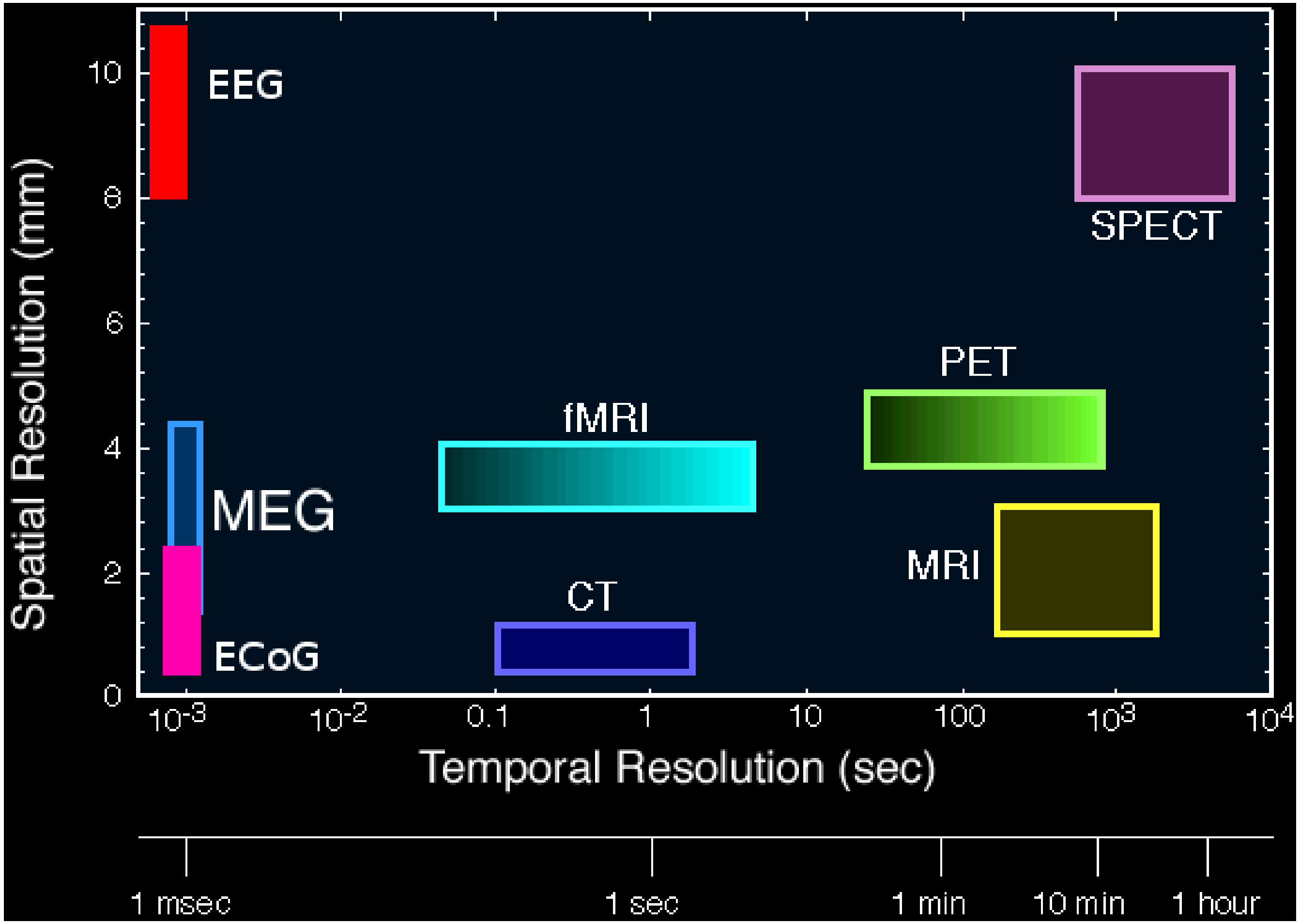
Portable & Cheap!

Electroencephalography(EEG)

Near Infra-Red Spectrophotometry (NIRS)

Measurement Devices – Performance

- Different detectors give different spatio-temporal resolution



- Measure different aspects of Neural Activation
  - FMRI, NIRS – heamodynamic response
  - EEG, MEG, EcoG, wire – electrical response

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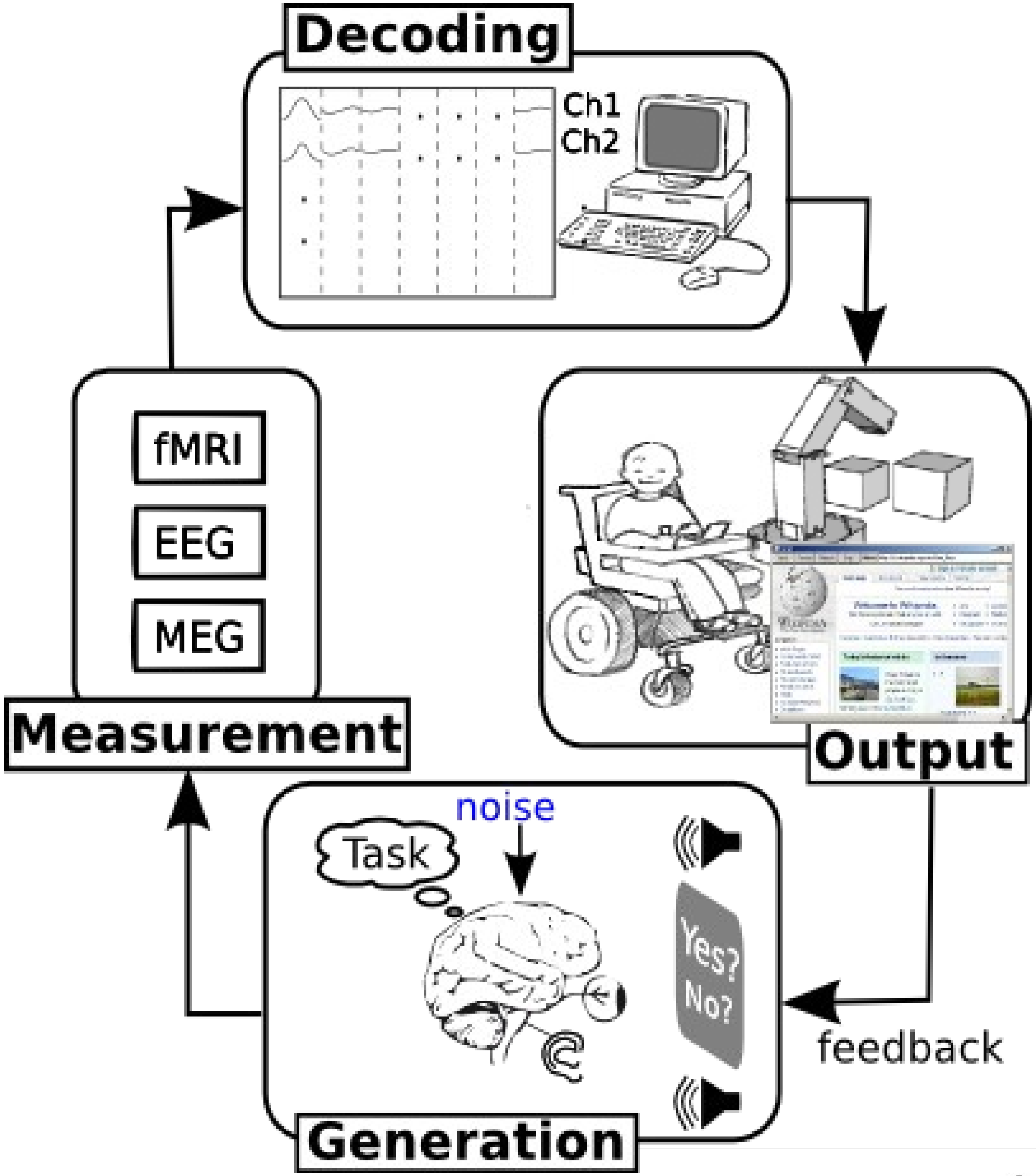
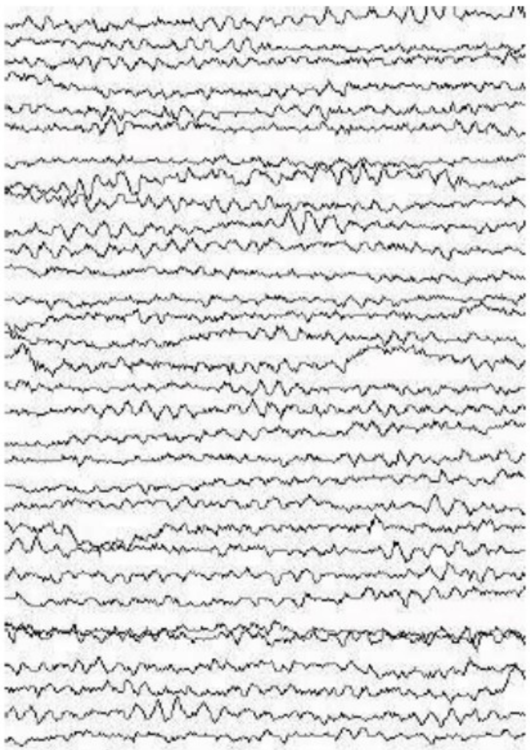
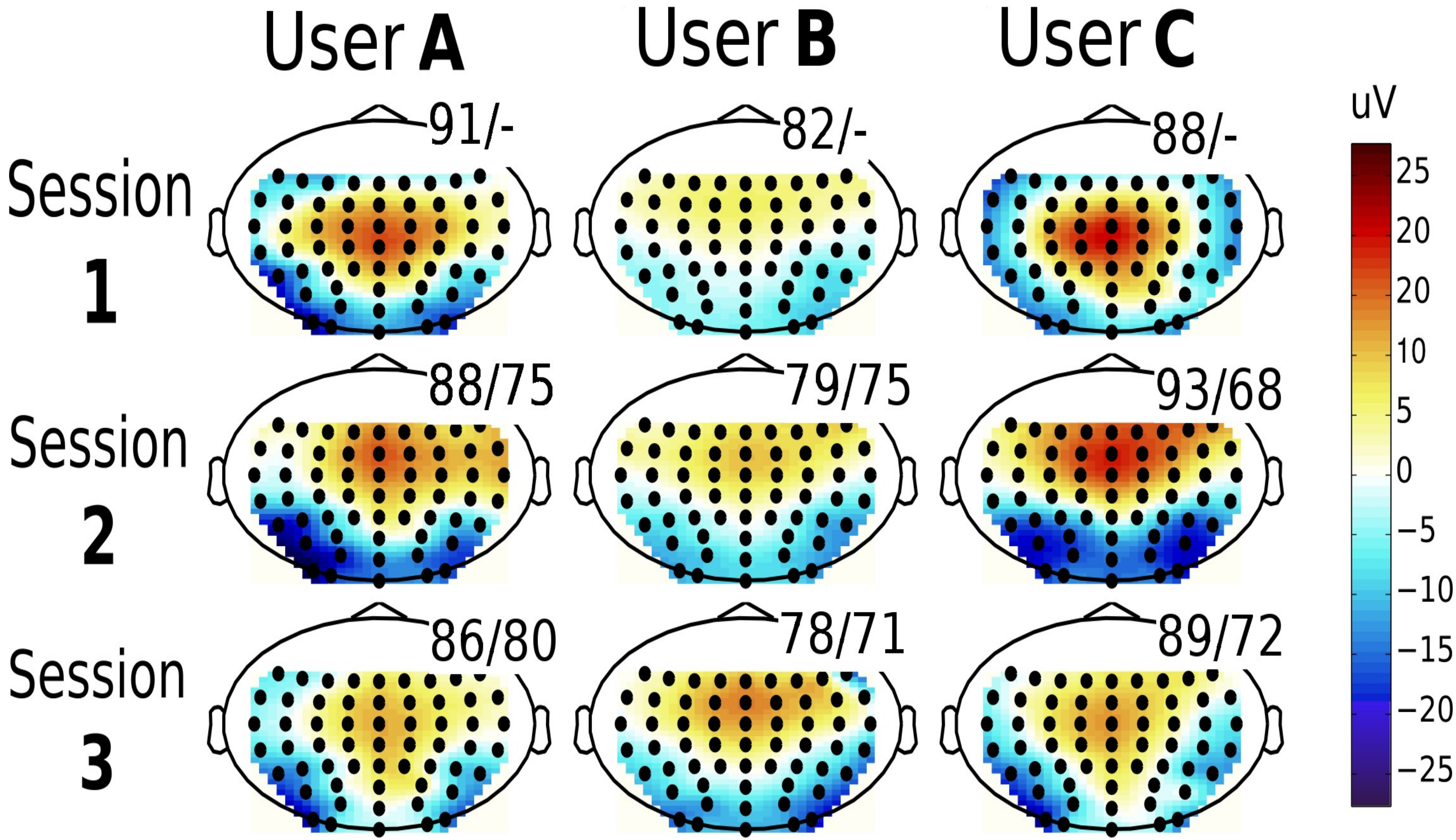




$$\mapsto \begin{cases} \text{yes} \\ \text{no} \end{cases} ?$$


User A
User B
User C
Session 1
Session 2
Session 3
91/-
82/-
88/-
88/75
79/75
93/68
86/80
78/71
89/72
uV
25
20
20
10
5
0
−5
−10
−15
−20
−25

Decoding Options

- We have 2 options
  - Train the user using neuro-feedback to generate a strong pre-defined signal, e.g. voltage >.5muV over electrode Cz
  - Train the machine to learn this users specific signal properties

We use machine learning and in particular classification to automatically decode the neural code for each particular subject.

- Shift the burden of learning off the patient and onto the computer
- Minutes to recognize relevant features, rather then weeks/months training a patient to modulate pre-defined features
- Let the system run itself – no intervention from experts required

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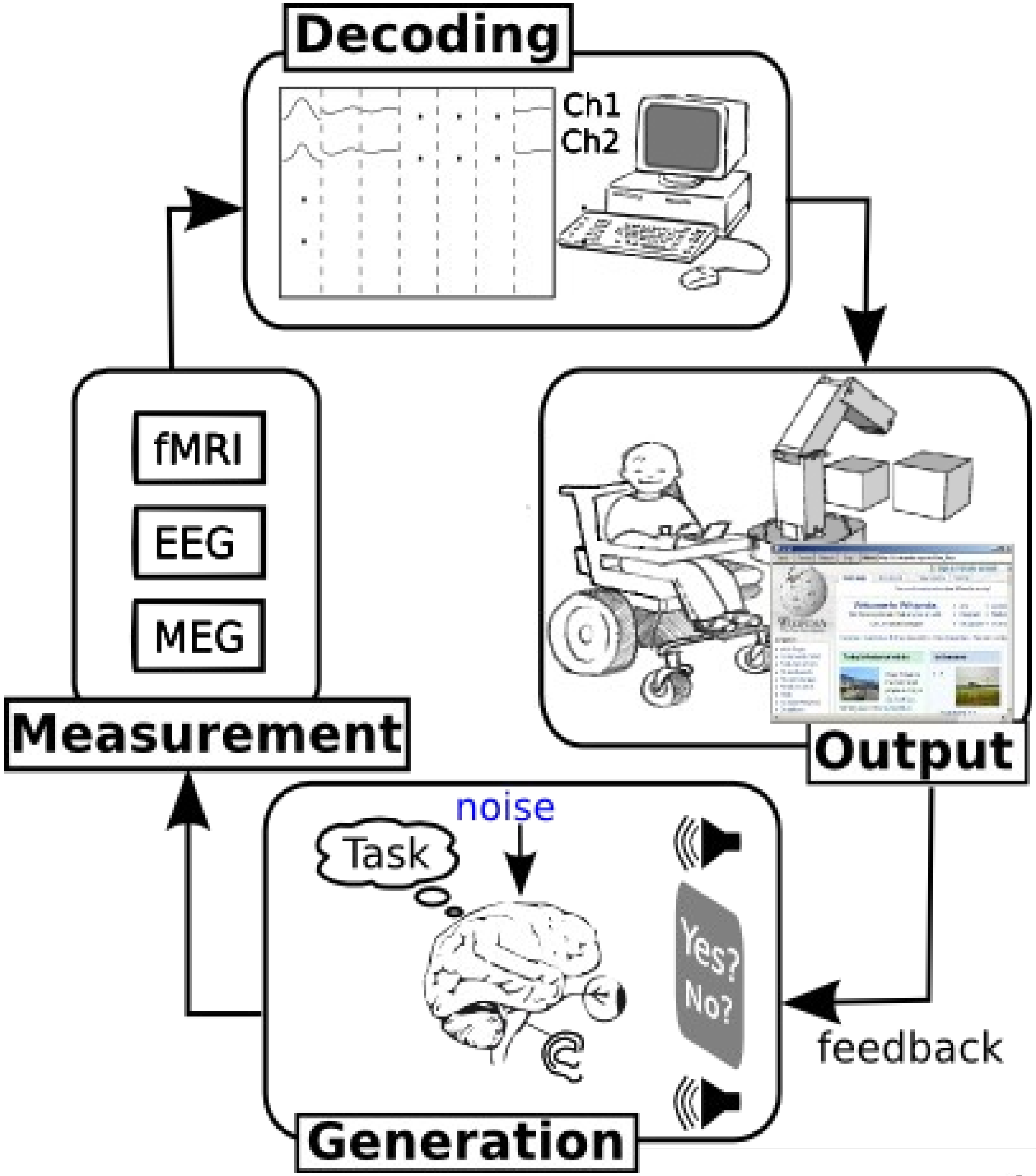


In fact this simple problem was 'solved' about 20yr ago:

- [Farwell & Donchin 1988] P300 Visual Speller
- [Birbaurmer N. 1992] Slow Cortical Potential BCI
- [Pfurtscheller G. et. al. 1992] mu-band Imagined Movement BCI

So what have we been doing since then?

Think back to the sci-fi ideal BCI... fast, accurate, intutive

- Building a demo BCI is easy...
- Building a usable BCI is hard!

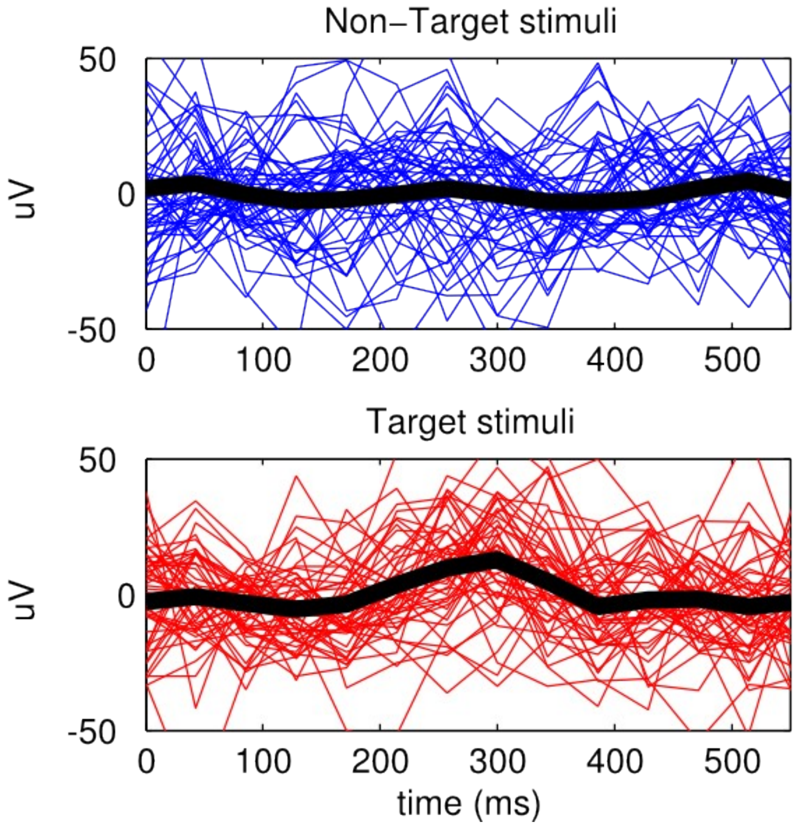
As with speech recognition, to be usable a BCI must be:

- Fast – <3s per binary decision
- Accurate – >90% correct decisions

Further (to a lesser extent) it should be:

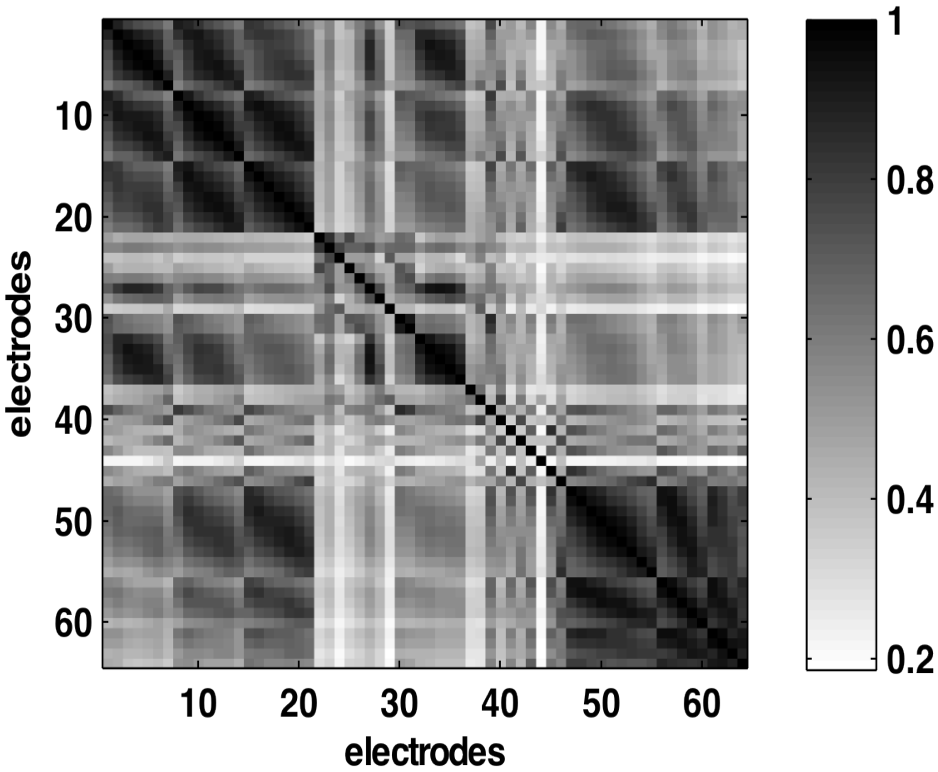
- Easy to use – no expert knowledge or human intervention to use
- Fast to setup – no long training times (for the user or decoder)
- Generally applicable – should work for everyone

Why is it so hard to make usable BCIs?



- Low signal to noise ratio (~1:5)
  - External noise sources
  - Other neural sources
  - Muscle artifacts – eye, neck, tongue (5-10x stronger than neural)
  - 50Hz line noise

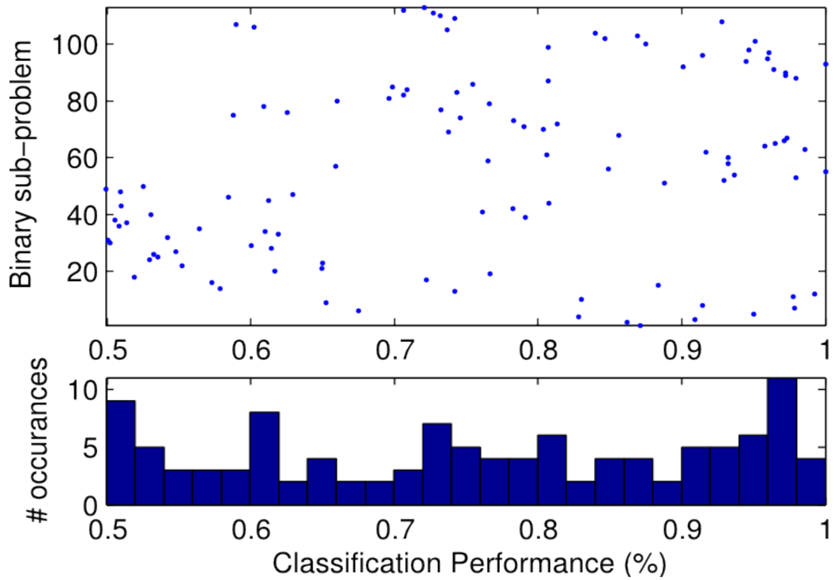
Why is it so hard to make usable BCIs?

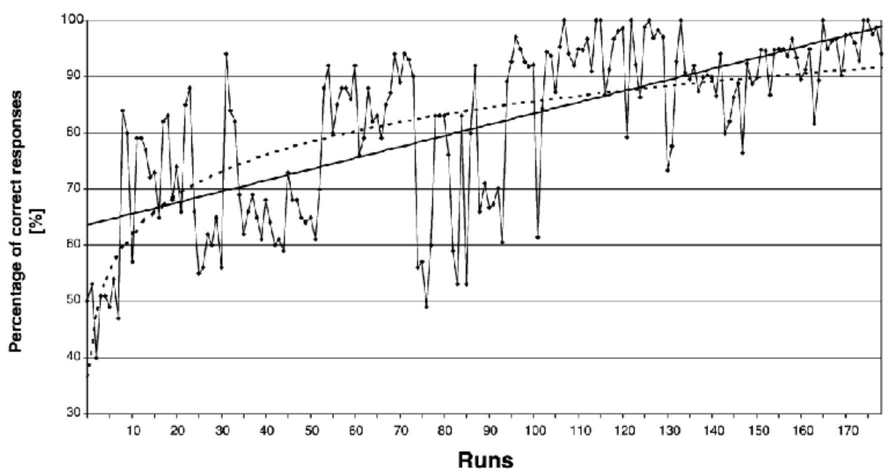


Low spatial resolution

- Due to signal propagation effects
- High sptial correlation between electrodes

Why is it so hard to make usable BCIs?





High levels of inter-subject variability

– BCI illiterates

High levels of inter-session variability

– And user learning

So why has BCI suddenly become so popular?

- Algorithms and Hardware
  - Signal-processing + Machine Learning (ML) algorithms
    - Sophisticated enough to make accurate deicsions on very little data
  - Hardware
    - Computational hardware cheap enough to run fancy algorithms
    - Recording hardware (i.e. EEG) cheap/small enough for many groups (including consumers) to afford

Challenges in BCI research

1) Increasing speed
2) Increasing accuracy
3) Addressing the problem of BCI illiterates
4) Reducing (removing) calibration-time – i.e. rapid user-adaptation/cross-subject generalisation
5) Continuous self-paced operation – i.e. separating commands from the background
6) Adapting to the non-stationarity of BCI signals
7) Exploiting neural plasticity/user learning to improve performance over time
8) Ease of use – make intention encoding more direct
9) Increasing speed+Accuracy ;-)

Summary

- BCIs communicate user intentions without the peripherial nervous system
- Intentions encoded in the selection of a mental task
- 2 main types of BCI – stimulus-dependent (evoked) and stimulus-independent (induced)
- BCI design problem is to make BCIs faster, more reliable, easier to user etc...
- Two approaches to doing this:

1) Improve the encoded signals strength by optimising the mental task

2) Improve the signal decoding by using advanced signal-processing/machine learning

Gross structure of a typical BCI experiment

Requirements : what do you need to build a BCI?

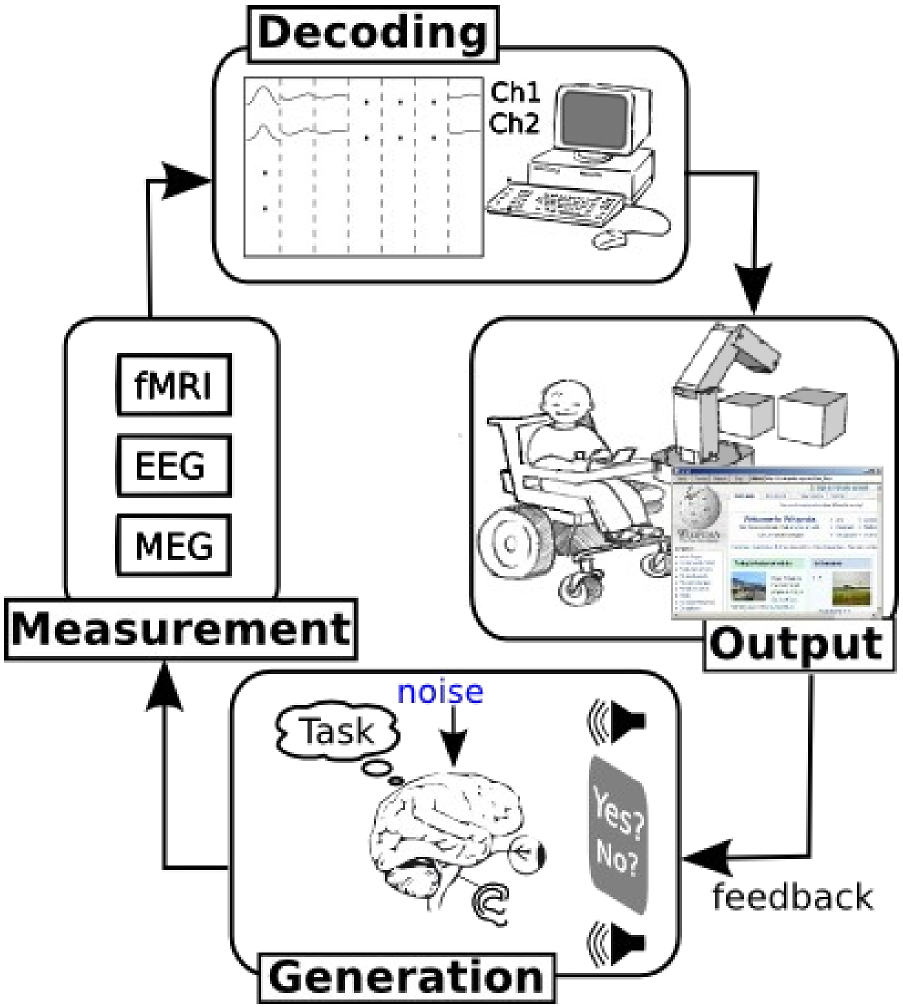
1) **Data acquisition**: Drivers to extract data from hardware

2) **Stimulus Generation**: makes stimuli that the subject will experience, for subject instruction, feedback, event-related stimuli

3) Something to **process** the signals, firstly to train the classifier, and secondly to decode the users mental state, i.e. do the BCI bit ;-)

4) Way of **annotating** data to what the subject was experiencing/doing at that time with what was measured from their brain/body, e.g. LH movement, reading instruction, watching cue, etc.

5) Way of **tracking** where we are in execution of the experiment flowchart, i.e. block, sequence, epoch number, and scheduling what should happen next



Break requirements into 4 independent communicating processes:

1)Data-acquisitation & annotation
- ·Get data from hardware
- ·Attach annotations (markers, events) to particular data sample

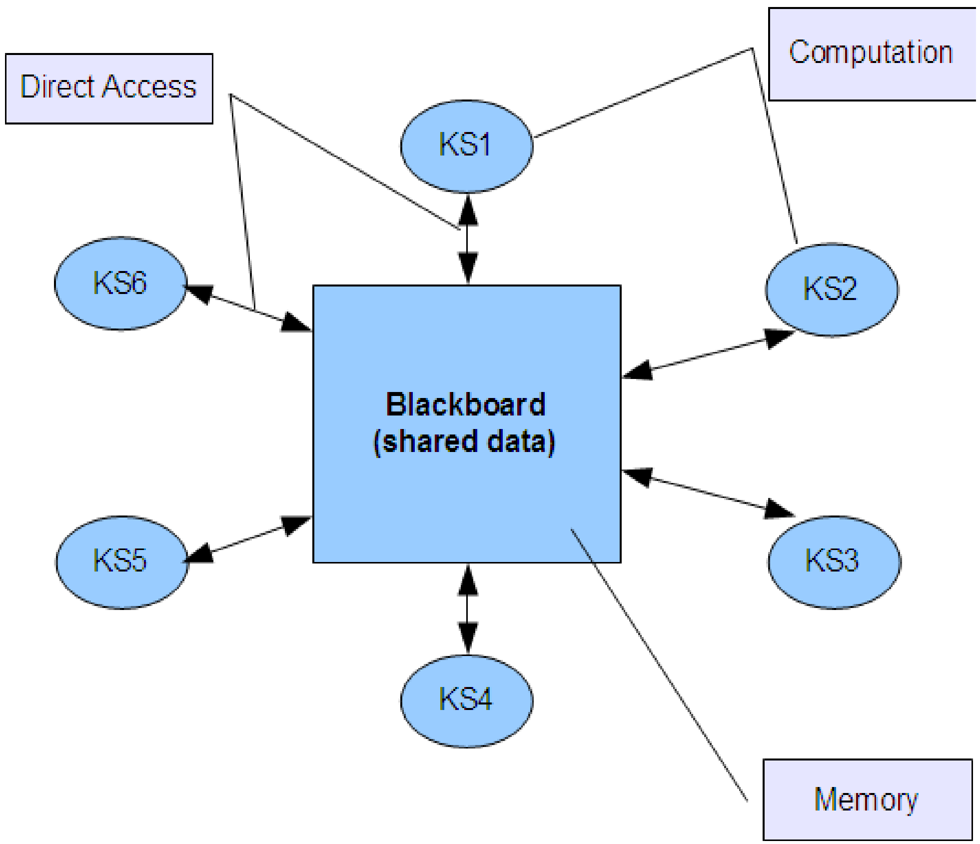
2)Stimulus generation
- · Make stimuli when requested by the expt controller
- · Make feedback based on predictions generated by the sig-processor

3)Signal Processing
- ·Process the data based on the annotationss, and generate predictions

4)Experiment control (scheduling)
- Control the flow of the experiment

Basic Idea:

- set of independent processes
- any process can send/recieve data-annotation events
- events are visible to all other processes
- Processes communication implemented by sending receiving events
- (N.B. As all events are saved with the data, annotations are automatically archived for later off-line use).
- Similar in concept to that used in 'Blackboard architectures' for AI, see <en.wikipedia.org/wiki/Blackboard_system>



Ft-buffer based Implementation

- Buffer-BCI framework implemented using the fieldtrip-buffer system (fieldtrip.fcdonders.nl/development/realtime)
- Ft-buffer provides:
  - Drivers for data-acquisation
  1) buffer storage for data (~last 1 minute data)
  2) buffer storage for events (~last 50 events)

Idea:

- Buffer events store represents the blackboard used for inter-process communication (IPC)
- Every event has timestamp (sample number) used for data-annotation

Start the different needed processes:

1) Start buffer (for annotation)

1.1) Start acquisition driver (if needed)

2) Start signal-processing

3) Start stimulus presentation

3.5) Start experiment scheduler (mostly merged with stimulus-presentation)

- Building BCI needs : acquisition and annotation, signal processing, stimulus presentation, and experiment scheduling
- Fieldtrip Buffer provides framework for acquisition and annotation
- Also provides a method for event/message passing between different processes
- Implement the other parts as independent processes communicating by passing events