ECE 370
Introduction to Biomedical Engineering

Brain-Computer Interfaces

Things in Perspective

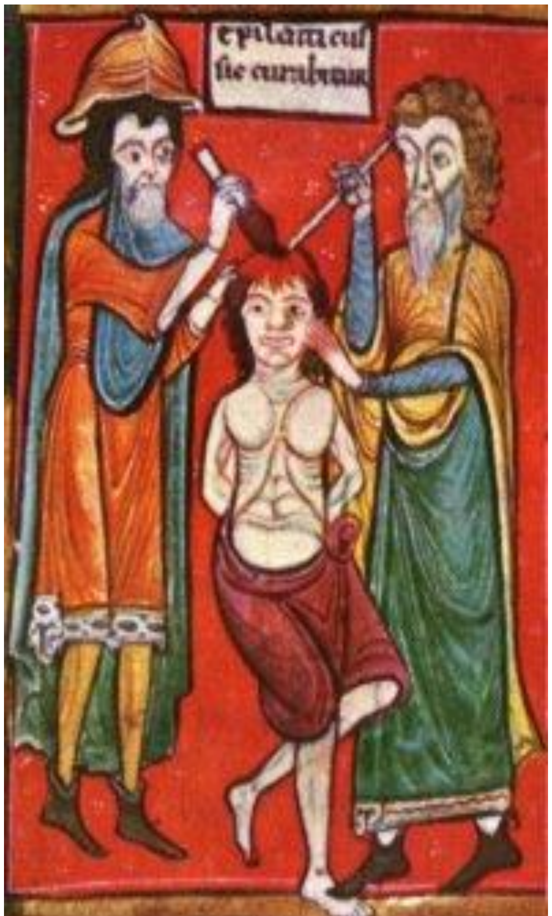
- **Imagine how debilitating it is to:**
  - Be paralyzed from the neck down (tetraplegia)!
  - Being unable to breath on your own (mechanical ventilation)!
  - Sometimes also being unable to talk!

Things in Perspective

- **Starbase 11, Stardate 3012.4 (i.e. January 5, 2326)**
  - "… Wheelchair constructed to respond to brain waves … A flashing light to say 'yes' or 'no' … Kept alive mechanically by a battery driven heart .. ."
  - Star Trek TV Series, 1966.
- **Where are we today?**

Things in Perspective

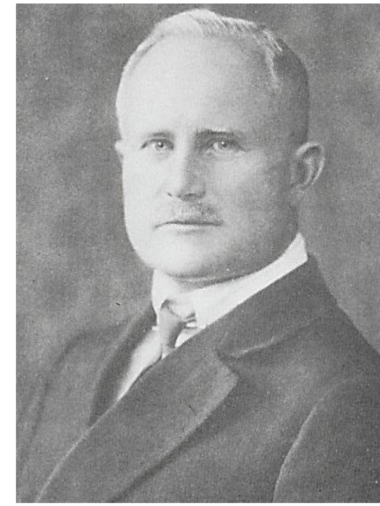
- **Technologies for the study of brain function**



Epilepticus sic curabitur ('The way to cure an epileptic') Sloane Manuscript, collection of medical manuscripts, end of the 12th century - British Museum, London

Jan Sanders Van Hemessen (1500-1566), The surgeon 1550, El Prado, Madrid

Things in Perspective



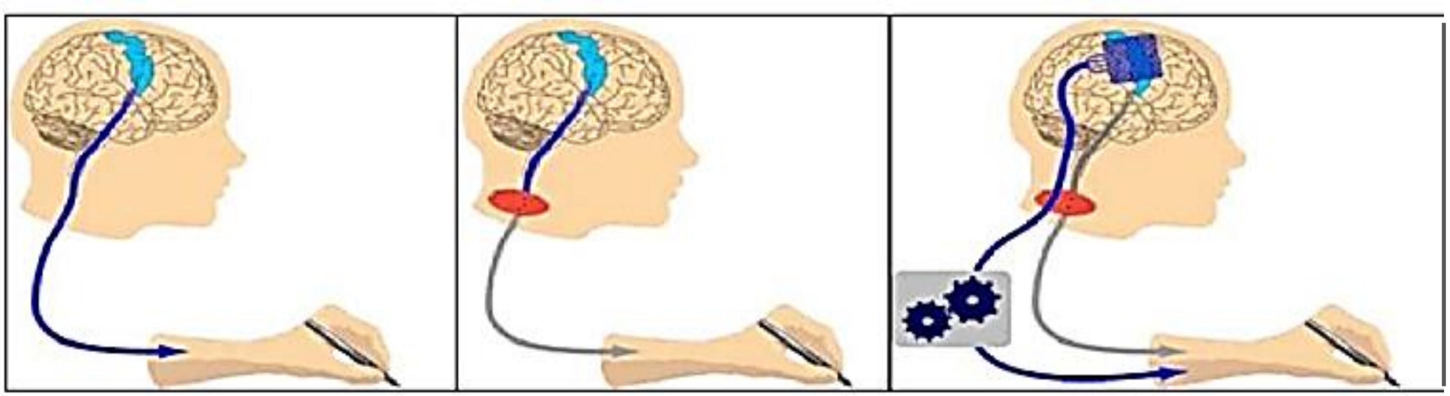
- **Recording brain signals from the human scalp**
  - 1924: Hans Berger discovers the EEG
  - Subsequently analyses the interrelation of EEG and brain diseases
- **First BCI described by Dr. Grey Walter in 1964**
  - Connected electrodes directly to the motor areas of a patient's brain (undergoing surgery for other reasons.)
  - The patient was asked to press a button to advance a slide projector
  - Dr. Walter recorded the relevant brain activity
  - Then, connected the system to the slide projector so that the slide projector advanced whenever the patient's brain activity indicated that he wanted to press the button.
  - Interestingly, the slide projector advanced before the patient pressed the button!
  - Control before the actual movement happens = the first BCI!
  - Unfortunately, Dr. Walter did not publish this major breakthrough.
- **BCI research advanced slowly for many more years.**
- **BCI research developed quickly during the last decade.**

What is a BCI?

"Brain–computer interfaces (BCI's) give their users communication and control channels that do not depend on the brain's normal output channels of peripheral nerves and muscles."

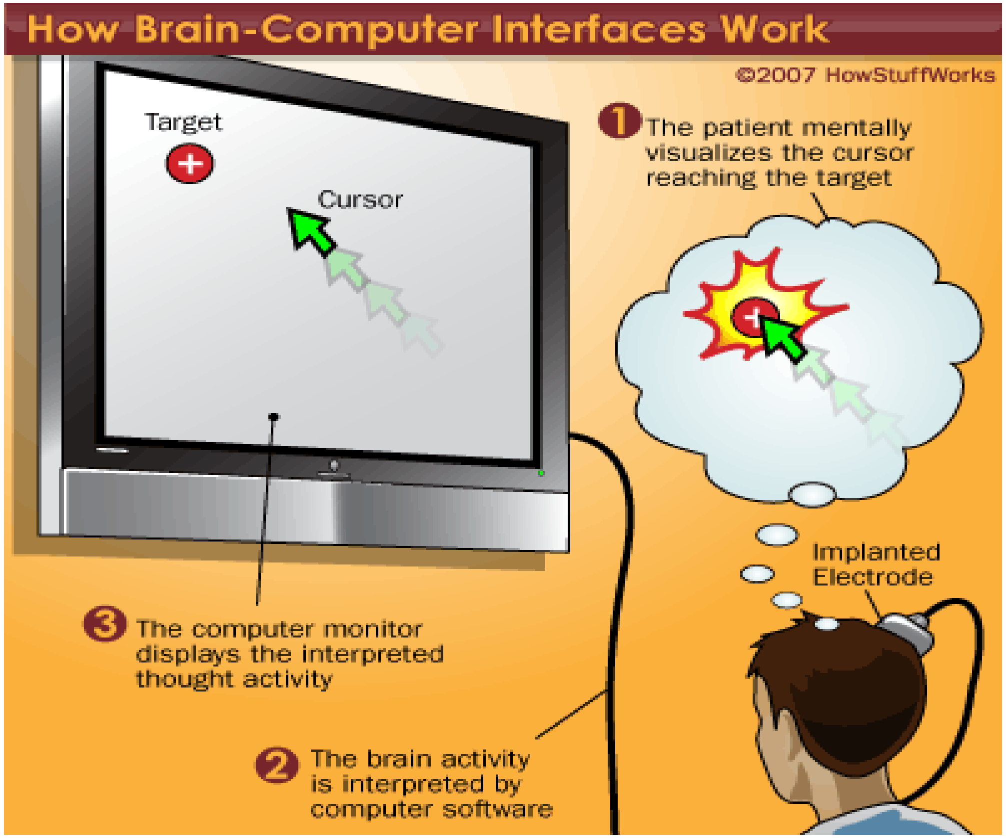
"A BCI changes the electrophysiological signals from mere reflections of CNS activity into the intended product of the activity: messages and commands that act on the world"

Wolpaw, 2002



What is a BCI?

- **Interface between the brain and computer**
  - Normally: hands and arms, voice
  - Could be damaged because of stroke, trauma, paralysis, or neuropathy
- **A Brain-Computer Interface (BCI):**
  - Read electrical signals or other manifestations of brain activity
  - Translate them into a digital form that computers can understand, and process
  - Convert them into actions
    - E.g. moving a cursor or turning on a TV
  - BCIs can help people with inabilities to control computers, wheelchairs, televisions, or other devices with brain activity

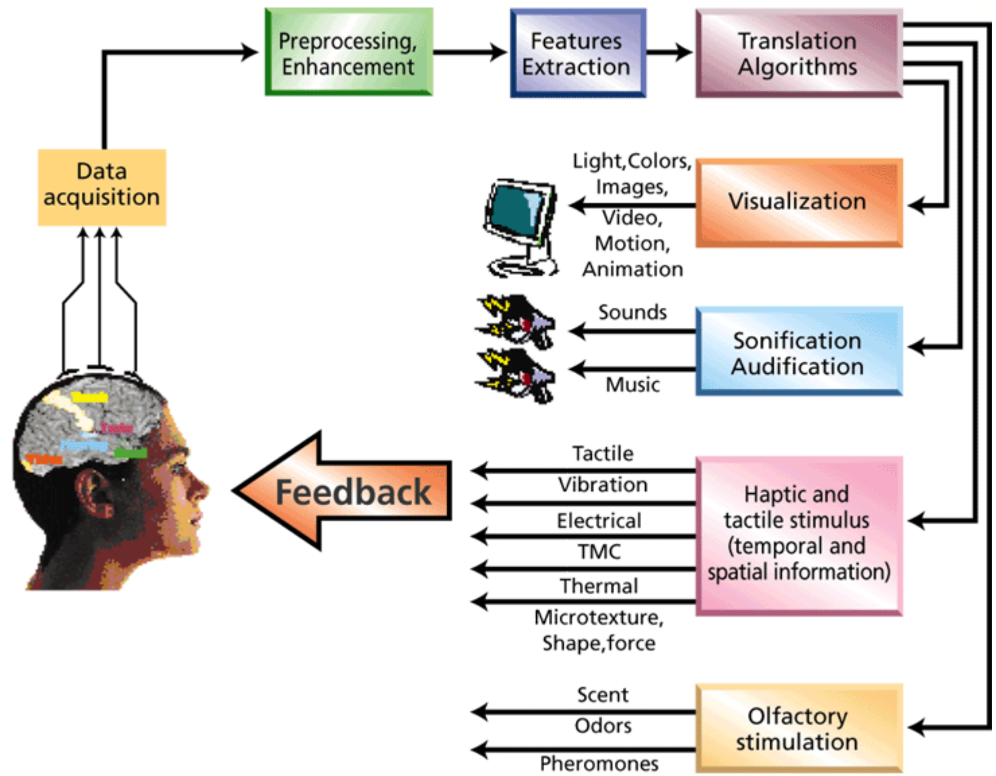


What is a BCI?

- **BCIs are <u>not</u> the same as neuroprosthetics**
- **Neuroprosthetics**
  - Use artificial devices to replace the function of impaired nervous systems or sensory organs.
  - Connect the nervous system to a device
  - E.g. cochlear implants, retinal implants.
- **BCIs**
  - Connect the brain (or central nervous system) with a computer system.
  - E.g. EEG → computer

Components of a BCI

- **The 3 major components of BCIs**
  1. Ways of measuring neural signals from the human brain
  2. Methods and algorithms for decoding brain states/intentions from these signals
  3. Methodology and algorithms for mapping the decoded brain activity to intended behavior or action.



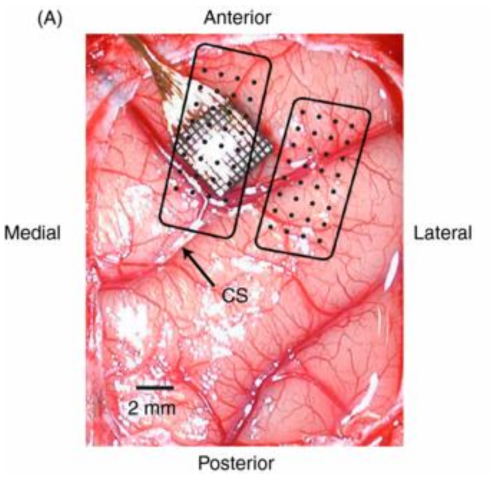
BCI System: Input

- **Brain signal can come from**
  - Invasive electrodes
  - Non-invasive measurements
    - EEG, fMRI, etc.

- **Underlying assumption**
  - Intentions have discernible counterpart in brain signal

BCI System: Input

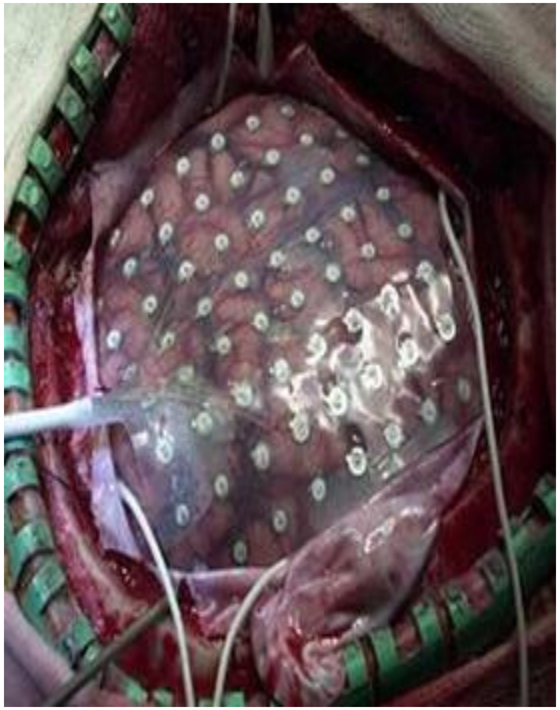
- **Invasive BCI**
  - Most accurate signal
  - Most risky
    - Can cause damage to brain, leaves brain exposed
  - Accuracy fades over time
    - Damage to the brain, bodies defenses attack foreign object, scar tissue
- **Example of artificial vision**
  - BCI containing 68 electrodes was implanted onto volunteer’s brain
  - Implant had permitted him to see rough images of large objects
  - Initially, allowed the volunteer to see shades of grey in a limited field of vision at a low frame-rate.
  - Able to use his imperfectly restored vision to drive slowly



BCI System: Input

- **Partially-Invasive BCI**
  - More accurate than non-invasive BCI, more risky
  - Less accurate than invasive BCI, less risky
  - Placed under the skull, but not in the brain

  - Electrocorticography (ECoG) is a very promising intermediate BCI modality.
    - higher spatial resolution,
    - better signal-to-noise ratio,
    - wider frequency range
    - first trialed on humans in 2004 on a teenage boy suffering from epilepsy to play Space Invaders.
    - This technique was used when the neural differences between vowels and consonants were discovered



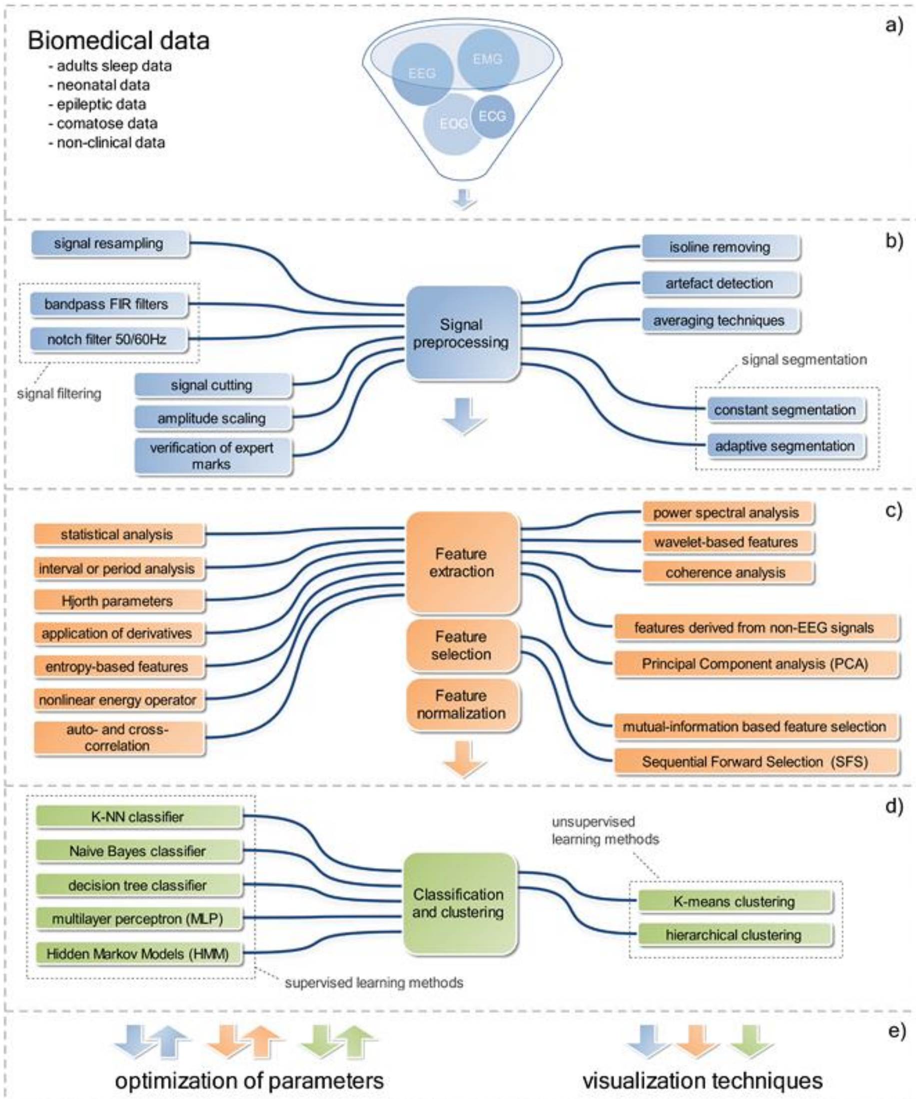
BCI System: Input

- **Non-Invasive BCIs:**
  - Less accurate signal
    - Cranium alters the signals that are picked up from the brain, can cause problems
  - Less risky
    - Brain isn't exposed, less risk to overall health

- **Electroencephalogy (EEG)**
  - Measures electical activity in brain
  - Non-invasive
  - Susceptible to noise
  - Easy to use + low cost + portable
  - Most commonly used device in BCIs
- **Magnetoencephalogy (MEG)**
  - Measures magnetic fields produced by electrical activity in brain
  - Non-invasive
  - Very accurate
  - High equipment requirements and maintenance costs (requires superconducting coils and extreme isolation)
- **Functional Magnetic Resonance Imaging (fMRI)**
  - Measures blood flow in brain using MRI (hemodynamics)
  - Blood flow correlates to neural activity
  - Studies the brain's function
  - Very accurate
  - Very high costs due to MRI

BCI System: Processing

- **Pre-processing**
  - Initial steps taken to improve the signal
  - E.g. recombining electrodes can improve SNR of EEG
- **Signal Enhancement**
  - Subsequent processing to improve signal quality
  - E.g. filtering to reduce noise
- **Feature Extraction**
  - Extract useful signal characteristics
    - Features should correlate with condition.
    - They must be detectable in single trial
  - E.g. Independent-Component Analysis and/or Common-Spatial Patterns
- **Translation Algorithms**
  - Methodology and algorithms for mapping the decoded brain activity to intended behavior or action.
  - Two principal approaches:
    - Brute force machine learning and training
      - Combine all imaginable features
    - Features with a functional correlate



BCI System: Actuation and Feedback

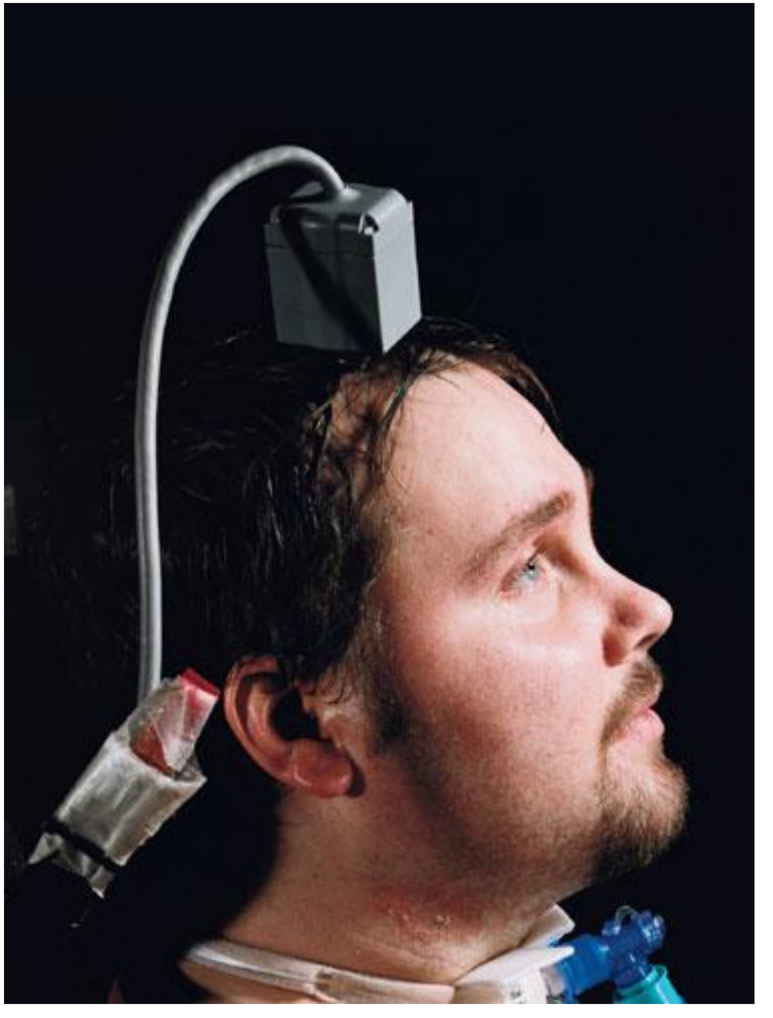
- **Construct devices which can perform the intended task**
  - Mouse cursor
  - Robotic arm
  - Sensory devices (vision, hearing, etc.)
- **Provide feedback to improve training and effectiveness**
  - Haptic
  - Visual
  - Auditory
- **Feedback can be included in the device itself**
  - E.g. robotic arm with feedback to enhance and simplify operation and improve safety

History - Monkey first …

- **1990: First successful experiments with monkeys**
  - Implanting electrode arrays into monkey brains
  - Recording of monkeys‘ brain waves
  - Offline reproducing of movements
- **2000: Monkeys control robots by thoughts**

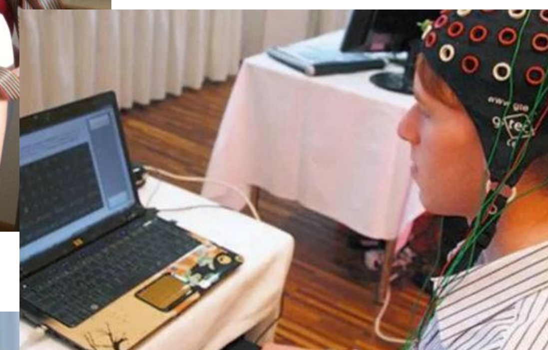
History - … Humans follow

- **2004: First human benefits from research**
  - Matt Nagle is able to control a computer and move a prosthetic hand
- **More non-invasive than invasive approaches**
- **Brain reading by eg. EEG, MEG or fMRI**



BCI Applications

- **Medical Rehabilitation**
  - Brain damaged by stroke
  - BCI used to teach patient how to move muscles to which the brain has forgotten how to control
- **Communication**
  - Communication with patients that have motor-neural disabilities
    - Locked-In Syndrome
  - Attach patient to BCI, output as cursor movement
- **Gaming**
  - Mindflex – EEG controlled obstacle course (2007)
  - OCZ Technology (2008) created a device for playing games controlled by EMG
  - NeuroSky – Star Wars Force Trainer (2009)



BCI Example

- **Woman moving robotic arm with intracortical implant**

EEG-based BCI

- **Sub fields of EEG-based BCI:**
  - Signal processing on the EEG
  - Cognitive task for the subject (psychology)
  - Designing computer application (HMS)
- **Typical pattern-recognition pipeline**
  - Preprocessing
    - Recombining electrodes can improve SNR
  - Feature extraction
    - Laplacian filters
    - Statistical recombination
      - Independent-Component Analysis
      - Common-Spatial Patterns
  - Classification

EEG-based BCI

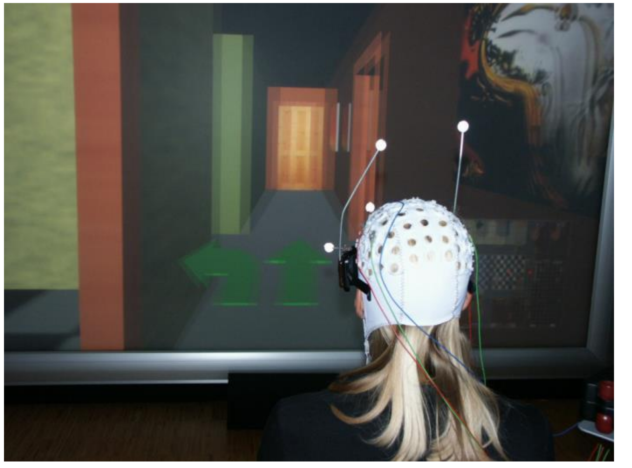
Feature Extraction

- **Signal is recorded in 2 or more conditions**
  - Features should correlate with condition.
  - They must be detectable in single trial
- **Two principal approaches:**
  - Brute force machine learning
    - Combine all imaginable features
  - Features with a functional correlate
    - Potential shifts: Slow cortical potentials
    - Rhythms: Alpha, mu, beta, etc.
    - P300: Particular waveform

EEG-based BCI

EEG Features

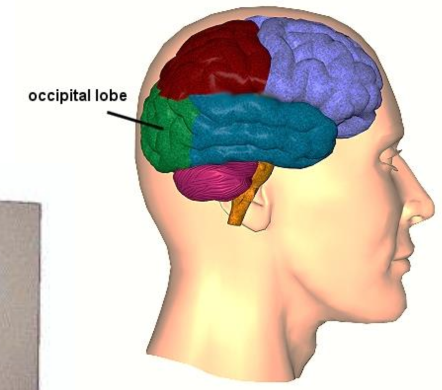
- **Sensorimotor Rhythm (SMR)**
  - Function of periodical brain activity
  - The predominance of a function
    - Expressed by spectral power
  - Many rhythms are ‘idling-rhythms’.
    - Alpha rhythm over occipetal lobe (~10Hz)
    - Mu rhythm over motor cortex (~10 Hz)
- **Slow cortical potentials (SCP)**
  - Low-pass filtered signal
  - E.g. Bereitschafts potential
  - Ability to self regulate
    - Also used for neurofeedback
    - To treat ADHD



University college, London & TU Graz
VR application, controlling a wheelchair

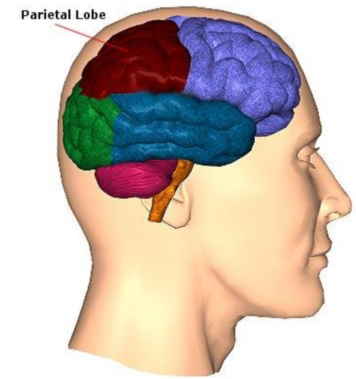
EEG-based BCI

- **Visual Evoked Potential (VEP)**
  - caused by visual stimulation
  - occurs with flashing lights (3 – 6 Hz)
- **Application**
  - Checkerboard with 64 fields
    - letters
    - words
  - “Splitting keyboard”

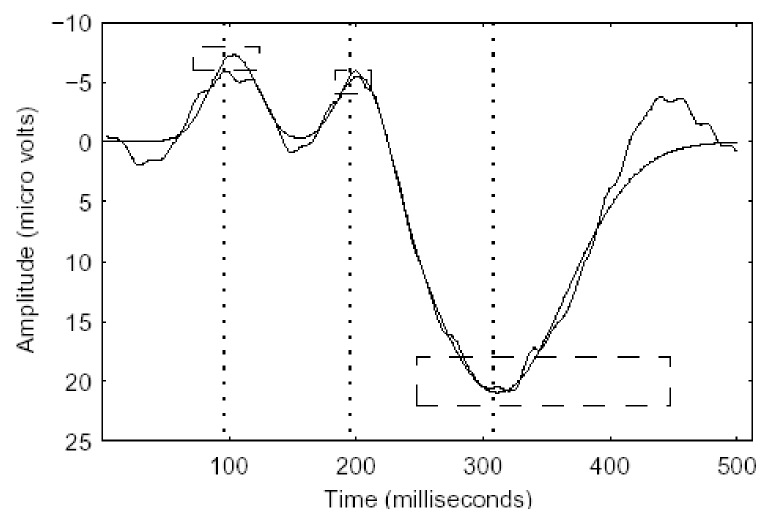


EEG-based BCI

- **P300**
  - An evoked potential
  - Less training
  - Indicate attended target
- **Features**
  - Positive curve on EEG after 300ms
  - Relevant stimulation
  - Strongest signal at parietal lobe

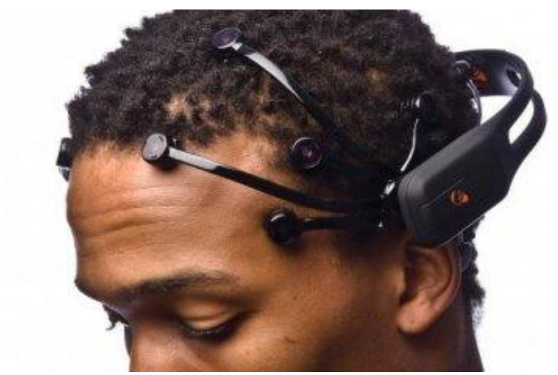


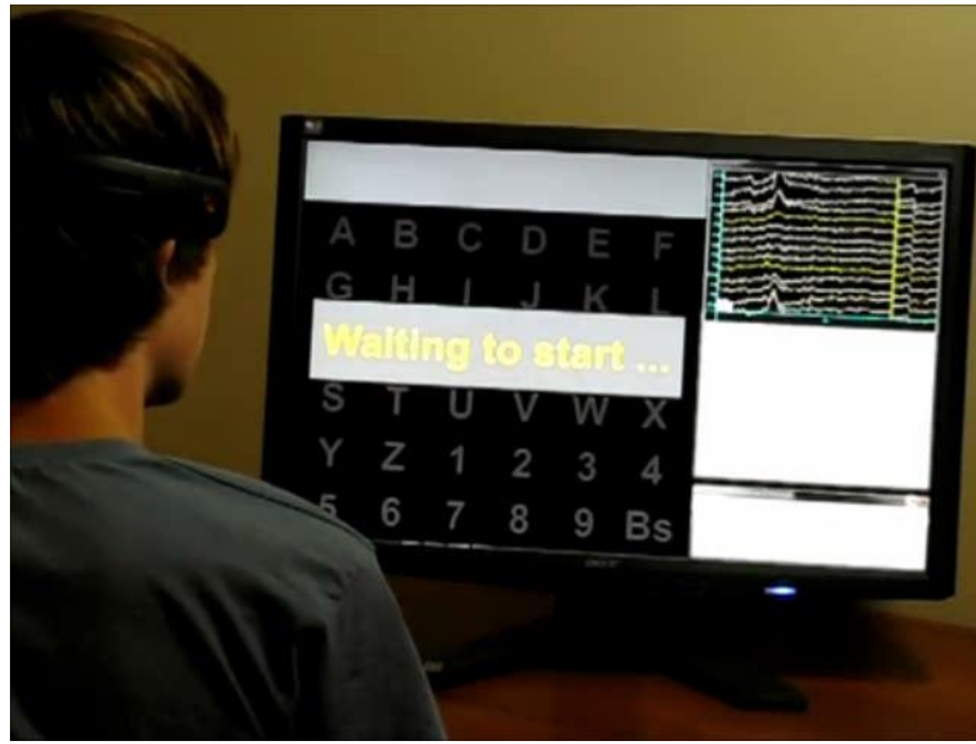
Outline of a P300 speller application. When target row/column is highlighted, it evokes a P300.



EEG-based BCI

- **P300 - Application**
  - Typing tool with 6x6 fields
  - Letter identification by column, row
  - Consecutive iteration
  - ~ 30 sec / letter





P300 Spelling Package in the BCI2000 open source research package, using the Emotiv EPOC Neuroheadset

EEG-based BCI

- **Applications are becoming more complex and more portable**

Emo-Active, Saintrino Technologies, Montreal, Canada

BCI Training

- **Subject: biofeedback**
  - Learning to control physiological 'parameters'
  - E.g. Heartrate, EEG-components
- **System: any Pattern Recognition method**
  - BCI challenge: Different sorts of data
- **Complexity of classifier**
  - Reduces 'meaningfulness' of transformation?
- **No 'continuous mutual learning'.**
  - Mostly epoch based
  - Update the system in between sessions
  - Danger of oscillations in feedback loop.

- **There is no between-subjects design yet**
  - Due to large inter-subject variability (?)

Clinical & Theoretical relevance

- **Most of the research is on healthy subjects**
- **Clinical research poses problems:**
  - Proper operation requires extensive training
  - Patients are only to learn control if they had it before the injury.
  - Small body of potential subjects
- **Birbaumer reports a**

  “significant increase in quality of life”

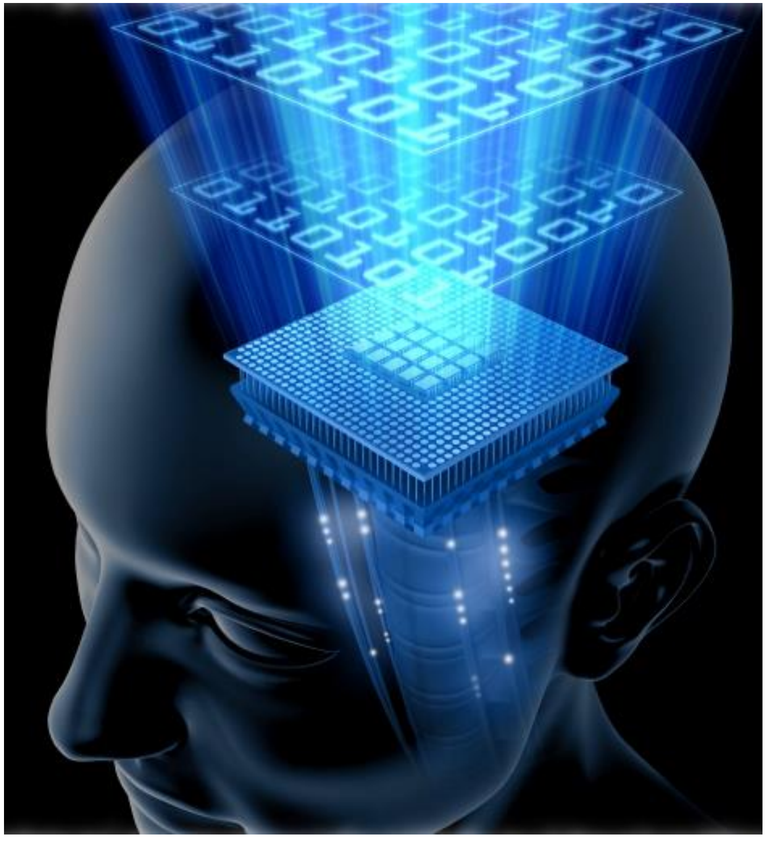
  They normally cannot communicate *at all*.

Ethical Considerations

- How can you obtain consent for a BCI from someone that can't communicate?
- Do the benefits outweigh the risks?
- What happens if someone wants to keep a thought secret and BCI detects it?
- What is the limit of what we will do with BCI?
- Could people use BCI to interrogate someone?

BCI Future Challenges

- **The brain is incredibly complex.**
- **There are chemical processes involved as well.**
- **The signal is weak and prone to interference**
  - i.e. reading brain signals is like listening to a bad phone connection. There's lots of static.
- **The equipment is less than portable.**



BCI Future Challenges

- **"It's always hard to make prediction, especially about the future"**
- **"640 KB RAM will be adequate for everybody in the future"**
  - Bill Gates, 1981
- **"Computers are interesting, but the mondial market for them is limited in the future to not more of 5 pieces per year"**
  - Thomas Watson, IBM president, 1949
- **"People will not wear scalp electrodes during normal daylife"**
  - Chief of Research and Development of a mobile phone company