Lecture 1: Introduction

Introduction to Modern Brain-Computer Interface Design

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Outline

1. What is a BCI?
2. Application Areas and Examples
3. Scientific Challenge
4. Available Tools

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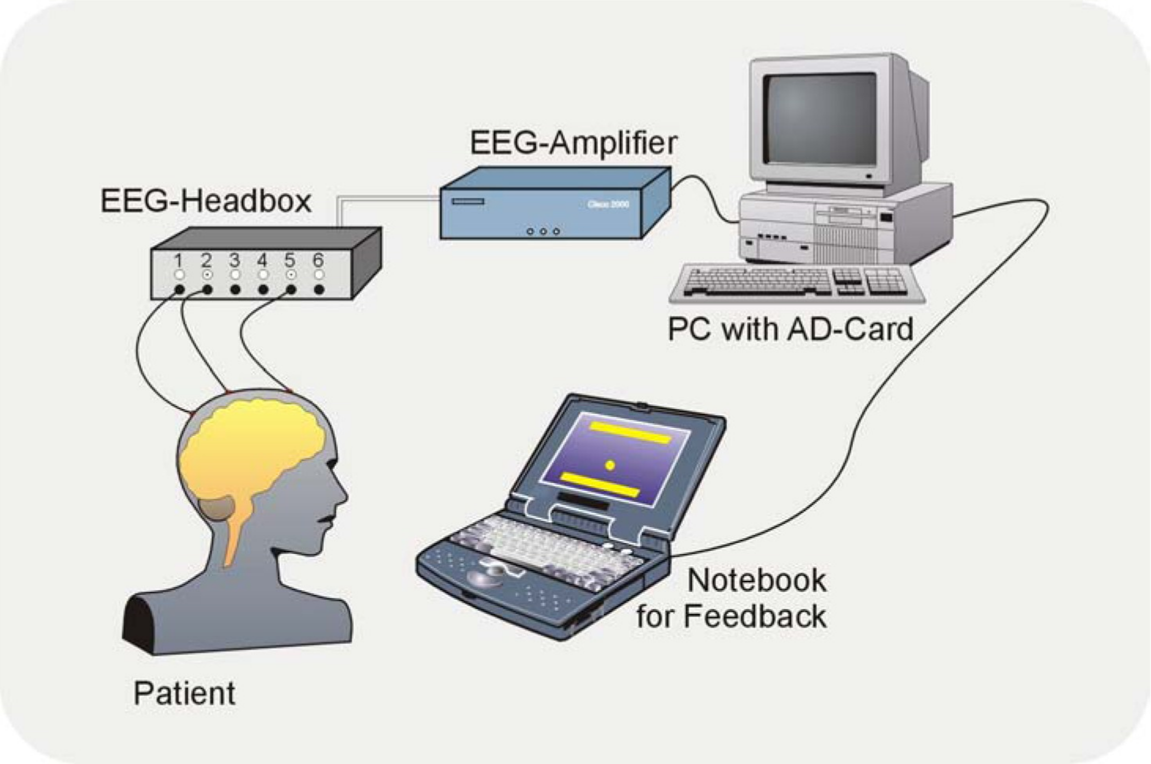
1.1 What is a BCI?

BCI: Traditional Definition

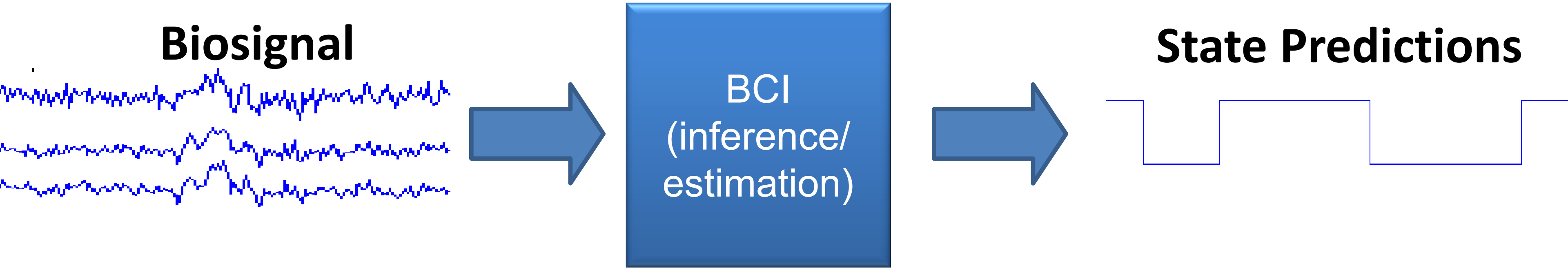
- “The goal of BCI technology is to give severely paralyzed people another way to communicate, a way that does not depend on muscle control.” (Wadsworth Center)



Schmidt, 2003

BCI: Our Definition

- "A system which takes a biosignal measured from a person and predicts (in real time / on a single-trial basis) some abstract aspect of the person's cognitive state."

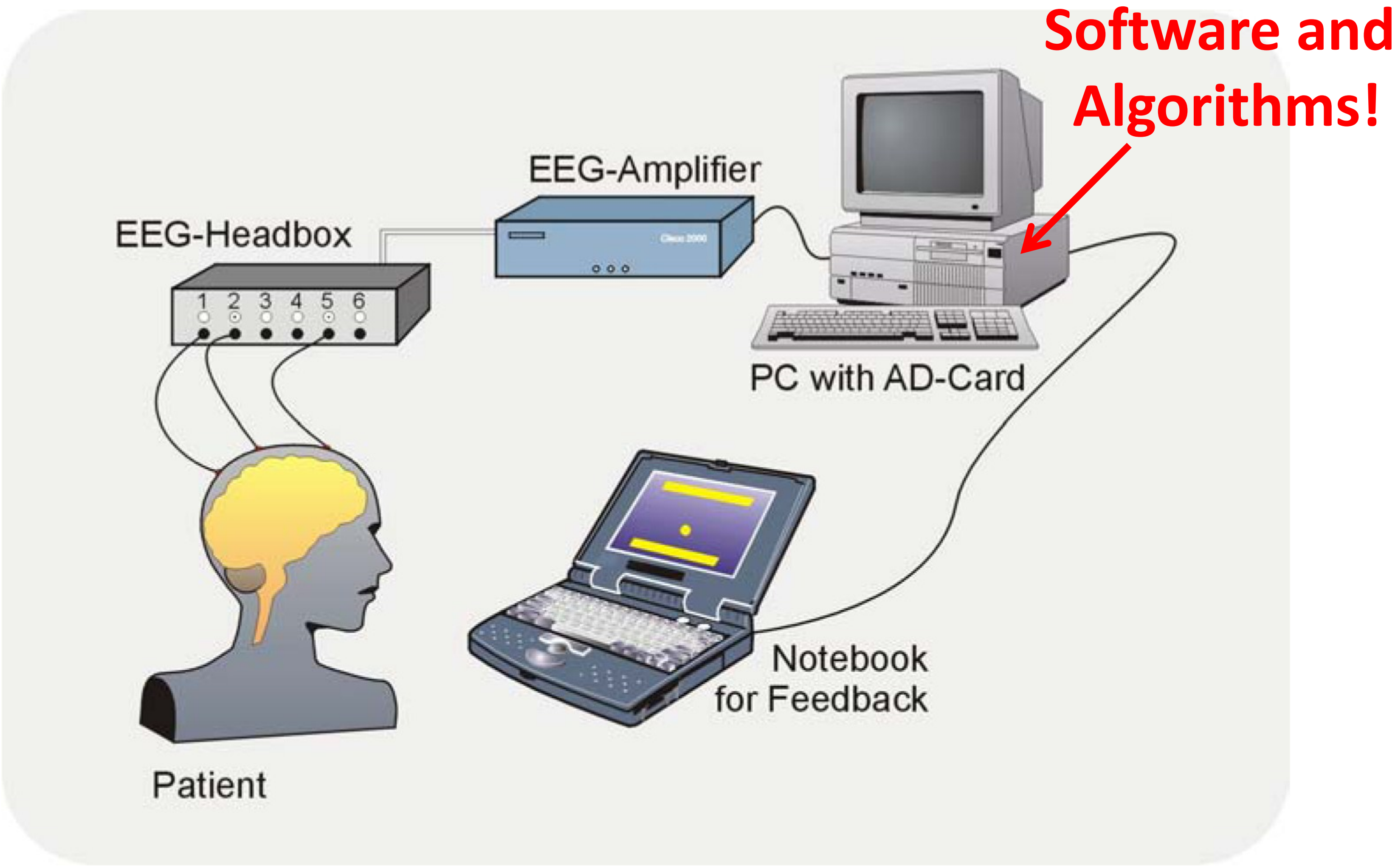


Three BCI Subtypes

- **Active BCI:** *"An active BCI is a BCI which derives its outputs from brain activity which is directly consciously controlled by the user, independently from external events, for controlling an application."*
- **Reactive BCI:** *"A reactive BCI is a BCI which derives its outputs from brain activity arising in reaction to external stimulation, which is indirectly modulated by the user for controlling an application."*
- **Passive BCI:** *"A passive BCI is a BCI which derives its outputs from arbitrary brain activity without the purpose of voluntary control, for enriching a human-computer interaction with implicit information."*

Zander et al., 2009

Parts of a Basic Setup

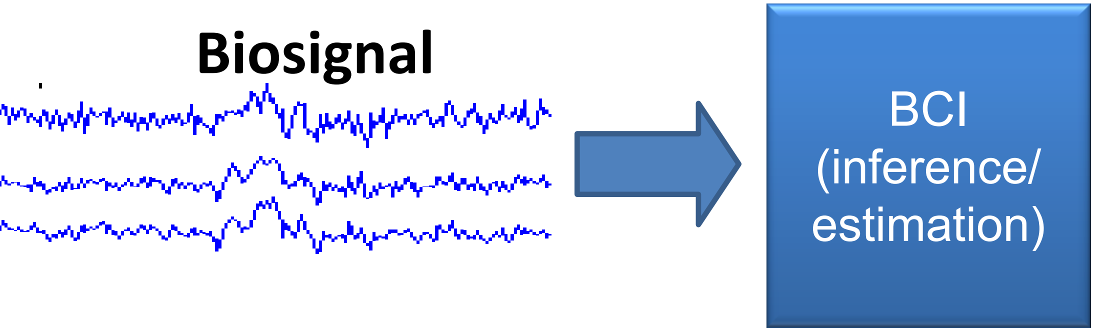


Schmidt, 2003

Parts of a Modern Setup

Jung et al., 2011

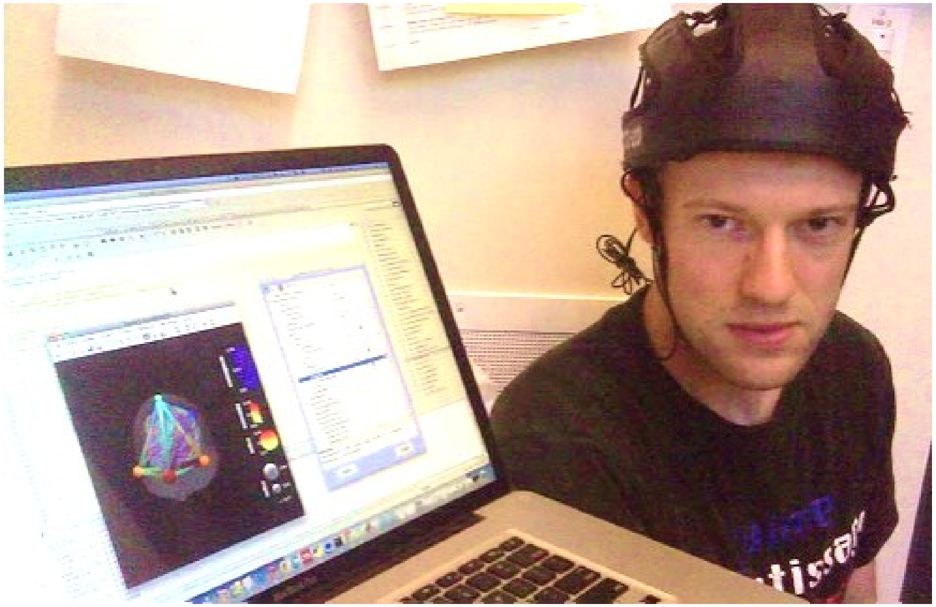
Biosignals and other Inputs



Brain Signals

- Electroencephalogram (EEG)

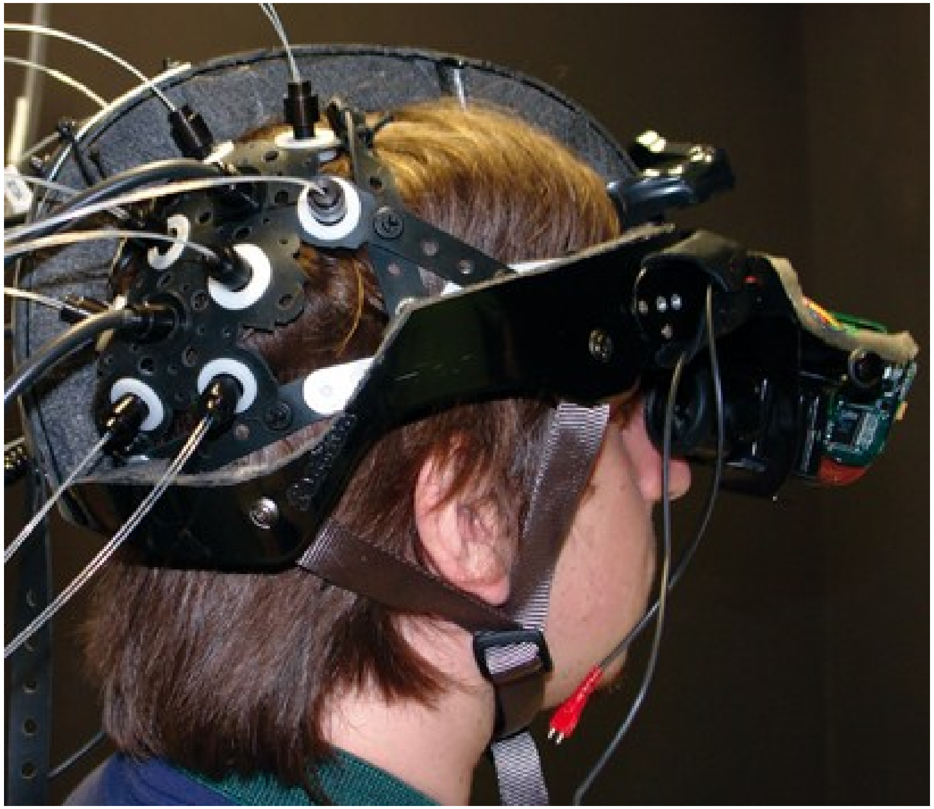
BioSemi B.V.



MINDO-16 (C.T. Lin et al.)

Brain Signals

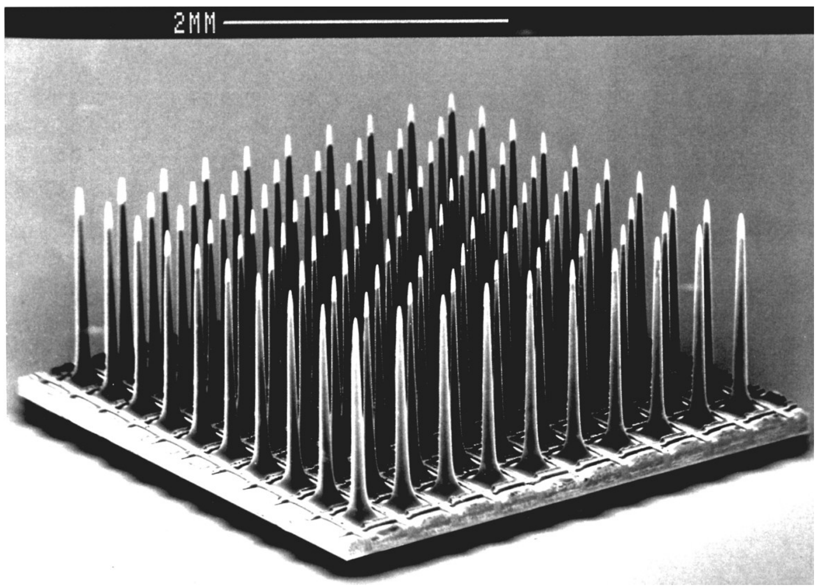
- Functional Near-Infrared Spectroscopy (fNIRS)



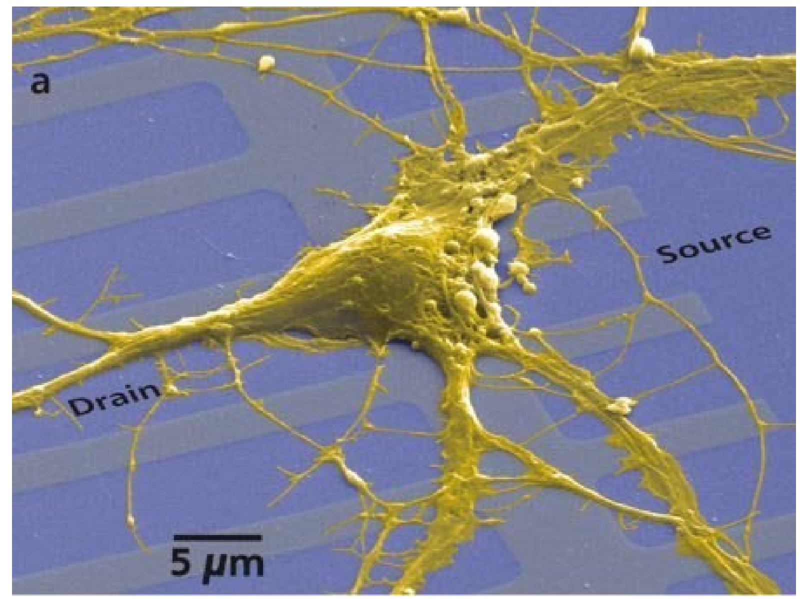
Seraglia et al., 2011

Invasive Brain Signals?

- Microarrays, Neurochips, ECoG, …



Utah Electrode



Cui et al., 2001

Room-sized Sensors?

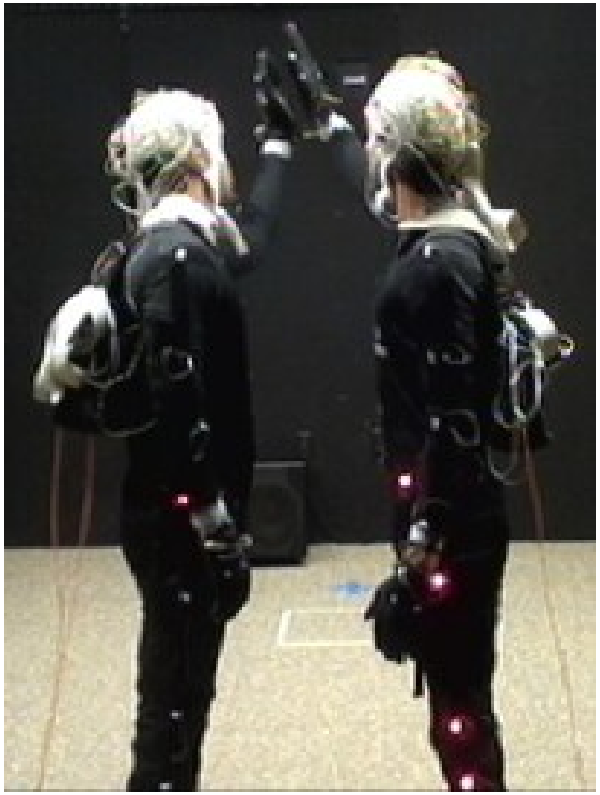
- Magnetoencephalograpy (MEG), functional Magnetic Resonance Imaging (fMRI)

NIMH

Sinai Hospital

Non-Brain Signals I

- Motion Capture, Eye Tracking



SCCN MoBI Lab

SensoMotoric Instruments
(EEG: Emotiv)

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Non-Brain Signals II

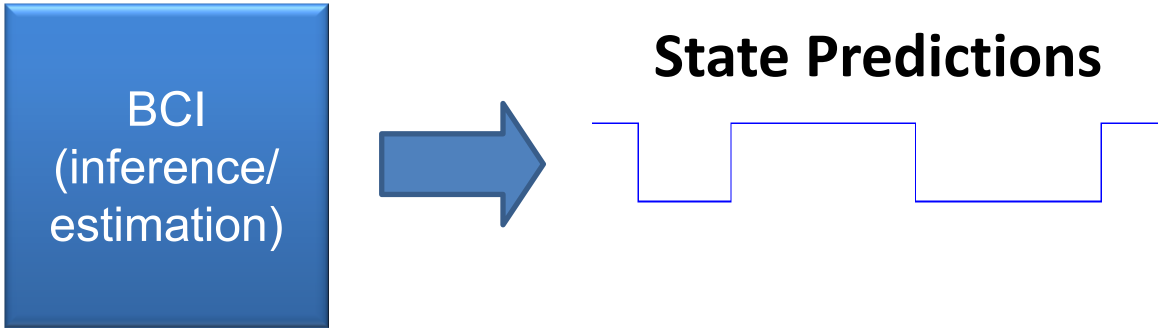
- Electromyography (EMG), Electrocardiography (ECG), Electrooculography (EOG)

Microsoft

Non-Brain Signals III

- **System or Application State** (stimulus presented?, current vehicle speed, …)
- **Environmental Signals** (line noise, room temperature, …)

BCI Estimates/Predictions



“Aspects of Cognitive State”

- Any aspect of the physical brain state that can be measured with sufficient single-trial reliability
- **Tonic state:** degree of “relaxation”, cognitive load, ...
- **Phasic state:** switching attention, type of imagined movement, …
- **Event-related state:** surprised/not surprised, committed error, event noticed/not noticed, …

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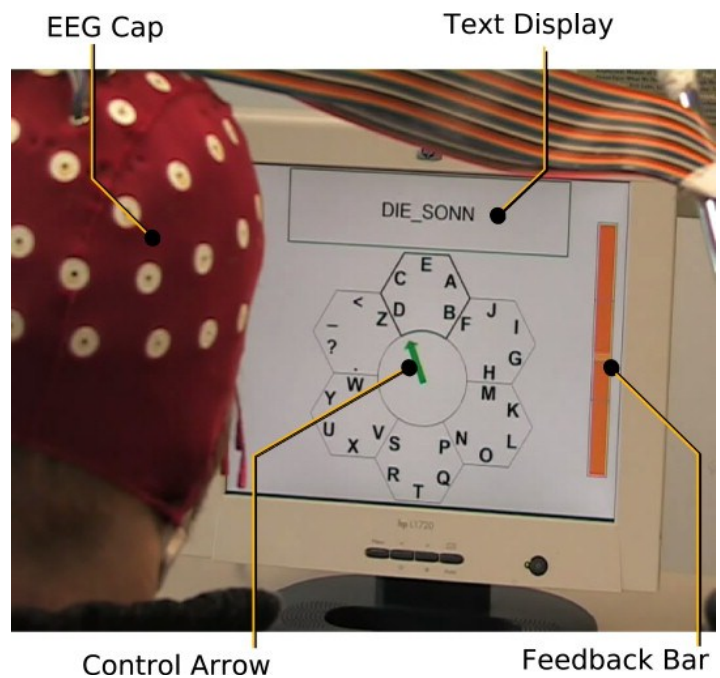
1.2 Application Areas and Examples

Communication and Control for the Severely Disabled

- Severe Disabilities: Tetraplegia, Locked-in syndrome
- **Speller Programs**

P300 Speller

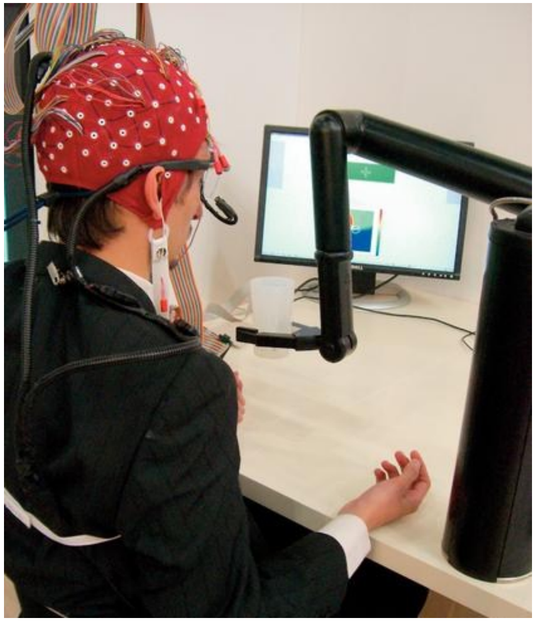


Hex-o-Spell (Blankertz et al.)

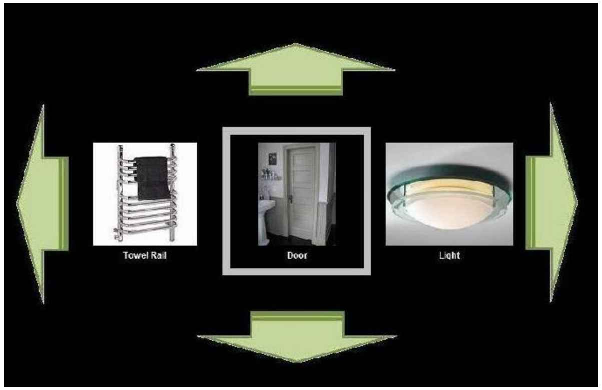
Communication and Control for the Severely Disabled

- Severe Disabilities: Tetraplegia, Locked-in syndrome
- **Prosthetic Control, Home Automation**

KU Leuven



Brain2Robot (Fraunhofer FIRST)



brain project, IGUI

Operator Monitoring

- **Braking Intent, Lane-Change Intent, Workload**

Haufe et al., 2011

Welke et al., 2011

Operator Monitoring

- **Workload / Fatigue / Alertness monitoring in Pilots, Air Traffic Controllers, Plant Operators**

The MITRE Corp., 2011

Forensics

- **Lie detection, Brain Fingerprinting, Trust assessment**

Farwell et al. 2000

Entertainment

- **Mood Assessment, “Thought Control”, Fast Response Detection**

Neurosky Mindset

Force Game Test

Health

- **Sleep Stage Recognition, Neurorehabilitation**

iBrain

Takata et al., 2011

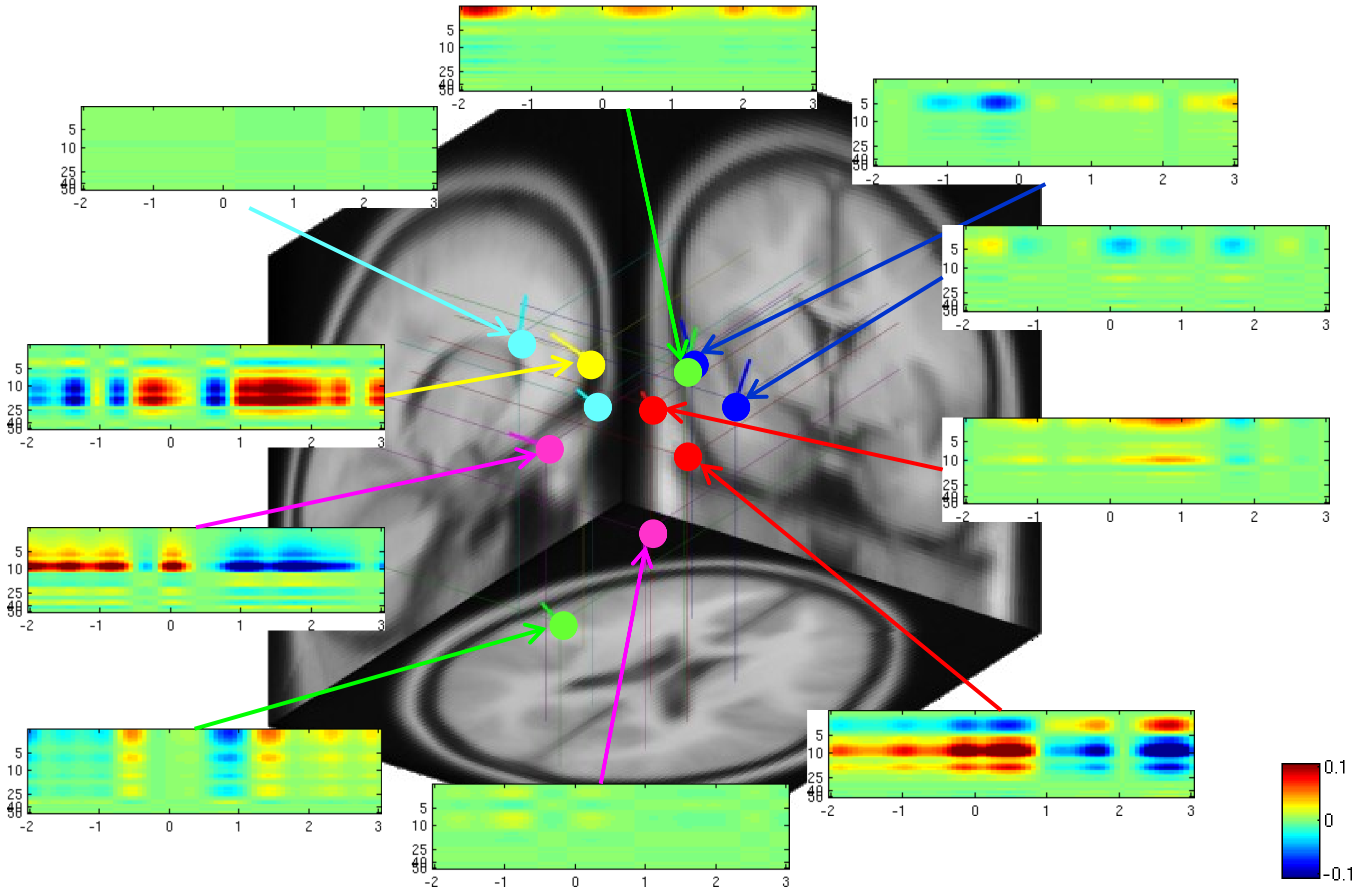
Social

- **Neurowear…**

necomimi BCI

Neuroscience

- **Multivariate Pattern Analysis / Brain Imaging**



Kothe et al., 2011

Neuroscience

- Study of information content and representations for neuroscientific questions
- **Also:** Closed-loop neuroscience experiments (experiment manipulations depending on brain state)

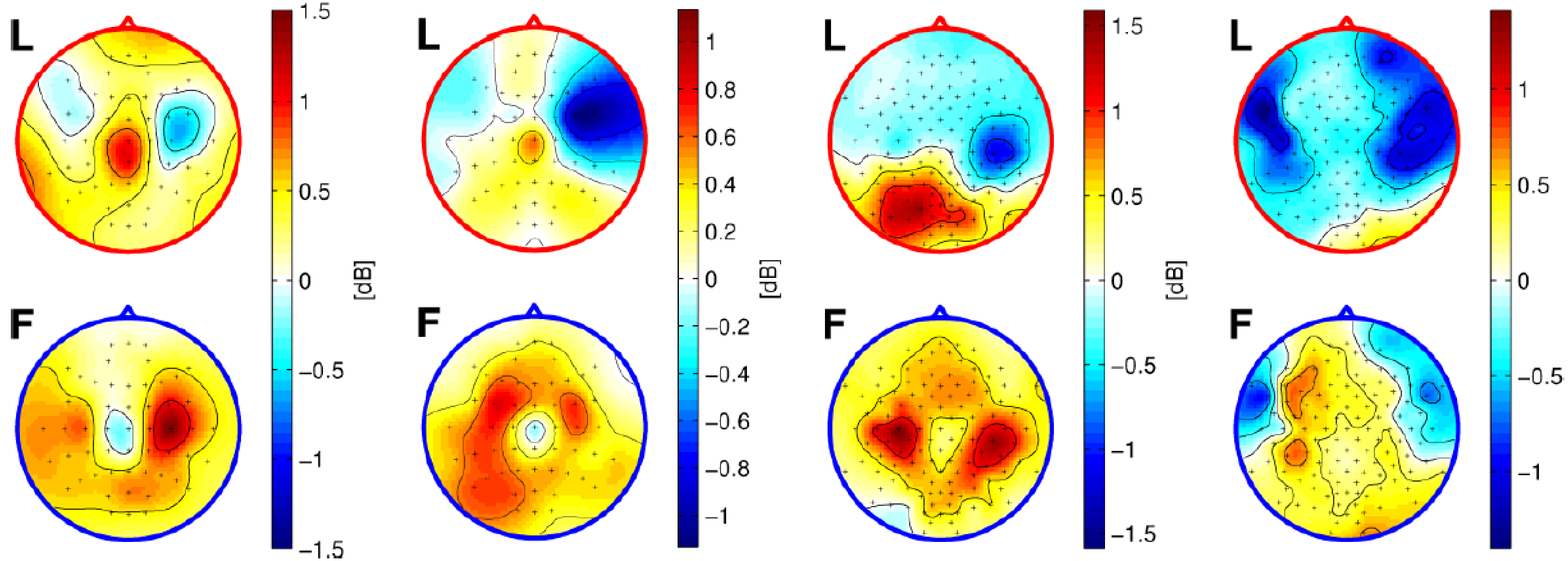
1.3 Scientific Challenge

Related Areas in Science

- **Theory is shared with:** Signal Processing, Machine Learning, Computational Intelligence, Neuroscience, Cognitive Science
- **Problems are similar to:** Computer Vision, Speech Recognition, Pattern Recognition, Time-Series Analysis, Control Systems & Robotics

Why is BCI Hard?

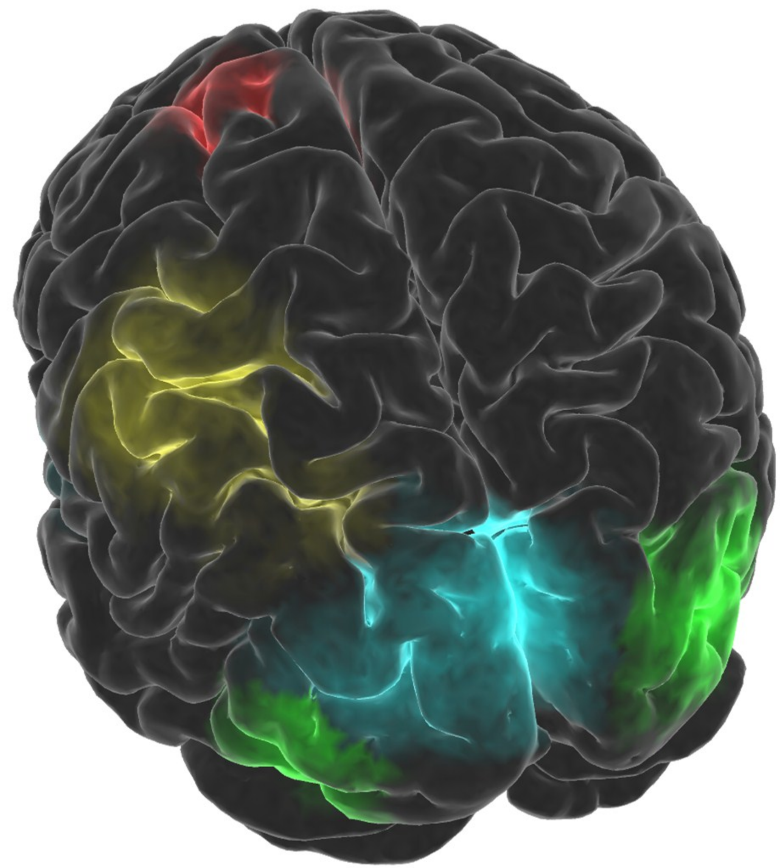
- Processing depends on unknown parameters (person-specific, task-specific, otherwise variable) – e.g., per-sensor weights as below:



Blankertz et al. 2007

Reasons for Variability

- Folding of cortex differs between any two persons (even monozygotic twins)
- Relevant functional map differs across individuals
- Sensor locations differ across recording sessions
- Brain dynamics are non-stationary at all time scales



Why else is BCI Hard?

- Signal-to-noise ratio is very challenging, so *sensitive* measures are hard to obtain
  - Relevant brain activity is small compared to interfering artifacts and compared to brain background activity
- *Specific* measures are even harder to obtain (with coarse-grained sensing)
  - Large collections of neurons are involved in many different activities, not just one
- Underlying phenomena are also highly diverse and rich and derived measures are still poorly understood – not always clear what to look for

And Furthermore

- EEG signals are mathematically complicated to handle since all sensors record almost the same signal (superposition of all brain activity)
- Therefore they need to be computationally (e.g., statistically) disentangled for optimum performance

Consequences

- Sophisticated signal processing is required
- All approaches are fundamentally statistical
- BCI systems must be *calibrated* before they can be used
- Calibration should entail as much information as available, e.g., example data, prior knowledge, large databases

1.4 Available Tools

BioSig

- Developed at TU Graz since at least 2002
- One of the oldest open-source BCI toolboxes, for MATLAB/Octave (cross-platform)
- *Large amount of functionality* from statistics and time-series analysis: Adaptive Autoregression (AAR), Blind Source Separation (BSS), Common Spatial Patterns (CSP), Classifiers (LDA, SVMs, …), Cross-Validation
- *Offline analysis only* -- no real-time hardware or computation support
- *Not easy to use* (no GUI, fairly complicated code, not very modular…)

BCI2000

- Developed at Wadsworth Center since 1999
- *Large, modularized C++ system*, primarily aimed at real-time acquisition, signal processing, stimulus presentation, experiment control, deployment; robust, “enterprise-grade” implementation
- Supports a *wide range of acquisition hardware* (currently 19 systems)
- Solid documentation, workshops, book, big community
- *Lack of advanced signal processing and machine learning* algorithms (tough extensions and in-house versions available)

OpenViBE

- Developed at INRIA, relatively young project
- Implemented in modular C++, focusing on *visual programming and dataflow programming*
- *Very user-friendly design, interface and documentation*
- Focus on basic signal processing building blocks, weaker support for complex information flows (machine learning, adaptive signal processing, …)
- Relatively hard to extend due to complex framework
- Supports a broad range of acquisition hardware (15 systems), runs on Windows and Linux

g.BSanalyze

- Commercial System developed by g.Tec
- MATLAB/Simulink-based framework
- Broad collection of turnkey algorithms, evaluation methods, etc.
- Extensive, high-quality graphical user interface
- Primarily supporting in-house amplifiers

BCILAB

- Developed since 2010 at Swartz Center for Computational Neuroscience, UCSD (precursors dating back to 2006)
- MATLAB-based, cross-platform, offline and online analysis; stand-alone versions available
- *Largest collection of BCI algorithms* from signal processing, machine learning, etc. (2012)
- *Complex Internal Framework* requiring expertise to extend
- Relatively little native support for acquisition systems (5), but can tie into real-time experimentation frameworks (BCI2000, LSL)

Other Packages

- **FieldTrip:** Popular MEG/EEG toolbox with online features
- **xBCI:** New C++ framework focused on online operation, GUI-centric, cross-platform
- **BF++**: Mature BCI framework (developed since 2000), although not very well known (offline analysis & modeling with UML and XML)
- **TOBI:** Protocol suite for BCI interoperability and data acquisition
- **PyFF:** Python-based BCI stimulus presentation system
- **BBCI:** In-house MATLAB-based system developed at TU Berlin; very comprehensive, potentially available for licensing
- **BCI++:** Relatively new C++ system, focused on human-computer interaction and virtual reality (still growing)

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L1 Questions?