US versus Europe

- The vision and framework to effectively utilize BCIs is more advanced in Europe. BCIs are just one piece of more advanced “hybrid bionic systems” already under design.
- There are new avenues being pursued in BCIs that transcend the control communication US paradigm.
- There is very solid and systematic analysis and design to improve performance of BCIs.
Modeling - Aalborg

Cuff electrodes

Myo-Junction Prosthesis
Spinal and Peripheral Nerve Prosthesis
Cortical Prosthesis

Modeling

Hybrid Bionic Systems

Scuola Superiore Sant’Anna
Modeling

Paolo Dario

Today: Bio-Sciences and Robotics getting closer...

Biological models for the design of biomimetic robots

• Robots as physical platforms for validating biological models
• New technologies for functional substitution

Integrating the natural and the artificial: Hybrid Bionic Systems

NATO Project
Collaboration with Stanford University 1989-1990

GRIP Project
Funded by the EU 1998-2001

Project funded by the Italian National Research Council 1990-1992

INTER Project
Funded by the EU 1993-1996

CYBERHAND Project
Funded by the EU 2002-2005

Collaboration with Rmwn University 1987-89
Modeling - Cyberhand

- Tf LIFE electrodes

Paolo Dario

Results from a rabbit with 4 different stimuli.
Modeling

Jointly designed Hybrid Bionic Systems

MODEL

INTERFACE

ROBOTIC SOLUTION

Anticipatory behaviour
Neural plasticity
Learning
Hybrid
Bionic System
Neural interfaces
Cortical interfaces
Natural interfaces
Actuators
Sensors
Mechanisms
Materials
Modeling – Animat Lab (CEA)
College de France

- Cognitive architectures (cortico-basal ganglia thalamus)
- Reinforcement learning (Actor critic and TD)
- Evolutionary neuro controllers

Psikharpax
Robur
Kodamat

Note: CEA has a state of the art robotics program with tele-operation, Micro manipulation, movement perception, and autonomous robots. For the sake of time and space we will not review them.

Modeling – The Artificial Rat
Psikharpax

Sensory Equipment
Visual
Auditive
Haptic (whiskers)
Vestibular
Odometry
Energy

Motor Equipment
Rearing
Prehension
Eye rotation
Head rotation
Wheels (legs)

Jean Meyer
BCI Modeling

Modeling - IDIAP

BCI Asynchronous Architecture: distributed intelligence

Jose Millan

Users address the task at high level and all the low level details are handled automatically:

behavior-based architecture

<table>
<thead>
<tr>
<th>Trial</th>
<th>Mental</th>
<th>Manual</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>219</td>
<td>156</td>
<td>0.71</td>
</tr>
<tr>
<td>2</td>
<td>189</td>
<td>155</td>
<td>0.82</td>
</tr>
<tr>
<td>3</td>
<td>175</td>
<td>117</td>
<td>0.67</td>
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<tr>
<td>Average</td>
<td>194</td>
<td>143</td>
<td>0.73</td>
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</table>
**Modeling - IDIAP**  

- **Error Recognition by P300.**

<table>
<thead>
<tr>
<th>Subject</th>
<th>Error %</th>
<th>Correct %</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>87.3</td>
<td>62.8</td>
</tr>
<tr>
<td>#2</td>
<td>74.4</td>
<td>75.3</td>
</tr>
<tr>
<td>#3</td>
<td>78.1</td>
<td>89.2</td>
</tr>
<tr>
<td>#4</td>
<td>80.9</td>
<td>87.3</td>
</tr>
</tbody>
</table>

Fast recognition of errors, and reliable interaction (70% higher bit xfer)

---

**Modeling - IDIAP**

- **Improving spatial resolution**

<table>
<thead>
<tr>
<th>Method</th>
<th>Subject 1</th>
<th>Subject 2</th>
<th>Subject 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>EEG</td>
<td>11.6%</td>
<td>10.4%</td>
<td>10.5%</td>
</tr>
<tr>
<td>LFP</td>
<td>3.7%</td>
<td>0.6%</td>
<td>4.9%</td>
</tr>
</tbody>
</table>
Modeling - Sant’Anna

**Augmenting BCIs - commercial applications.**

BCIs are slow and should minimize the cognitive load (be non exclusive). To be useful they have to augment human’s output pathways.
Modeling – Sant’Anna

The novel scheme of natural interfaces, based neuroscience models

Two main advantages:
1) the movements detected by the interface are naturally associated with motor behaviours and do not put any additional cognitive burden on the person
2) these movements occur (0.5s to 1s) in advance respect to main motor behaviours
Modeling Sant’Anna

Digital Signal Processing (DSP) for BCIs
BCI Features and adaptive kernels for single trial movement related potentials (MRP)

Optimization of feature extraction

Optimization of classifier

Single-channel EEG signal

$\theta = [\alpha_1, \alpha_2, ..., \alpha_L]$  

DWT

Coefficient Transformation

SVM

$P_e$ (training set)

Parameters of the kernel

Average misclassification error on the test set (6 subjects)

21.6 Optimized wavelet

26.9 Daubechies wavelet
Signal Processing - EPFL

P300 BCI to learn environment control
- Adaptive Spatial filters (virtually created from the channels)
  - Maximize distance of class means (GED)
- Bayesian Linear Discriminant Analysis for a BCI
- Learns in one shot

Signal Processing - Berlin

- Systematic analysis of variability of single event responses for BCIs: intra subject, inter subject and operand condition (open-close loop).

Klaus Muller, Fraunhofer
Signal Processing - Berlin

- What features?

Klaus Muller Faunhofer

Signal Processing - Berlin

- What classifiers?

Klaus Muller Faunhofer
**Signal Processing - Berlin**

- **Results**

  Mean error (%): LEFT vs. RIGHT at -120 ms before keystroke

<table>
<thead>
<tr>
<th>filter</th>
<th>ch</th>
<th>FD</th>
<th>FDₚ</th>
<th>LPM</th>
<th>SVM</th>
<th>k-NN</th>
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</thead>
<tbody>
<tr>
<td>0.4–5</td>
<td>mc</td>
<td>3.7</td>
<td>3.3</td>
<td>3.7</td>
<td>3.2</td>
<td>21.6</td>
</tr>
<tr>
<td>0.4–5</td>
<td>all</td>
<td>3.3</td>
<td>3.1</td>
<td>4.0</td>
<td>3.6</td>
<td>23.1</td>
</tr>
<tr>
<td>none</td>
<td>mc</td>
<td>18.1</td>
<td>7.0</td>
<td>8.3</td>
<td>8.5</td>
<td>29.5</td>
</tr>
<tr>
<td>none</td>
<td>all</td>
<td>29.3</td>
<td>7.5</td>
<td>9.1</td>
<td>9.8</td>
<td>34.0</td>
</tr>
</tbody>
</table>

* Channel: left (l), right (r), or all 27 electrodes (*all* is from subject a).  

Klaus Muller Faunhofer

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**Signal Processing - Freiburg**

- **Inference of movement direction from MUA and LFPs.**

Ad Aertsen, Freiburg
Performance of SUA and LFPs (8 channels)

- Single-trial decoding of movement direction
- Separate sets of training and test trials
- Quantification of decoding accuracy by percentage of correctly classified trials.

Different classifiers

From left to right: Penalized linear discriminant analysis, Support Vector Machine (SVM) with radial basis function kernel, SVM with linear kernel, Multivariate Gaussian Model, Population Vector.

Ad Aertsen, Freiburg
Signal Processing - Freiburg

- Frequency bands of tuning

Relative amplitudes (to baseline before cue)

Relative amplitudes (mean across each band)

- How spatial information helps LFPs

Ad Aertsen, Freiburg
Signal Processing – Freiburg

• Cosine tuning prominent in all the three frequency bands!

• Human experiments with ECoG grids (5 epileptic patients)

Ad Aertsen, Freiburg

T = 50 ms before movement onset

6–13 Hz

16–42 Hz

63–200 Hz

≤ 4 Hz

Ad Aertsen, Freiburg

T = 125 ms after movement onset

Central sulcus

Border between M1 and PM
Signal Processing - Freiburg

- Movement related potentials are tuned

Movement direction can be decoded from MRPs

- Single-trial decoding of movement direction
- Separate sets of training and test trials
- Quantification of decoding accuracy by probability of correct classification
Signal Processing - Freiburg

- Movement direction in ECoG and LFPs

- Intracortical (LFP)
- Epicortical (EFP)

Ad Aertsen, Freiburg

Signal Processing – Sta Lucia

- Improve spatial resolution of EEG thru functional neuroimaging
- Understand interplay between brain areas (function connectivity) by Granger causality
Steps to improve the spatial details of recorded EEG Data

Insert the geometry of skull and dura mater in inverse calculation

From scalp to cortical EEG in RoIs

Scalp EEG

Linear inverse estimates within a RoI are collapsed (mean)

"Virtual" electrode

M1 Hand area RoI
I hope to have provided evidence for my assessment of the US Europe state of BCI research.

I would like to thank the groups that hosted us in Europe for their hospitality, literature and frank discussions.

I hope to have interpreted correctly the materials that were provided to us.