Big and Crucial Issues (BCIs) in BCIs

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The past twenty years have witnessed remarkable advances in fundamental neuroscience research and next-generation neurotechnologies. Among the major forerunners in this areas are brain-computer interfaces (BCIs).

However, even with immense advancements, BCIs are still not in widespread and routine use, except for some exciting neuroprosthetic studies recovering lost functions of patients. We need to understand and more importantly overcome the obstacles or challenges that impede the widespread use of BCIs.
Big and Crucial Issues (BCIs) in BCIs

- We lack new sensors and technologies to measure high-quality *neural, physiological, behavioral, and contextual* data in real-world environments.

- We need advanced signal-processing and machine-learning algorithms to jointly analyze multi-modal data.

- What are the **sensible real-world applications** of BCIs? Are we heading in the right direction?

- How to improve the accuracy and robustness of BCIs? We need to alleviate **human variability** both across different individuals and within the same individual over time.
BCIs in a Well-controlled Laboratory

Laboratory Research

Mobile Brain/Body Imaging (MoBI)

Laboratory Research

Typical EEG experiment

EEG data at Fz

Trial

0
30
0 μV
-30

0 400 600 ms

Average ERP

7 μV
0
-7 μV

ERP peak

Real-world Neuroimaging

Makeig, et al., Int’l Journal of Physiology, 2009
Mobile Brain/Body Imaging (MOBI)

Spatial Navigation
Challenges with the MoBI Technology

MoBI has gained increasing attention (two international conferences) and made a lot of progress in recent years. However, there is still room for improvement.

- The bio-sensing modalities (e.g. EEG, ECG, galvanic skin GSR, eye-gaze, pupillometry, etc.) are typically bulky, costly, inconvenient, and laborious.
- The technology is restricted to well-controlled laboratory environments.
- Existing systems lack a method to automatically tag cognitively meaningful events.
**Dry and Wireless EEG Sensors and Systems**

- Dry and non-prep EEG sensors
- Wearable EEG Headgears

**Cognionics**

High-density (64-chan) EEG Cap
A Truly Wearable Multi-modal Biosensing Platform for Real-World Neuroimaging

We have developed a low-cost wearable multi-modal bio-sensing system capable of recording (neuro)physiological signals, eye-gaze overlaid on world view, and motion capture in real-world settings.

**Wearable sensors**
- World camera- Subject’s visual perspective
- Eye Camera: Tracking subject’s pupil
- EEG: Subject’s brain activity
- ECG: Subject’s Heart Rate and Heart-Rate Variability
- PPG: Photoplethysmogram detects volumetric changes in blood in peripheral circulation.

**A wearable computer**
- Data acquisition from sensors
- Control the sampling rate of each sensor
- Using a digital filter on the sensor data if analog filtering has not been done.
- Time-stamping the sensors’ data for synchronization
- Record the data on itself or send the time-stamped data using Wi-Fi to a remote machine.

Software on a Host Computer

Software

• Synchronizes data from different sensors with the capability to handle lags, disconnections, bursts etc.
• Real-time estimates eye-gaze and pupillometry
• Real-time process the EEG and ECG data
• Recognizes and tags objects (e.g. faces, human bodies, chairs, etc.) in real-time using deep learning methods.
• Easy, fast, and user-friendly calibration between world and eye cameras to accurately map the eye-gaze on subject’s world view.
Demo of a Multi-modal Biosensing Platform
A Truly Wearable Multi-modal Biosensing Platform for Cognitive Experiments

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**Wearable sensors**
- World camera- Subject’s visual perspective
- Eye Camera: Tracking subject’s pupil
- EEG: Subject’s brain activity
- ECG: Subject’s Heart Rate and Heart-Rate Variability
- PPG: Photoplethysmogram
- GSR, HR, HRV, blood pulse waves, perfusion, etc.
- IMUs for full-body motion capture
Multi-modal Physiological Monitoring During a Gameplay
Big Crucial Issues (BCIs) in BCIs

- New sensors and technologies to measure high-quality neural, physiological, behavioral, and contextual data in real-world environments.

- Advanced signal-processing and machine-learning algorithms to jointly analyze multi-modal data.

- What are the sensible real-world applications of BCIs? Are we heading in the right direction?

- How to improve the accuracy and robustness of BCIs? We need to alleviate human variability both across different individuals and within the same individual over time.
Difficulties in Observing Distributed EEG dynamics

Scalp EEG signals appear to be noisy because they are a mixture of signals generated in many brain areas.
Independent Component Analysis

Car Kit Demonstration
March 8, 2005

Courtesy of SoftMax, Inc
ICA decomposition

ICA separates brain and non-brain signals contributing to multi-channel EEG recordings. This allows direct analysis of distinct source activities in response to stimulus presentation and subject’s behavior.
Off-line Analysis and Visualization of EEG Source Dynamics

EEGLab Toolbox

EEGLAB – An Open Source Environment for Electrophysiological Research

Over 100,000+ downloads over the past 14 years!

EEGLab Toolbox

Source Information Flow Toolbox (SIFT)

BCILab Toolbox

Neuroelectromagnetic Inverse Source Localization Toolbox

Scalp map

Patch-based SBL

SLORETA

Arnaud Delorme

Zeynep Akalin Acar

Christian Kothe

Tim Mullen
Real-time Data Processing Pipeline

Mullen et al., *IEEE TBME*, 2015.
UCSD Chancellor’s Dissertation Award, 2015.
DEMO: Real-time Artifact Removal, Source Modeling and Effective Connectivity

Demonstration of Hardware and Software for Real-Time Modeling and Visualization of Electrophysiological Source Dynamics and Connectivity Using Wearable Electroencephalography

Tim Mullen, Christian Kothe
Institute for Neural Computation, UC San Diego

Mike Chi, Trevor Kerth
Cognionics, Inc

June 12, 2013
Challenges with the Analysis of Multi-modal Signals

• Even with immense advancements in signal processing and AI, the algorithms are restricted to analyze data from a single modality (e.g. EEG, or HRV).
  
  It is unclear how to fuse the information from the neural, physiological, behavioral and contextual data.

• The signal-processing and AI technologies are restricted to well-trained engineers or computational neuroscientists.
  
  No standard operating procedure or validation criterion was ever developed.
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中美首份 8000 字长文解析全球热点脑机接口

• “硅谷 Live（服务号：guigumitanv）联合哈佛大学脑科学中心科学家及行业专家学者，共同打造中美首份脑机接口行业分析长文，深度解构脑机接口领域技术路线，描绘脑机接口商业化趋势及学科地图，预见前所未见。

• Silicon Valley Live (service number: guigumitanv) and Harvard University Brain Science Center scientists and industry experts and scholars, together to build the first long-term analysis of the brain-computer interface industry in China and the United States, deep deconstructing the technical route of the BCI field, depicting the commercialization of BCI trends and subject maps are foreseen.

Source：
脑机接口市场规模

将达到数千亿美元，横跨数个科技领域

- ADHD脑机接口反馈治疗：460亿美元
- 大脑监测系统：120亿美元
- EEG/EMG设备：25亿美元
- 教育科技：2500亿美元
- 游戏产业：1200亿美元
Steady-state visual evoked potentials (SSVEP)

SSVEP are signals that are natural responses to visual stimulation at specific frequencies.
BCIs based on SSVEPs

- **Steady-state visual evoked potential (SSVEP):** Brain’s electrical response to repetitive visual stimulation
Demonstration
A high-speed SSVEP BCI

High ITR ~ 325.33 ± 38.17 bits/min in a cue-guided BCI task. Nakanishi et al., IEEE TNSRE, 2018.

The high BCI performance can be attributed to:
- A well-designed coding (i.e., visual stimuli) method using a joint frequency-phase modulation
- Advanced decoding (i.e., target identification) approach based on Task-related Component Analysis (TRCA).

What are the applications of SSVEP BCIs in real-world environments? Are we heading in the right direction?
Glaucoma

- **66.8 million** people currently have glaucoma; this will increase to **80 million** by 2020.
- **At least 50%** of people with glaucoma do not know they are affected. Another **20%** are glaucoma suspects.

### Glaucoma Patients

<table>
<thead>
<tr>
<th>Country</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>US</td>
<td>3M</td>
</tr>
<tr>
<td>Japan</td>
<td>3M</td>
</tr>
<tr>
<td>China</td>
<td>21M</td>
</tr>
</tbody>
</table>

### Aging Population

<table>
<thead>
<tr>
<th>Country</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>US</td>
<td>69M</td>
</tr>
<tr>
<td>Japan</td>
<td>42M</td>
</tr>
<tr>
<td>China</td>
<td>217M</td>
</tr>
</tbody>
</table>

### Total

- **34%** of total glaucoma population
- **40%** of total aging population

Source: United Nations
Assessing Visual-Field Deficits

Standard Automated Perimetry (SAP) for Glaucoma Diagnosis

Siamak Yousefi et al., IEEE TRANSACTIONS ON BIOMEDICAL ENGINEERING
The smartphone renders mfSSVEP stimuli and measures EEG/EOG data from the on-board bio-amplifiers.
Results from mfSSVEP and Standard Perimetry of Glaucomatous and Health Eyes.

Developing a Passive BCI: From Research to Reality
A Near-Naturalistic Driving Simulator at BRC of NCTU
A Lane-Keeping Sustained-attention Task for Studying the Associations between the EEG activity and Task Performance

Reaction Time (RT)

Huang et al., 2005, 2007.
Network Dynamics with and without Motion Cues

Effective connectivity between EEG independent processes estimated under (A) K$^+$ and (B) K$^-$ conditions.

Drowsiness Monitoring & Mitigation System

A Smartphone-based Drowsiness Monitoring & Mitigation System

A Drowsiness Monitoring & Mitigation System

Problems with the training-data collection:

- Time-consuming and labor-intensive
- The pilot data do not always contain useful information to train a good model because of day-to-day variability in the associations between EEG and performance.
Variability in the Associations between EEG and Drowsiness

Correlations between EEG spectral time series and task performance

Small intra-subject variability

Large intra-subject variability

Small inter-subject variability

Large inter-subject variability

(Wei, unpublished)
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Subject-Transfer Framework

Assumptions:
1. Large-scale existing data provide models that lead to a good BCI model.
2. The calibration data provide useful information to select supportive source models with similar task-relevant brain responses.

Wei et al., NeuroImage, 2018.
Estimate Drowsiness using EEG Spectra

Wei et al., Neuroimage, Jul. 2018.
Summary

- New sensors and technologies to measure high-quality neural, physiological and behavioral data in real-world environments.
- Develop advanced signal-processing and machine-learning algorithms to jointly analyze multi-modal data.
- Focus on sensible applications of BCIs in real-world environments.
- Develop a big-data and machine-learning approach to reduce the complications of human variability and improve the accuracy and robustness of BCIs.