Thinking Out Loud:

Research and Development of
Brain–Computer Interfaces

N. Jeremy Hill

Max Planck Institute for Biological Cybernetics, Tübingen, Germany
Stephen Hawking (1942—)
Stephen Hawking (1942—)

- world-renowned theoretical physicist
Stephen Hawking (1942—)

- world-renowned theoretical physicist
- bestselling popular-science author
Stephen Hawking (1942—)

- world-renowned theoretical physicist
- bestselling popular-science author
- Ph. D. supervisor
Stephen Hawking (1942—)

- world-renowned theoretical physicist
- bestselling popular-science author
- Ph. D. supervisor
- public speaker

Despite having Amyotrophic Lateral Sclerosis (ALS) since age 21.
Stephen Hawking (1942—)

- world-renowned theoretical physicist
- bestselling popular-science author
- Ph. D. supervisor
- public speaker
- TV actor
- husband
- father

...despite having Amyotrophic Lateral Sclerosis (ALS) since age 21.
Stephen Hawking (1942—)

- world-renowned theoretical physicist
- bestselling popular-science author
- Ph. D. supervisor
- public speaker
- TV actor
- husband
Stephen Hawking (1942—)

- world-renowned theoretical physicist
- bestselling popular-science author
- Ph. D. supervisor
- public speaker
- TV actor
- husband
- father
Stephen Hawking (1942—)

- world-renowned theoretical physicist
- bestselling popular-science author
- Ph. D. supervisor
- public speaker
- TV actor
- husband
- father

...despite having Amyotrophic Lateral Sclerosis (ALS) since age 21.
The Locked-In State

- Brainstem stroke
- Guillan-Barré Syndrome
- Multiple Sclerosis
- Cerebral Palsy
- ALS and related motor-neuron diseases
The Locked-In State

- Brainstem stroke
- Guillan-Barré Syndrome
- Multiple Sclerosis
- Cerebral Palsy
- ALS and related motor-neuron diseases

can lead to

- Locked-In Syndrome (LIS): quadriplegia + inability to speak
The Locked-In State

- Brainstem stroke
- Guillan-Barré Syndrome
- Multiple Sclerosis
- Cerebral Palsy
- ALS and related motor-neuron diseases

can lead to

- Locked-In Syndrome (LIS): quadriplegia + inability to speak
- “Completely Locked-In” Syndrome (CLIS): complete inability to communicate due to lack of voluntary muscle control, despite intact cognitive functions
ALS

Amyotrophic Lateral Sclerosis (aka Lou Gehrig’s disease / Maladie de Charcot)

- is a progressive degeneration of motor neurons;
- has no known cure;
- is inherited in 10% of cases, sporadic in 90%;
- typically leads to CLIS within 2–5 years;
- is not fatal per se (if artificial ventilation is provided after breathing fails);
- causes (directly) relatively little cognitive degeneration (maybe none?).
Amyotrophic Lateral Sclerosis (aka Lou Gehrig’s disease / Maladie de Charcot)

- is a progressive degeneration of motor neurons;
- has no known cure;
- is inherited in 10% of cases, sporadic in 90%;
- typically leads to CLIS within 2–5 years;
- is not fatal per se (if artificial ventilation is provided after breathing fails);
- causes (directly) relatively little cognitive degeneration (maybe none?).

- Worldwide incidence is 120,000 diagnoses per year (2 per 100,000).*
- Worldwide prevalence is 400,000 at any one time (6 per 100,000).*
- Frequency is roughly 1/10 that of Multiple Sclerosis.
- est. 8000 cases in Germany today (based on US prevalence of 10 per 100,000).

*source: “International Alliance of ALS/MND Associations on the Internet” July 2007
http://www.alsmndalliance.org/whatis.html
Measuring Brain Activity

Electroencephalography (EEG)
Measuring Brain Activity

Department of Epileptology,
University of Bonn, 2004

Electrocorticography (ECoG)

Warning:
brain surgery photo coming next
Measuring Brain Activity

Department of Epileptology,
University of Bonn, 2004

Electrocorticography (ECoG)
Measuring Brain Activity

Implanted microelectrode array (Cyberkinetics, Inc)

Figure from Hochberg et al. Nature, July 2006.
Measuring Brain Activity

Near Infra-Red Spectrophotometry (NIRS)
Measuring Brain Activity

Magnetoencephalography (MEG)

Functional Magnetic Resonance Imaging (fMRI)

MMP PhDnet Workshop, Frankfurt-am-Main July '07
Liefer-Herr-Birbaumer-
Hoffentlich-kommen-sie-mich-besuchen,-wenn-dieser-
Brief-sie-erreicht-hat,-ich-danke-ihrnen-und-ihrem-team-
und-besonders-Frau-Kübler-sehr-herzlich,-denn-sie-
alle-haben-mich-zum-ABC-schützen-gemacht,-der-oft-
die-richtigen-buchstaben-trifft.-Frau-Kübler-ist-eine-
motivationskünstlerin.ohne-sie-wäre-dieser-brief-
Nicht-zustande-gekommen,-er-muss-gefeiert-werden.-
Dazu-möchte-ich-sie-und-ihr-team-herzlich-einladen.-
eine-gelegenheit-findet-sich-hoffentlich-bald.

Mit-Besten-Grüssen-Ihr-
(vollständiger Name des Patienten)

Brain-Computer Interface (BCI) technology also has potential value for

- people with spinal-cord lesions
- stroke recovery
- neurofeedback (as therapy for ADHD, depression, anxiety, . . .)
- any user who needs an “extra hand” (e.g. astronauts wearing pressurized gloves)
- anybody (computer games)
Video from Cyberkinetics, Inc
Room for Improvement

For practical use, current BCIs are so slow and inaccurate that almost any other method is preferable:
Room for Improvement

For practical use, current BCIs are so slow and inaccurate that almost any other method is preferable:

- voice-recognition systems
- shoulder joysticks
- tongue joysticks
- eyetrackers
- head pointers
- sip-and-puff switches
- blink switches
- ...
- human interaction
For practical use, current BCIs are so slow and inaccurate that almost any other method is preferable:

- voice-recognition systems
- shoulder joysticks
- tongue joysticks
- eyetrackers
- head pointers
- sip-and-puff switches
- blink switches
- ...
- human interaction

...where the user is able to use them.
Room for Improvement

Our goals are:

- develop BCIs as a useful complement to other technologies;
- improve current BCIs until they are better than the other technologies;
- make BCIs work for users who have no other options.
Room for Improvement

Our goals are:

- develop BCIs as a useful complement to other technologies;
- improve current BCIs until they are better than the other technologies;
- make BCIs work for users who have no other options.

There has not yet been a convincing, successful case of communication by a “completely locked-in” user.
Challenges

- Induction
- Measurement
- Decoding
- Integration

Induction methods:
- learn to self-regulate cortical DC potential;
- focus attention on one of a set of concurrent stimuli;
- imagine moving parts of the body;
- imagine something else (mental arithmetic, mental rotation, ...).

Measurement:
- EEG, NIRS
- ECoG, micro-electrode
- other future technology.

Application:
Nessi by Michael Bensch
Challenges

- **Induction**
- Measurement
- Decoding
- Integration

**Induction methods:**

- learn to self-regulate cortical DC potential;
- focus attention on one of a set of concurrent stimuli;
- imagine moving parts of the body;
- imagine something else (mental arithmetic, mental rotation, ...).
Challenges

- Induction
- Measurement
- Decoding
- Integration

Measurement

- EEG, NIRS
- ECoG, micro-electrode
- other future technology...
Challenges

- Induction
- Measurement
- Decoding
- Integration

“Yes”
“No”

Application: Nessi by Michael Bensch
Challenges

- Induction
- Measurement
- Decoding
- Integration

Application: *Nessi* by Michael Bensch
Induction strategies

Imagined-movement: animation by Sandra Cordero and Navin Lal
Induction strategies

Imagined-movement: CEBIT demo by Fraunhofer FIRST, Berlin
Induction strategies

Visual grid-speller: video by Inst. Medical Psychology, Tübingen University
Induction strategies

Encoding:
- Output: binary representation

Decoding:
- Input: binary representation
- Output: prediction of the next letter

Prediction:
- Given a sequence of binary inputs, predict the next letter

Modulation:
- Channel 1: [1 0 0 ... 0]
- Channel 2: [1 0 0 ... 0]

Demodulation:
- Classification of the input sequence

Codebook C:
- Matrix of binary values

Time:
- Representation of the sequence as a function of time
Induction strategies

Imagined movement and the visual grid are the fastest and most promising induction methods so far.

But: for users in CLIS, we may need to invent further methods.
Why Non-Visual?

In the CLIS state, patients are functionally blind:
– eyes cannot be opened at will;
– eyes may move involuntarily (often rolling up);
– lens cannot be refocused or gaze directed;
– no microsaccades, so images fade out (Troxler effect);
– no saccades, so no integration of visual scenes: the fovea images a fixed 2 deg. spot, and resolution is very low in most of the visual field;
– long immobility of the eye often leads to infections;
Why Non-Visual?

- In the CLIS state, patients are functionally blind:
Why Non-Visual?

• In the CLIS state, patients are functionally blind:

  – eyes cannot be opened at will;
  – eyes may move involuntarily (often rolling up);
  – lens cannot be refocused or gaze directed;
  – no microsaccades, so images fade out (Troxler effect);
  – no saccades, so no integration of visual scenes: the fovea images a fixed 2 deg. spot, and resolution is very low in most of the visual field;
  – long immobility of the eye often leads to infections;
Motor-imagery-based BCI shows promising results with normal subjects, and patients with extensive paralysis (Kübler et al 2005, Neurology 10). So far it has not worked with patients in CLIS. Why?

- Can the patient still imagine movement?
Why Non-Motor?

- Motor-imagery-based BCI shows promising results with normal subjects, and patients with extensive paralysis (Kübler et al 2005, Neurology 10). So far it has not worked with patients in CLIS. Why?
  - Can the patient still imagine movement?
  - Can the motor and premotor cortex still produce ERD/ERS during motor imagery?

⋆ EEG is still the most attractive technology for clinical BCI.
⋆ Most of the EEG signal comes from pyramidal neurons.
⋆ ALS kills the pyramidal neurons of the motor cortex.
Why Non-Motor?

- Motor-imagery-based BCI shows promising results with normal subjects, and patients with extensive paralysis (Kübler et al 2005, Neurology 10). So far it has not worked with patients in CLIS. Why?
  - Can the patient still imagine movement?
  - Can the motor and premotor cortex still produce ERD/ERS during motor imagery?
  - (...and are these in fact the same question?)

⋆ EEG is still the most attractive technology for clinical BCI.
⋆ Most of the EEG signal comes from pyramidal neurons.
⋆ ALS kills the pyramidal neurons of the motor cortex.
Why Non-Motor?

- Motor-imagery-based BCI shows promising results with normal subjects, and patients with extensive paralysis (Kübler et al 2005, Neurology 10). So far it has not worked with patients in CLIS. Why?
  - Can the patient still imagine movement?
  - Can the motor and premotor cortex still produce ERD/ERS during motor imagery?
  - (...and are these in fact the same question?)
  - Are ALS patients' motor cortices still intact enough to (re)learn to do so?
    - EEG is still the most attractive technology for clinical BCI.
    - Most of the EEG signal comes from pyramidal neurons.
    - ALS kills the pyramidal neurons of the motor cortex.

★ EEG is still the most attractive technology for clinical BCI.
★ Most of the EEG signal comes from pyramidal neurons.
★ ALS kills the pyramidal neurons of the motor cortex.
Auditory stimulation in EEG
Auditory stimulation in EEG

[Diagram of brain with electrodes and auditory stimulation symbols]
Auditory stimulation in EEG
Auditory stimulation in EEG
Auditory stimulation in EEG
Auditory stimulation in EEG
Auditory stimulation in EEG
Tactile stimulation in MEG
Tactile stimulation in MEG

![Graph showing tactile stimulation in MEG](image)
Decoding

Event-Related Desynchronization in motor imagery: classify imagined left hand movement vs. imagined right hand movement based on power in 10 Hz-band of estimated pre-motor cortex sources in the left and right hemispheres.
Maximum-Margin Classification
Maximum-Margin Classification
Maximum-Margin Classification

[Diagram showing two sets of data points with a linear boundary dividing them]
Maximum-Margin Classification
Maximum-Margin Classification
Maximum-Margin Classification
Maximum-Margin Classification

One extra parameter to find (regularization parameter $C$): how much to penalize cases like this.
Maximum-Margin Classification
Decoding

Event-Related Desynchronization in motor imagery: classify imagined left hand movement vs. imagined right hand movement based on power in 10 Hz-band of estimated pre-motor cortex sources in the left and right hemispheres.
The Volume Conduction Problem
Blind Source Separation

source 1

time

source 2

time

ground truth

source 2

source 1
Blind Source Separation

sensor 1

mixed

sensor 2

time

time

sensor 1

sensor 2
Blind Source Separation

signal 1

time

signal 2

whitened

signal 1

signal 2

time
Blind Source Separation

I.C. 1

whitened and rotated

I.C. 2

I.C. 1
Jason Farquhar (MPI Tübingen) has developed a single optimization method which combines the principles of *maximum-margin classification* and *blind source separation*. It can automatically tune in to the right frequency, time window and spatial filter:
Spatial, temporal, spectral...

Jason Farquhar (MPI Tübingen) has developed a single optimization method which combines the principles of *maximum-margin classification* and *blind source separation*. It can automatically tune in to the right frequency, time window and spatial filter:
Spatial, temporal, spectral...

Jason Farquhar (MPI Tübingen) has developed a single optimization method which combines the principles of *maximum-margin classification* and *blind source separation*. It can automatically tune in to the right frequency, time window and spatial filter:
Jason Farquhar (MPI Tübingen) has developed a single optimization method which combines the principles of *maximum-margin classification* and *blind source separation*. It can automatically tune in to the right frequency, time window and spatial filter:
Spatial, temporal, spectral...

Jason Farquhar (MPI Tübingen) has developed a single optimization method which combines the principles of *maximum-margin classification* and *blind source separation*. It can automatically tune in to the right frequency, time window and spatial filter:
Spatial, temporal, spectral... 

Jason Farquhar (MPI Tübingen) has developed a single optimization method which combines the principles of *maximum-margin classification* and *blind source separation*. It can automatically tune in to the right frequency, time window and spatial filter:

![Graphs showing frequency and time components of signal](image)
Jason Farquhar (MPI Tübingen) has developed a single optimization method which combines the principles of *maximum-margin classification* and *blind source separation*. It can automatically tune in to the right frequency, time window and spatial filter:
Spatial, temporal, spectral...

Jason Farquhar (MPI Tübingen) has developed a single optimization method which combines the principles of maximum-margin classification and blind source separation. It can automatically tune in to the right frequency, time window and spatial filter:
Video: Emotiv.com
Thank you for listening.
Cheap supervised rotation with CSP

- Sensor 1

- Sensor 2

- Mixed

- Time

- Sensor 1

- Sensor 2
Cheap supervised rotation with CSP
Cheap supervised rotation with CSP
Cheap supervised rotation with CSP
Cheap supervised rotation with CSP
Cheap supervised rotation with CSP

![Graph showing data points in a plane, with clusters indicating different classes. Red and blue points are visible, forming distinct patterns.](image-url)
Cheap supervised rotation with CSP
CSP: outlier- (artifact-) sensitivity
CSP: outlier- (artifact-) sensitivity
CSP: outlier- (artifact-) sensitivity
CSP: outlier- (artifact-) sensitivity