Recent Trends in Brain-Computer Interface

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OUTLINE

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  - Where it is used?
  - Main elements of a BCI system
  - Current non-invasive BCI systems
  - Types of EEG based BCI systems
  - Which is the best EEG based BCI?
- Challenges
- The Future
MOTIVATION

- Explosive growth of BCI

Explosive growth of BCI research. Shaded bars are all articles. Open bars are articles with one or more authors who attended one or both of the first two international BCI meetings. (Based on Medline search with all relevant keywords and other sources.)


List of BCI research centres (not exhaustive)

<table>
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<th>Institution</th>
<th>Sensor</th>
<th>Human/Model</th>
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Source: http://donoghue.neuro.brown.edu/bcilabs/bcilabs.htm
INTRODUCTION

- **What is BCI (or BMI)?**
  - Interface without using any peripheral nerves or muscles

- **What is BCI used for?**
  - Communication system
    - For disabled individuals
  - Biometrics
  - Device control
    - Wheel chair movement, prosthetics control, flight/ space control, rehabilitative (assistive) technologies and virtual reality (entertainment)

- **Invasive methods**, ECoG - effective but not popular

- **Non-invasive BCI methods** – EEG, MEG, PET, fMRI, NIR
  - EEG is the most common

• **Types of EEG based BCI**
  - P300-VEP, mental task, SSVEP, motor imagery, SCP
WHERE IT IS USED - COMMUNICATION SYSTEM

Disabled individuals

- Individuals that have lost **most or all** motor function ('locked in' syndrome)

Causes

- Progressive neuromuscular diseases like amyotrophic lateral sclerosis (ALS) or muscular dystrophy
- Non-progressive – stroke, traumatic brain injury, spinal cord injury

These users could use BCI to communicate with others to express their needs, feelings, etc.

- Eg. of a communication BCI system: brain controlled word processing software

Biometrics

- The common biometric is fingerprint
- Others - DNA, hand geometry, palm print, face (optical and infrared), iris, retina, signature, ear shape, odor, keystroke entry pattern, gait, voice, etc.
- But these biometrics can be compromised at some stage
- Biometrics based on BCI is fraud resistant – since thoughts can’t be forged!
WHERE IT IS USED - DEVICE CONTROL

Disabled individuals

- Restoring mobility – eg. to control wheelchair movement
- Environmental control – eg. to control TV, power beds, thermostats, etc.
- Prosthetics control (motor control replacement) – to control artificial limbs
- Rehabilitative (assistive) control – to restore motor control (eg: strengthen/ improve weak muscle)

Healthy subjects

- Environmental control (hands off control) – eg. control of external devices when hand are tied doing something else
- Virtual reality (for entertainment like computer games like MIND PACMAN)
- Flight/ space control – eg. pilots/ astronauts becoming temporarily paralysed due to high altitude (flight), high gravity (space shuttle take-off), trauma, etc.

- Currently, assisting the disabled patients is the main goal of BCI
MAIN ELEMENTS OF A BCI SYSTEM

Signal processing → Feature extraction → Decision process

Digital Data

A/D, amplification, etc.

Instrumentation and protocol design based on which BCI method

Subject

Translation algorithm

Device commands specific for the application

Communication or control achieved

Feedback element (in certain cases)

Normally, this is done in a PC or MAC

ICCIIS 2007, Madurai, India
Current non-invasive BCI systems 1 - EEG based BCI

- The most common BCI
  - Non-invasive, low cost, portable, ease of use
  - Electrodes are attached to the scalp to record brain’s electrical activity
  - EEG is the cumulative effect of thousands or more neurons (in the cortex) that are activated during a certain thought
  - In microVolts range - highly attenuated by skull and scalp (so needs high amplification)

Example of a recorded EEG signal

Example of an electrode placement
Current non-invasive BCI systems 2 - PET based BCI

- A tracer medium (radioactive isotope with short half life) is injected in blood
  - Tracer medium moves in blood and decays by emitting a positron
  - Gamma photons are generated when positron annihilates with electron
  - Scanner measures these gamma photons
  - So, changes in blood flow due to specific brain activity could be detected
- Eg. subject thinks of moving right hand, brain activity detected in left hemisphere and vice versa
- This detected brain activity could be translated for BCI application
- Not popular
  - Too expensive and bulky – cyclotron needed for generation of tracer medium and bulky
  - Partially invasive (as it requires radioactive injection), though no surgery
  - Waiting period (typically an hour) before the system can be used
  - Not suitable for continuous usage
Current non-invasive BCI systems 3 - fMRI based BCI

- Detects changes in blood flow and blood oxygenation (i.e. haemodynamics) in the brain
  - Due to changes in oxygen levels in hemoglobin that generates magnetic resonance
  - Image intensity variations show brain activation areas
  - This could be translated for BCI application
- Not popular
  - Bulky scanner
  - Too slow vascular response - local response to this oxygen utilisation occurs after a delay of approximately 1-5 seconds, with peaks at 4-5 s
  - Possible detrimental effects due to prolonged exposure
  - No mobility for subjects
Current non-invasive BCI systems 4 - NIR based BCI

- Relatively new method
- Near infrared spectroscopy (NIRS) is a spectroscopic method utilising the near infra-red region of the electromagnetic spectrum (from about 800 nm to 2500 nm)
- Penetration is deeper into skull as it uses NIR
- NIR light is emitted and the reflection from the blood cells (specifically, oxygen level in haemoglobin) is used as a measure of blood flow
- This blood flow denotes activation of brain areas (activation deduced from images with higher reflectance intensity)
- Sometime known as optical method as NIR produces intensity images
- Mobility not limited (unlike fMRI) as the sensor-detector can be fixed on the skull
- Slow vascular response (order of a few seconds) is a main hindrance
- Also, most of NIR energy is reflected, a small portion of NIR energy might be absorbed by the brain cells – potentially damaging in the long run
Current non-invasive BCI systems 5 - MEG based BCI

- Similar to EEG but uses measurements of magnetic fields rather than electric fields
- Measures the magnetic field generated by the brain outside the scalp
- Temporal resolution is better than EEG
- High cost and difficulty in obtaining proper MEG readings
  - Ultra-sensitive magnetic field detectors are needed
  - Shielding from other magnetic sources are necessary
- Mobility is restricted
EEG BASED BCI 1 – P300 VEP BCI

VEP
- Visual evoked potential is component in EEG that is in response to an external visual stimulus like a visualising a picture or flash of light
- The recorded signal consist of spontaneous EEG and VEP
- The spontaneous EEG is many times higher in amplitude as compared to VEP
- Hence, measures like averaging from many trials are needed to obtain VEP

P300
- P300 (or P3) is the 3rd positive component in VEP
- Evoked around 300 ms after stimulus onset
- P300 components encountered in VEP is limited to 8 Hz
- Maximal in midline (like Cz, Pz, Fz, etc)
- Evoked in a variety of decision-making tasks and in particular, when a target stimulus is recognised
**EEG BASED BCI 1 – P300 VEP BCI**

**SPELLING PARADIGM MATRIX (DONCHIN PARADIGM)**

- Consist of alphanumerical characters on screen
- EEG (i.e. spontaneous EEG + VEP) recorded when rows and columns flashes
- Each trial would consist of 12 flashes
- Trail are repeated, typically 15, 20 or 40 times
- Averaging from trials is performed to reduce unrelated spontaneous EEG
- LPF (cut-off at 8 Hz) and P300 peak detected around 300-400 ms* and amplitude stored
- The row and column containing the target (focused) character will have a higher P300 amplitude compared to row or column that do not contain the target character

\[
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<th>C3</th>
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</table>
\end{array}
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Which is the focused character? Ans: N

* sometimes, other ranges like 300-500 or 400-600 ms are also used
EEG recorded when users think of different mental tasks covering a wide range of cognitive abilities

- No vocalizing or physical movements

**Example of used mental tasks**

- Baseline - subjects relax and think of nothing in particular
- Letter composing - subjects mentally compose a letter to someone
- Maths – subjects do nontrivial multiplication problems, such as 42 times 18
- Visual counting - subjects visually imagined sequential numbers being written on a blackboard with the previous number being erased before the next number is written
- Geometric figure rotation - subjects imagine a figure being rotated about an axis
EEG BASED BCI 2 - MENTAL TASK BCI

- These mental tasks exhibit inter-hemispheric differences
- For example: maths task (left hemisphere), visual task (right hemisphere)
- How is the activated hemisphere detected?

**Asymmetry ratio**

- Defined by
  \[
  AS = \frac{E_1 - E_2}{E_1 + E_2}
  \]

  where \(P1\) is the energy in EEG one channel in the left hemisphere and \(P2\) is the energy of EEG in another channel but in the right hemisphere
- For example
  - AS using O1 and O2 will be positive for maths activity as compared to object rotation activity (visual)
  - AS for baseline task will be near zero
- So, we can use baseline (B) and two tasks (M and O) to construct a communication method
EEG BASED BCI 2 - MENTAL TASK BCI

- **Translation algorithm** - translates the sequence of detected mental tasks into a command/output

  - Eg: for wheelchair movement
    - Task sequence MBO -> turn left
    - Task sequence OBM -> turn right

  - For communication, Morse code could be used to translate the sequence of mental task into alphabets

  - Eg: Letter I in Morse code is ‘dot dot’

  - So, the sequence: OBOB or (MBMB) could denote letter I

  - Baseline denotes the end and start of a new mental task

EEG BASED BCI 3 - SSVEP BCI

- SSVEP is the response to a visual stimulus modulated at a frequency higher than 6 Hz
- Maximum in the visual cortex, specifically in the occipital region
- Each target flickers with a specific frequency
- Photic driving response in brain causes the frequency (and its harmonics) to appear in SSVEP
- So, determination of SSVEP frequency is enough to decide on the focused target

EEG BASED BCI 3 - SSVEP BCI

- Flicker frequency selection can be up to 45 Hz (higher is better, why?)

**Example**

- Flicker frequencies: 1 (9 Hz), 2 (10 Hz), 3 (11 Hz), …..0 (16 Hz), # (17 Hz)
- Avoid harmonics (eg: since 9 Hz is used, do not use 18, 27, 36 or 45 Hz)
- Normalised FFT magnitude is computed from 4 s SSVEP
- Peak detection (above a certain threshold) is used to determine the frequency
- Once detected, the number appears on screen and subject moves on to look at another number

Which is the number focused?

Ans: 17 Hz, so ‘#’

EEG BASED BCI 4 - MOTOR IMAGERY BCI

- Voluntary movement is composed of 3 phases: planning, execution and recovery
- Even during imaginary movement (motor imagery), there is the planning stage

**During planning (just before movement)**

**ERD/ERS**

- ERD and ERS occur in micrometer (alpha), beta frequency ranges
  - ERD - EEG attenuation in primary and secondary motor cortices during preparatory stage which peaks at movement onset
  - contralateral hemisphere (eg: left hand motor imagery, ERD in right side of brain)
- ERS – EEG amplification, ipsilateral hemisphere

**Gamma burst**

- There is also sharp EEG increase in gamma frequency range
EEG BASED BCI 4 - MOTOR IMAGERY BCI

- Eg: Imagined movements of left hand and right hand

- Discrimination of these imagined movements can be used for BCI

**How?** An example:
- Compute PSD of EEG in C3, C4 and CZ a 1 s-period
- Compute sum of PSD (SPSD)
- $C_{3SPSD} - C_{ZSPSD} > C_{4SPSD} - C_{ZSPSD}$: Left hand
- $C_{4SPSD} - C_{ZSPSD} > C_{4SPSD} - C_{ZSPSD}$: Right hand
- $C_{4SPSD} - C_{ZSPSD} \approx C_{4SPSD} - C_{ZSPSD}$: No motor imagery (as an example)

Figure from http://brain.fuw.edu.pl/~durka/papers/microstr/node12.html#fig:ERDS
**EEG BASED BCI 5 - SCP BCI**

- SCP – potential shifts in EEG (around 1-2 Hz) and can last several seconds
- Humans can control SCP using feedback and positive reinforcement mechanism
- Negativity SCP can be generated with task such as readiness to move or mobilisation of resources for cognitive tasks
- Positivity SCP can be generated during execution of cognitive tasks or simply in inactive states
- Self regulation of SCP can be used to generate a binary signal or even menu/letter selection on screen
- The main problem: requires extensive training, typically a few months

WHICH IS THE BEST EEG BASED BCI?

Each method has its own advantage/disadvantage

- Some methods don’t require training (like P300 VEP) but this method requires many trials (slow response)
- Motor imagery has fast response but performance not satisfactory
- Methods like SSVEP has been shown to be successful using only 1 active channel but requires users to gaze at flashing blocks, which is only practical for short time use (typically a few minutes)
- Mental task has fast response and don’t require any visual interface but performance is not stable over time
- SCP requires extensive training but once mastered, performance is relatively stable
CHALLENGES IN BCI

- Lab environment
  - Most of the work is still in the lab and tested on healthy subjects (mainly students)
  - It is not clear how the design will require adaptation for real users (like disabled people) and in real noisy environments
- BCI system can’t be ON all the time
  - So, will need separate algorithms for ON/ OFF in addition to BCI algorithms
- Performance
  - Performance is only in acceptable range after extensive training/ fine tuning
- Individual BCI not universal BCI
  - Extensive fine tuning results in individual BCI not universal design
- Time
  - The response of BCI systems are still slow for practical applications (eg: typically 3 characters per minute)
- Plasticity
  - Long-term effects of BCI on health and the long-term performance of BCI is unstable
- Ethics
  - This is especially an issue on using BCI with those already completely paralysed
THE FUTURE

- Complete working BCI systems - realisable in a decade or so
- EEG based BCI is the most practical, portable, and cheap enough
- Requires multi-disciplinary approach
  - Clinicians (neurologists, physiatrists), psychologists, engineers, computer scientists, neuroscientists, etc.
- Governments and industries must play a role too

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