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Brain Machine Interface using EEG

Sci-fi to Reality

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BRAIN MACHINE INTERFACE USING EEG

Abstract:

A BMI/BCI system provides a new method of communication and control between the human brain and the computer. The brain consists of billions of neurons and these neurons communicate via minute electrochemical impulses which generate movement, expressions, emotions and words. Mental activity leads to changes of electrophysiological signals. Brain-computer interface (BCI) is a collaboration between a brain and device that enables signals from the brain to direct some external activity, such as control of a cursor or a prosthetic limb. The interface enables a direct communications pathway between the brain and the object to be controlled and is also helpful for treatment of severely paralyzed or locked-in people.

Keywords: Brain Machine Interface, EEG, P-300, Evoked Potentials, Mu and Beta Rhytms.

1. Introduction

A Brain Machine Interface (BMI) or Brain Computer Interface (BCI) is the system which takes brain signals as input and gives person's cognitive state (i.e. thought process or state of mind) as output. The brain's activity can be measured by many methods like Electroencephalography (EEG), Magnetoencephalography (MEG), Electrocorticography (ECoG), Functional Near Infrared Spectroscopy (fNIRS) etc. Of all these systems, EEG is most economical, least bulky and easy to use method for BMI applications.

This paper explains underlying principles of brain machine interface using EEG. The paper is divided into seven sections. Following sections review the basic anatomy of brain and give thorough overview of EEG, clarifying what we measure and how we measure the brains activity. Later sections, give the understanding of BMI system architecture and classification of BMI systems. At the end, current research trends and applications are discussed.

2. Anatomy of Brain

Human brain being most complicated machine, consists of neurons as many in number as there are stars in our Milky way galaxy [1]. It controls and regulates all functions and tasks performed by body. Our brain consists of three major parts namely cerebrum, cerebellum and brain stem.

The cerebrum is the largest part of the brain (Figure 1), accounting for 85 percent of the organ's weight. The distinctive, deeply wrinkled outer surface is the cerebral cortex, which consists of gray matter. Beneath this lies the white matter. Cerebrum is divided into right and left hemispheres. It performs higher functions like interpreting touch, vision and hearing, as well as speech, reasoning, emotions, learning, and fine control of movement. [2]

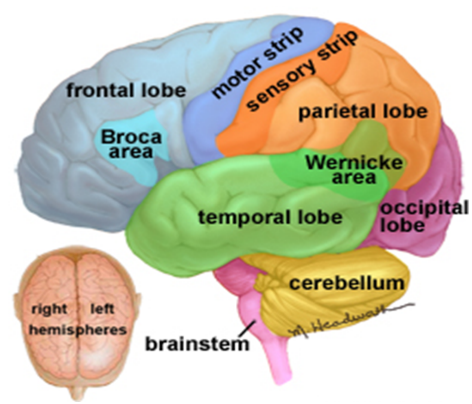


Figure 1: Parts of Human Brain [2]

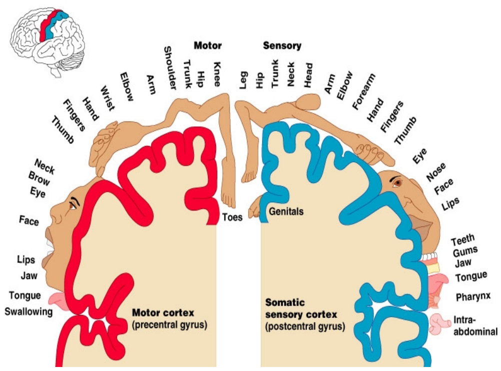


Figure 2: Sensory (Right) and Motor (Left) Strip [3]

The cerebellum is located under the cerebrum. Its function is to coordinate muscle movements, maintain posture, and balance. The brainstem includes the midbrain, pons, and medulla. It acts as a relay center connecting the cerebrum and cerebellum to the spinal cord. It performs many automatic functions such as breathing, controlling heart rate and body temperature, wake and sleep cycles, digestion, sneezing, coughing etc.

The cerebrum is further divided into four lobes: frontal, temporal, parietal, and occipital. Table 01 lists the function performed by each lobe. Each lobe may be divided, once again, into areas that serve very specific functions. It's important to understand that each lobe of the brain does not function alone. There are very complex relationships between the lobes of the brain and between the right and left hemispheres.

Notice the two important areas in cerebrum called sensory strip and motor strip (see Figure 02). The sensory strip is in the parietal lobe, near the border of the frontal lobe. The strip is involved in registering sensation that are connected specific body parts or body functions. Motor strip is located at the frontal lobe and controls all muscle movements including the ones that are necessary for speech. If we compare brain with controller chip, then sensory strip may be regarded as input pins of controller while motor strip can be considered as output pins.

Table 1: Functions performed by different Lobes of Cerebrum

Lobe	Function
Frontal Lobe	Personality, Behavior, Emotions, Judgment, Planning, Problem solving Speaking and Writing, Body movement, Intelligence, Concentration
Parietal Lobe	Interprets language, Sense of touch, Pain, Temperature (*Sensory strip*) Interprets signals from Vision, Hearing etc
Temporal Lobe	Memory, Hearing, Sequencing and Organization
Occipital Lobe	Interprets vision (color, light, movement)

3. Electroencephalography

3.1. Basic of EEG

Electroencephalography (EEG) is a *non-invasive* technique for continuously monitoring brain's activity. It was first observed by German psychiatrist Hans Berger in 1924. It involves placing electrodes on the scalp and measuring the electrode potential of each electrode.

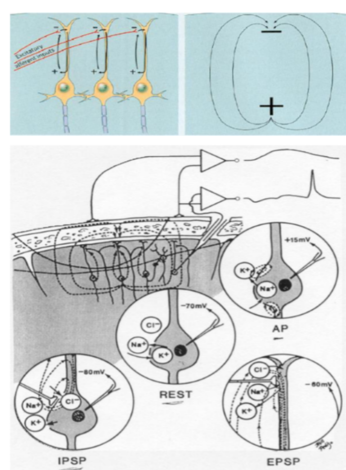


Figure 3: EEG measurement [4]

Neurons which are basic building blocks of our nervous system transmit their energy or "talk" to each other through tiny gap called synapse. Whenever a neuron receives a signal, it's membrane electric potential changes. These signals are passed along by generating action potentials along the neuron. This electrical activity always occurs inside a live brain that is whenever there is any sensory, imagery or motor action happening or even during sleep. The electrodes of EEG on scalp detect the *weighted effect* of this electrical activity of *pyramidal cells* (i.e. neurons just under the scalp). Being a weighted measurement of many nerve cells, EEG has lower spatial resoultion but good temporal resoultion.

3.2. Measurement System (International 10-20 System)

There are many methods by which EEG electrodes are placed. The internationally standardized *10-20 system* is usually employed to record the spontaneous EEG. In this system 21 electrodes are located on the surface of the scalp, as shown in Figure 4A and B. The positions are determined as follows: Reference points are *nasion*, which is the delve at the top of the nose, level with the eyes; and *inion*, which is the bony lump at the base of the skull on the midline at the back of the head. From these points, the skull perimeters are measured in the transverse and median planes [5].Electrode locations are determined by dividing these perimeters into 10% and 20% intervals which is why it is called 10-20 system. Following this pattern, we will get the electrode layout as shown in Figure 4C.

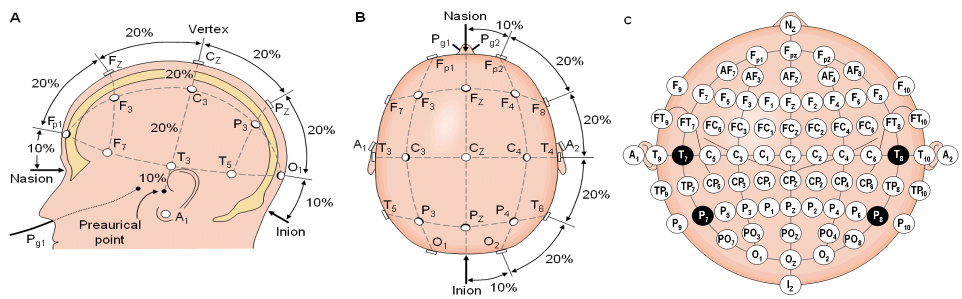


Figure 4 : Electrode Placement according to international 10-20 system [5]

The locations and nomenclature of these electrodes are standardized by the American Electroencephalographic Society. In this diagram the circles containing numbers and letter represent the electrodes. Letter represents the region of brain like F for frontal and C for central and numbers indicate the location. Odd numbers are on left side and even numbers are on right side. Lower the number means it is close to center line and center line is represented by letter ‘z’ indicating zero.

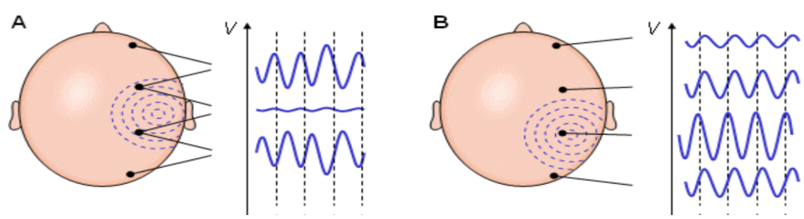


Figure 5: EEG measurement (A) Bipolar (B) Unipolar [5]

EEG signal strength is very small, in the order of microvolts. Therefore, in-order to increase signal to noise ratio, we take differential measurement of two electrodes using differential amplifier with high input impedance to remove the common-mode noise. Thus, EEG is relative measurement. The measurement can be bipolar Figure 5A in which the potential difference between a pair of electrodes is measured or it can be unipolar Figure 5B in which potential of each electrode is compared either to a neutral electrode or to the average of all electrodes.

3.3. Spectrum of EEG

Frequency spectrum of EEG reveals frequency content of signal. It has bandwidth about 50Hz. Figure shows the spectrum of typical EEG signal. The bandwidth is further divided into more commonly observed frequency bands as listed in Table. For example, if we take EEG measurement of person sleeping we will see most of the frequency content will be less than 4 Hz which is called Delta band. Likewise, we have Theta, Alpha, Beta mu bands. Note that Mu waves diminishes with movement or imagination of movement. We will see later that this property is used in control applications.

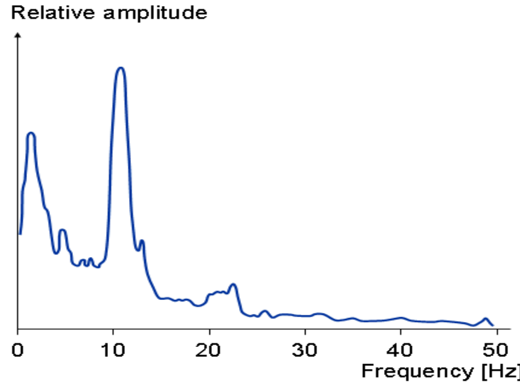


Figure 6: Frequency Spectrum of typical EEG signal [5]

4. EEG BASED BMI SYSTEM ARCHITECTURE

4.1. System Block Diagram

Like any communication or control system, a BCI has input (e.g. electrophysiological activity from the user), output (i.e. device commands), components that translate input into output, and a protocol that determines the onset, offset, and timing of operation. Figure 7 shows these elements and their principal interactions. Signals from the brain are acquired by electrodes on the scalp and processed to extract specific signal features (e.g. amplitudes of evoked potentials or sensorimotor cortex rhythms, firing rates of cortical neurons) that reflect the user's intent.

These features are translated into commands that operate a device (e.g. a simple word processing program, a wheelchair, or a neuro-prosthesis). The important point to notice here is that this whole system involves two adaptive controllers i.e. Brain and BMI system. So, success rate depends on the interaction of two adaptive controllers. The user must develop and maintain good correlation between his or her intent and the signal features employed by the BCI; and the BCI must select and extract features that the user can control and must translate those features into device commands correctly and efficiently. [6]

Table 2: EEG wave bands [5]

Type	Frequency	Location	Use
Delta	0.5-4 Hz	everywhere	occur during sleep, coma
Theta	4-8 Hz	temporal and parietal	correlated with emotional stress (frustration & disappointment)
Alpha	8-13 Hz	occipital and parietal	reduce amplitude with sensory stimulation or mental imagery
Beta	13-30 Hz	parietal and frontal	can increase amplitude during intense mental activity
Mu	8-13 Hz	frontal (motor cortex)	diminishes with movement or intention of movement

4.2. Signal Acquisition

Signal Acquisition is the process of obtaining desired signal (preferably in digital domain) and removing unwanted noise. Signal Acquisition is done is two steps. Firsts step is signal conditioning which is removal of unwanted noise/artifacts followed by amplification. Second step is Analog to digital conversion.

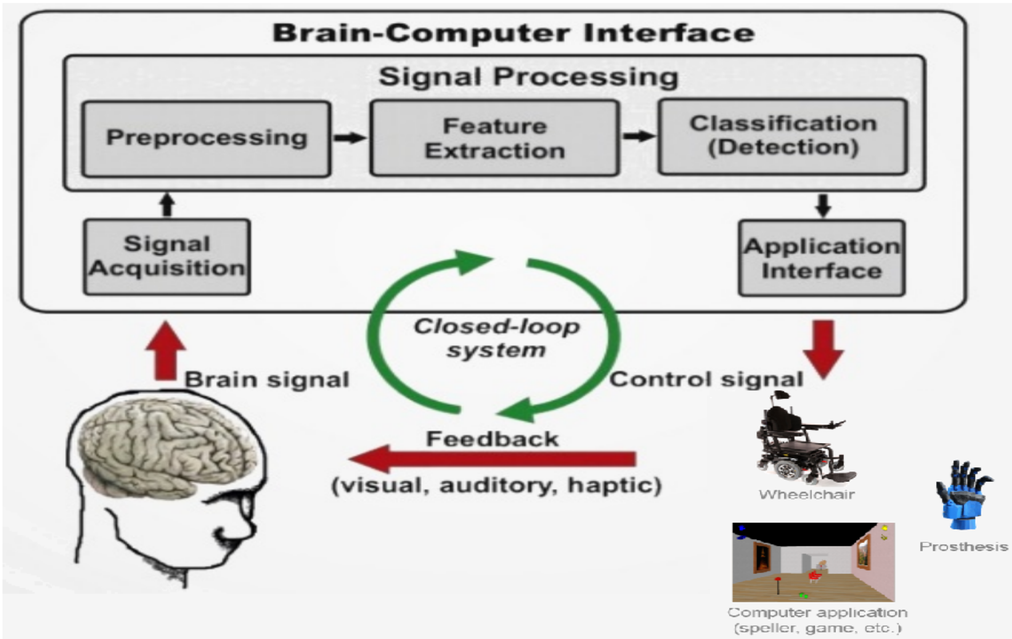


Figure 7: Basic Block Diagram of BMI System [6]

Unwanted noise can be:

a. Biological noise i.e. EMG, Eye blinks or skin effects
b. Electromagnetic Noises: Power line (50/60 Hz), Strong radio stations Environmental EM fields
c. Measurement Noise: Movement of electrodes during measurement, Electrode/sensor degradation or malfunction

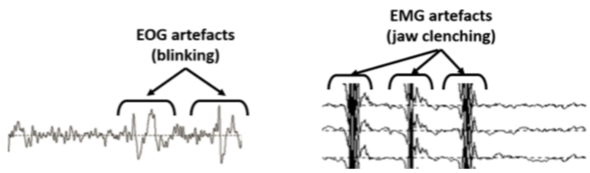


Figure 8: Biological noise due to Eye Blinks (Left) and EMG artifacts (Right) [7]

Filter banks are used to remove above mentioned noise. Figure 9 shows the commonly used filters and their purpose. In-order to further reduce the noise we use averaging filter for data collected over pre-defined repeated time windows.

4.3. Signal Processing

Signal processing involves Feature extraction and Algorithm development. The digitized signals are subjected to one or more of a variety of feature extraction procedures, such as spatial filtering, voltage amplitude measurements, spectral analyses, or single-neuron separation. This analysis extracts the signal features that encode the user’s messages or commands. BCIs can use

signal features that are in the time domain (e.g. evoked potential amplitudes or neuronal firing rates) or the frequency domain (e.g. mu or beta-rhythm amplitudes). In general, the signal features used in present-day BCIs reflect identifiable brain events like the firing of a specific cortical neuron or the synchronized and rhythmic synaptic activation in sensorimotor cortex that produces a mu rhythm. Knowledge of these events can help guide BCI development.
Effective algorithms adapt to each user on 3 levels.

Figure 9: Typical filter bank for EEG signal acquisition

Algorithm development involves converting features into commands. In BCI systems, algorithm should include three level of adaptation:

- 1st level of adaptation-To user's signal features on 1st access to BCI. Calibrating Mu band, P300 amplitude etc.
- 2nd level adaptation - To spontaneous variations i.e. Time of day, hormone level, environments, recent events, fatigue, illness
- 3rd level adaptation -To adaptive capacity of brain, experience, plasticity – Depends on interaction between brain & BCI system [6]

4.4. Output

Output device can be any controllable machine. The system can be used for answering yes/no questions or for word processing. It can be used to control objects like wheelchair or can be channel of communication in games or virtual reality. Usually, computer screen is used for visual feedback and the output is the selection of targets or cursor movement.

5. CLASSIFICATION OF BMI SYSTEMS

5.1. Dependent vs Independent Systems

A dependent BCI does not use the brain's normal output pathways to carry the message but activity in these pathways is needed to generate the brain activity (i.e. EEG) that does carry it. In contrast in Independent BCI the activity in these pathways is not needed to generate the brain activity. For example, if our BMI system requires the movement of eye gaze to get input signal then its dependent BMI. If it does rely on any output channels of brain to muscles, then it's called independent BMI. [6]

5.2. Synchronous vs Asynchronous

Synchronous Systems are system which analyze brain signals during predefined time windows and any signal outside the predefined window is ignored. While asynchronous system continuously analyze brain signals no matter when the user acts. [7]

5.3. Evoked Potentials vs Spontaneous

The inputs to certain BMI systems are evoked potentials or spontaneous potentials. Evoked potentials are signals reflected in EEG from stereotyped sensory stimulation. The stimulation is given by BMI system. The participant/ user selects the stimulation depending on desired output. P-300 is typical example of Evoked potentials discussed in section. The BMI system detects the reflected change in EEG and gives the output accordingly. While BMI system having spontaneous inputs the system does not involve on generation of such stimulation. E.g. EEG rhythms over sensorimotor cortex). [8]

6. PRESENT-DAY BMI SYSTEM

BMI is a highly multidisciplinary field. After its first successful demonstration in 1999, that ensembles of cortical neurons could directly control a robotic manipulator, the field has shown remarkable progress. Given below are few present-day applications and current research trends in BMI technology.

6.1. Visually Evoked Potentials

Visually Evoked Potentials (VEP) is type dependent BCI system and uses the concept of evoked potentials. The system detects the EEG patterns in primary visual cortex. Example of such system involves stimulating the user with a light having certain frequency. The EEG signals around visual cortex will have peaks in spectrum at that frequency component and its harmonics. Figure shows one implantation. In this application, user faces a screen displaying several virtual buttons that are flashed at different rates. Once the user directs his/her gaze at a button, the system determines the frequency of the photic driving response over the user's visual cortex. When the frequency matches that of a displayed button, the system concludes that the user wishes to select it.

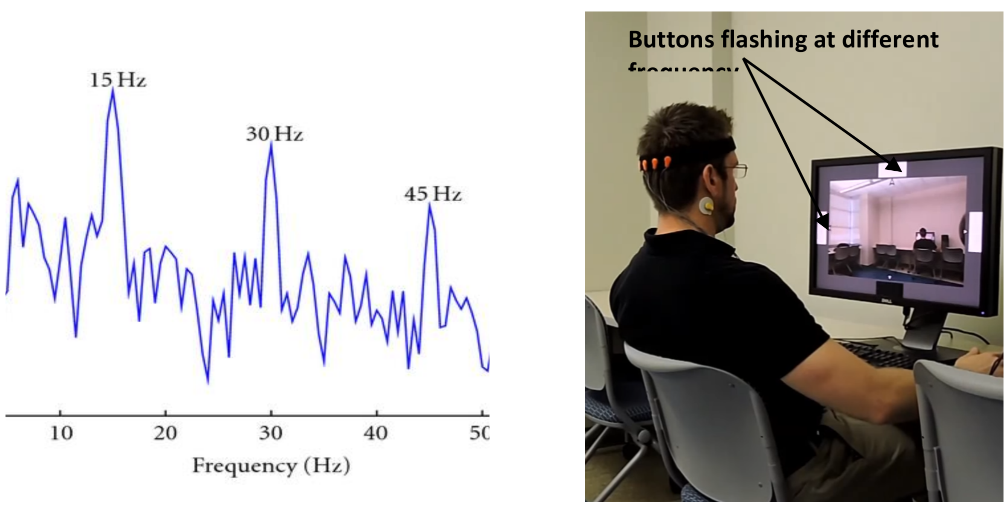


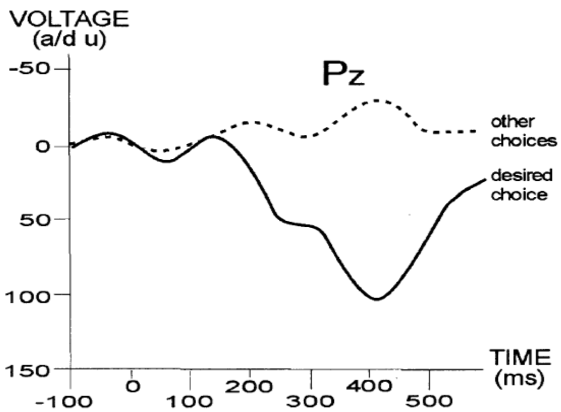
Figure 10: Visual Evoked Potentials [7](Left) EEG Spectrum (Right) Application [9]

6.2. P-300

P300 evoked potentials follows the concept of independent BMI. The P300 is a positive deflection in the electroencephalogram (EEG) time-locked to auditory or visual stimuli.

It is typically seen when participants are required to attend to rare target stimuli presented within a stream of frequent standard stimuli, an experimental design referred to as the oddball paradigm. The P300 amplitude varies as a function of task characteristics such as discriminability of standard and target stimuli, loudness of tones, overall probability of the target stimuli, the preceding stimulus sequence, and the electrode position. Mostly observed in central and parietal regions. [10]

Figure shows the example of BMI system using P-300. This is speller program for typing letters by merely focusing on the letters of interest. The screen flashes one row at a time. In the given figure, the user wants to type letter ‘O’. The user focuses on letter ‘O’ and when the row containing letter ‘O’ flashes positive deflection in her EEG signal is recorded, which by counting number of rows, the BMI system predicts what letter she wants to type in.



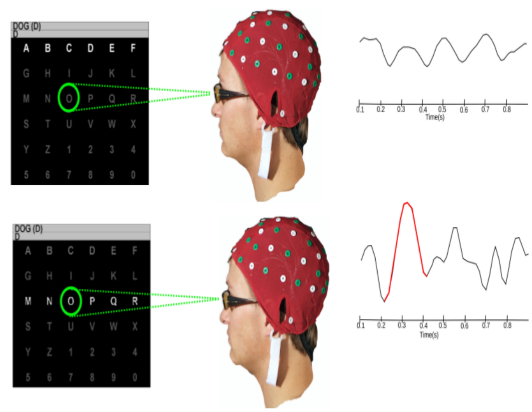
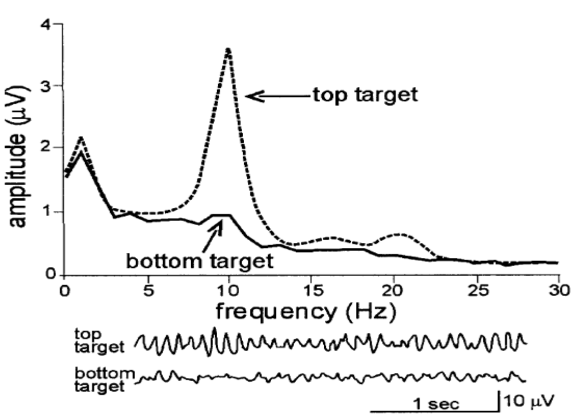


Figure 11 : (Left) P-300 waveform [6](Right) Speller Program using P-300 [7]

6.3. Mu and Beta Rhythms

In awake people, primary sensory or motor cortical areas often display 8–12 Hz EEG activity when they are not engaged in processing sensory input or producing motor output. This idling activity, called mu rhythm comprises a variety of different 8–12 Hz rhythms, distinguished from each other by location, frequency, and/or relationship to concurrent sensory input or motor output.



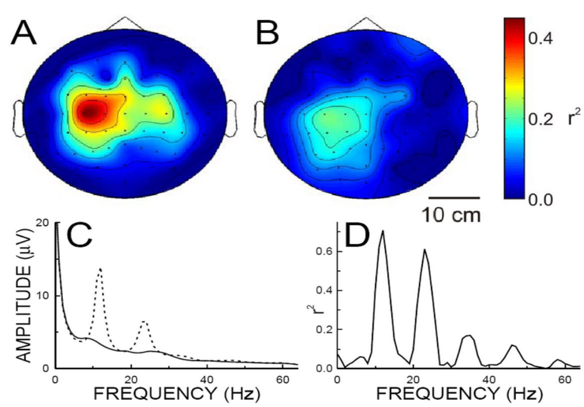


Figure 12 : (Left) Decrease in Amplitude of EEG spectrum at Mu rhythm (Right) Difference between actual movement and imagery movement [6]

These mu rhythms are usually associated with 18–26 Hz beta rhythms. While some beta rhythms are harmonics of mu rhythms, also some are separable from them. Movement or preparation for movement is typically accompanied by a decrease in mu and beta rhythms, particularly contralateral to the movement. This decrease has been labeled ‘event-related desynchronization’ or ERD. [8]

7. CONCLUSION

Brain Machine interface is very interesting field which gives us chance to expand the capabilities of human brain, potential to bring science fiction into reality. EEG based BMI systems are the hope for severely and partially paralyzed patients in that one day they can reacquire basic forms of communication and motor control. It holds the promise of bringing sight to the blind, hearing to the deaf and words to unspoken emotions.

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