ABSTRACT

**BRAIN COMPUTER INTERFACE BASED NEUROREHABILITATION
TECHNIQUE USING A COMMERCIALLY AVAILABLE EEG HEADSET**

by
Abhineet Mishra

Neurorehabilitation has recently been augmented with the use of virtual reality and rehabilitation robotics. In many systems, some known volitional control must exist in order to synchronize the user intended movement with the therapeutic virtual or robotic movement. Brain Computer Interface (BCI) aims to open up a new rehabilitation option for clinical population having no residual movement due to disease or injury to the central or peripheral nervous system. Brain activity contains a wide variety of electrical signals which can be acquired using many invasive and non-invasive acquisition techniques and holds the potential to be used as an input to BCI. Electroencephalogram (EEG) is a non-invasive method of acquiring brain activity which then, with further processing and classification, can be used to predict various brain states such as an intended motor movement. EEG provides the temporal resolution required to obtain significant result which may not be provided by many other non-invasive techniques. Here, EEG is recorded using a commercially available EEG headset provided by Emotiv Inc. Data is collected and processed using BCI2000 software, and the difference in the Mu-rhythm due to Event Related Synchronization (ERS) and Desynchronization (ERD) is used to distinguish an intended motor movement and resting brain state, without the need for physical movement. The idea is to combine this user intent/free will with an assistive robot to achieve the user initiated, repetitive motor movements required to bring therapeutic changes in the targeted subject group, as per Hebbian type learning.

BRAIN COMPUTER INTERFACE BASED NEUROREHABILITATION
TECHNIQUE USING A COMMERCIALLY AVAILABLE EEG HEADSET

by
Abhineet Mishra

A Thesis
Submitted to the Faculty of
New Jersey Institute of Technology
in Partial Fulfillment of the Requirements for the Degree of
Master of Science in Biomedical Engineering

Department of Biomedical Engineering

May 2013

APPROVAL PAGE

**BRAIN COMPUTER INTERFACE BASED NEUROREHABILITATION
TECHNIQUE USING A COMMERCIALLY AVAILABLE EEG HEADSET**

Abhineet Mishra

Dr. Richard A. Foulds, Thesis Advisor   Date
Associate Professor of Biomedical Engineering, NJIT

Dr. Sergei Adamovich, Committee Member   Date
Associate Professor of Biomedical Engineering, NJIT

Dr. Mesut Sahin, Committee Member   Date
Associate Professor of Biomedical Engineering, NJIT

BIOGRAPHICAL SKETCH

Author: Abhineet Mishra

Degree: Master of Science

Date: May 2013

Undergraduate and Graduate Education:

- Master of Science in Biomedical Engineering,
  New Jersey Institute of Technology, Newark, NJ, 2013

- Bachelor of Technology in Electronics and Communication Engineering,
  Rajasthan Technical University, Kota, Rajasthan, India, 2010

Major: Biomedical Engineering

Presentations and Publications:

Abhineet Mishra and Richard A. Foulds, *"Detection of user intent in neurorehabilitation using a commercial EEG headset,"* 39th Annual Northeast Bioengineering Conference, IEEE, 2013.

Abhineet Mishra, Deniz Ozgulbas, Eren Alay, Eun Kim, Tara L. Alvarez, *"Checking the saliency of the stimuli on central versus peripheral visual field,"* 39th Annual Northeast Bioengineering Conference, IEEE, 2013.

To my parents for their love and support
and mentors for having faith in me.

ACKNOWLEDGEMENT

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ACRONYMS

BCI	Brain Computer Interface
BMI	Brain Machine Interface
EEG	Electroencephalogram
EMG	Electromyogram
CVA	Cerebrovascular Accidents
TBI	Traumatic Brain Injury
SCI	Spinal Cord Injury
ALS	Amyotrophic Lateral Sclerosis
EOG	Electrooculogram
ECG	Electrocardiogram
EP	Evoked Potential
ERP	Event Related Potential
MEG	Magnetoelectroencephalogram
ERD	Event Related Desynchronization
ERS	Event Related Synchronization
TCP/IP	Transmission Control Protocol/Internet Protocol
UDP	User Datagram Protocol
CAR	Common Average Reference
VRML	Virtual Reality Modeling Language
VR	Virtual Reality

CHAPTER 1

INTRODUCTION

1.1 Problem Statement

Cerebrovascular Accidents (CVA), commonly known as Stroke, Traumatic Brain Injury (TBI), Spinal Cord Injury (SCI), Amyotrophic Lateral Sclerosis (ALS) are few among many diseases severely affecting the channel of interaction between brain and its operated entities [1]. In the United States, they are the leading cause of disability affecting over a million individuals annually and substantially more across the globe [1] [2] [3]. As per the National Stroke Association, after a year post stroke, a third of all affected patients have poor or non-existent residual hand motor function, despite intensive treatment and rehabilitation. Significant functional recovery after this initial year is rare despite novel interventional approaches recently applied in the chronic stage, like bilateral arm training or constraint-induced movement therapy [4] [5]. The associated treatment cost also ranges between $100K and $2M, which includes inpatient care, rehabilitation, and follow-up [2] [6].

Currently available treatments deeply rely on the ability of the patient to perform actions with the affected arm or hand, and therefore require a moderate degree of residual motor function. There are however, many patients who do not have such residual function and therefore cannot use the plegic hand at all for training purposes. At present, there is no treatment available for this condition. Under such condition a brain computer interface (BCI) system which decodes brain signals to identify end-effecter action or behavior can provide an effective & affordable rehabilitation system.

1.2 Literature Review/Background Search

Many different approaches have been used rehabilitate subjects who have had cerebrovascular accidents. But the novelty of this approach is the synchronization between the intention to move and the movement of a robot. This effectively allows the therapeutic movement to be triggered by the user's imagination.

1.2.1 Current State of Rehabilitation

Traditional approaches towards rehabilitation can be qualified as bottom-up approaches. They act on the distal physical level (bottom) aimed at influencing the neural system (top), with resulting rehabilitation due to the mechanism of neural plasticity. Another approach is the top-bottom defining the rehabilitation therapies based on the state of the brain after stroke, driven by neural plasticity. Detailed classification is shown in the figure 1.1.
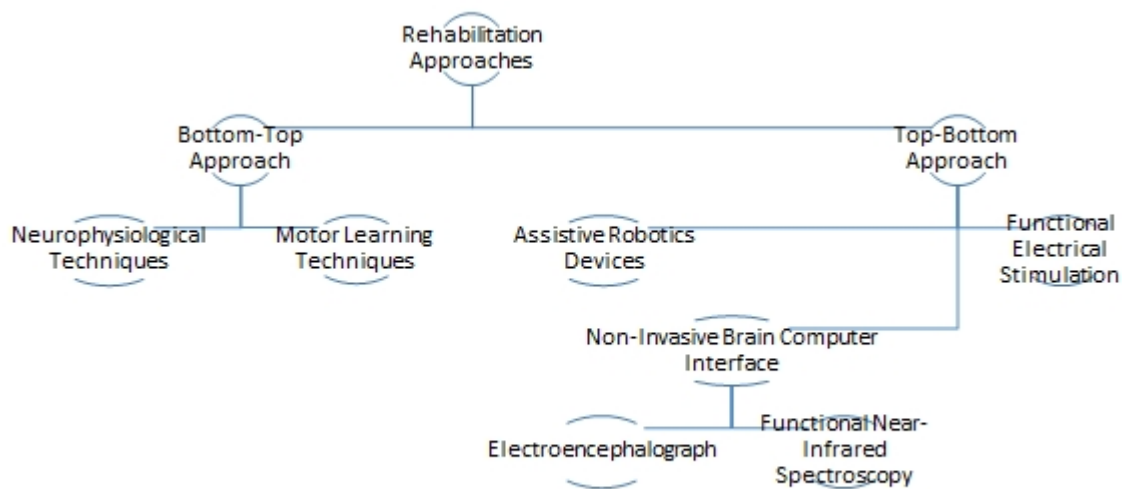
Figure 1.1: Classification of rehabilitation approaches post stroke.

Source: [7]

Apart from all these techniques other factors also affect the rehabilitation outcomes; these include a high degree of motivation and involvement/engagement of patients with their family, cognitive functions and attention. Sometimes these factors also influence the inclusion or exclusion criteria for the subjects in research studies.

Conventional bottom-top approaches do not restore a normal gait pattern in the majority of stroke patients [8] giving reason to use robots in assistive training for both upper and lower extremity. These devices provide safe, intensive, and task oriented rehabilitation to people with mild to severe motor impairments after neurological injury [9]. In principle, robotic training could increase the intensity of therapy with quite affordable costs, and offer advantages such as: i) precisely controllable assistance or resistance during movements, ii) good repeatability, iii) objective and quantifiable measures of subject performance, iv) increased training motivation through the use of interactive (bio)feedback. In addition, this approach reduces the amount of physical assistance required to walk reducing health care costs [10] and provides kinematic and kinetic data in order to control and quantify the intensity of practice, measure changes and assess motor impairments with better sensitivity and reliability than standard clinical scales [9] [10] [11]. Combined with a visual feedback provided via immersive virtual environment (see Figure 1.2) they can prove out to be an effective method of rehabilitating stroke subjects [12] [13]. Virtual environment provides some added advantages like:

- Real-time feedback - Therapists and patients receive real-time feedback.

- Inspiring and motivational - Thanks to gaming elements, training becomes inspiring and motivational. Being immersed in a game environment often has an effect where patients stop concentrating on their limitations and pain. Positive feedback is given to stimulate patients.

- Controlled environment - The therapist can customize challenging exercises in a very controlled environment. Different levels of difficulty can be applied by giving feedback to the patient through loop speed and gain based on patient's performance.

Figure 1.2: Motek's virtual environment with assistive treadmill for gait training.

Source: [14]

Limitation with this extra-ordinarily effective method of providing therapy is in its inclusion criteria. All such therapy requires a certain degree of voluntary movement post stroke i.e. if a subject cannot move their limb at all, they cannot benefit from robotic-virtual environment therapy.

1.2.2 Imagination, Intention and Motor functions

The Human brain is like a black box containing the neural representation of the actions, behavior, responses etc. It would be best if one could somehow steer into it to get full access to its endogenous functioning and get answers to many intriguing questions. But, reality is slightly opaque, forcing researchers and clinicians to rely on introspections, mental chronometry and inference of cognitive brain functions from measurements of remote physiological correlates.

Action representation is one of such issues, having conflicting point of views. Some mechanisms consider it to be internally represented/ endogenously driven whereas other found it to be direct transformation of ingoing activity into outgoing activity [15]. Following the former, it can be warranted that motor imagery, when defined and used properly can be a key to understanding motor representations and the cognitive content of actions.

Imagination is the ability to form images and sensations that are not perceived through sight, hearing or other senses. It is further classified into two types: Visual Imagery and Motor Imagery. Visual imagery refers to the imagination of visual representation of the scenes, for example, imagining a fruit or any flower. Whereas, motor imagery refers to the visual images related to the action. It is further classified into two types: internal and external. If one imagines a limb movement, he/she can imagine it as first person i.e. individual is doing that task themselves or as a second person i.e. imagining somebody doing that action. This study focuses only on internal motor imagery. A close functional equivalence between motor imagery and motor preparation is suggested by the positive effects of imagining movements on motor learning, the

similarity between the neural structures involved, and the similar physiological correlates observed in both imaging and preparation [15]. The reason for taking imagery to be in close relation with action preparation/ intention is its ability to conserve the spatial-metric property, i.e. the time needed to perform an actual action like picking up an object from a table is found to be equal to the time taken to perform the same task in imagination [15]. Its vividness can also be understood by the change in heart and respiration rate of an individual while watching an involving sport. The idea is that we feel our self to be so immersed in the sports that our brain starts to respond as if we are not only watching but playing that game as well. It was better explained with the theory of mind and discovery of mirror neurons.

During 1980s and 1990s, a remarkable thing was discovered inside a macaque brain by a group of Italian neurophysiologists. This discovery was not accepted initially but was widely supported by the scientific community with time. That thing is known as 'Mirror Neuron', and with the help of advances in non-invasive technologies like fMRI and PET Scans, it was later on found to exist in human brain as well [16] [17]. Using microelectrodes that recorded from individual neurons, those Italian investigators observed that the same neuron fired both when the monkey grasped an object, such as a raisin, and when it observes a human or another monkey performing the same specific action. Mirror neurons respond only to intentional motor actions. This is the first evidence that there is an area in the motor cortex that can respond specifically and only to goal-directed, relational actions. To illustrate, consider a pupil learning a motor skill like learning a musical instrument. While pupil watches the teacher, neurons in his brain relevant to motor preparation and planning will fire as if he were actually preparing the

action he is viewing. Similarly, the teacher's feeling during pupil's performance would be based on the discharge of the same neurons in his own brain that were firing while he was preparing and executing the correct movements. This very striking result supports the idea of representing neurons as a common substrate for motor preparation and imagery.

Motor images and motor preparation have different subjective contents. Only the final content of motor preparation is open to the subject's judgment, so the action, once executed, can be recognized by him to correspond (or not) to his intent. By contrast, the content of motor images can be accessed consciously. This difference between the two situations may be one of degree, however, rather than one of kind, in which case if motor preparation (normally very brief) could be prolonged, the intention to act would progressively become a motor image of the same action. If this were the case, the non-conscious to conscious transition would be determined by solely by the time allowed for the preparation processes to access awareness [15]. This idea of getting access to intention when it is not followed by execution was further supported by studies on amputees. They reported, that amputees seem to have clear image of their intended action [18]. These data suggests that if the action were actually executed, the content of the motor representation would not reach consciousness because it would be cancelled as soon as the corresponding movement is executed (perhaps by the incoming signal generated by execution itself). By contrast, if only motor imagery occurred with execution deliberately blocked or delayed, the representation would be protected from cancellation and would become accessible to conscious processing.

1.3 Concept Formulation

Access to the intention/conscious free will via imagination opens the gate for the clinical population with no residual movement (post stroke) to benefit from robot assisted, immersive virtual environment training. A Brain computer interface system can allow accessing the intentions of the subject within 200msec which is close to average human response time to visual stimuli [19]. The core of this whole rehabilitation method is to synchronize the intended movement of the subject with robot assisted execution and virtual environment feedback. It will be a perfect top-bottom approach of the rehabilitation, exploiting neuroplasticity to rehabilitate subjects not depending on the expected activation in peripheral limb. The hypothesis and expected result post training is that, with time subject will gain strength to move their affected limb on their own or with minimal assistance.

Secondarily, effectiveness of a commercially available and cost effective EEG headset is also analyzed towards brain computer interface, with an idea to make this system cost effective. Whether, it is possible to use them to detect EEG features and identify changes in the brain states to independently control the rehabilitation system. Since, the user is expected to cooperate and imagine the exact movement replicated by the robot, all that is needed by a BCI system is a signal indicating initiation of the imagined movement to allow its synchronization with the robot movement. This produces the requirement of the BCI system to distinguish a resting state with motor imagination or movement.

Chapter 2

ELECTROENCEPHALOGRAPH

2.1 The EEG Signal

It is not possible to measure a single neuron's action potential extracellularly, as its amplitude is too small to be picked up by the EEG. It does not last long enough (0.3ms) to accumulate sufficient power together with other synchronously firing neurons [20]. Release of neurotransmitters to the synapse is triggered when an action potential reaches the axon terminal [21]. There exist two kinds of neurotransmitters: one causes an influx and the other an outflow of positive ions by changing the permeability of the postsynaptic neuron's membrane [22] and thereby influences the neuron's potential difference.

This is referred to as either excitatory postsynaptic potential (when positive) or inhibitory postsynaptic potential (when negative) [23]. Postsynaptic potentials vary in their amplitude between 50 and 100mV (measurement on the scalp) [20], last over 100ms [24] and constitute the main source of the EEG-signal.

For an electrical signal to be strong enough to be detectable the following requirements have to be satisfied [21]:

- many neurons must fire synchronously

- those neurons must be aligned in parallel so that their potential sum rather than cancel out (see figure 2.1)
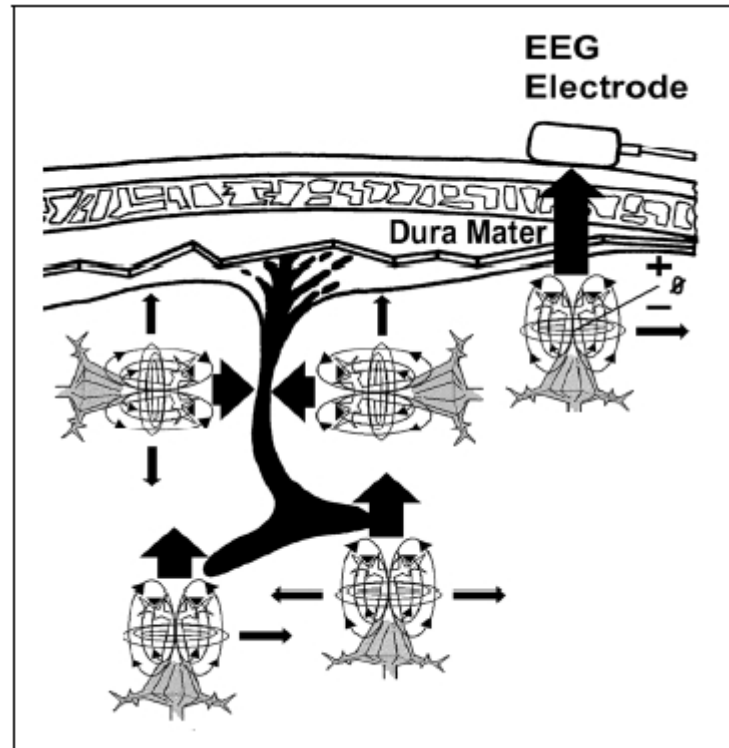
Figure 2.1: Cortical generators of electric currents. Thick arrows represent the propagation of electrical currents that can be picked up by the EEG electrode.

Source: [25]

The electroencephalography is defined as a graphic representation of the potential difference between two different cerebral locations plotted over time [26]. It is important to note here that the signal of each channel is always plotted as the difference to a reference electrode, even though the name of the reference channel is often omitted.

2.2 Artifacts

As discussed earlier, EEG is designed to record cerebral activity, but it also picks up electrical activities arising from locations other than the brain. The recorded activity that is not of cerebral origin is termed artifact and can be divided into physiological and extra physiological artifacts. While physiological artifacts are generated from the patient, they

arise from sources other than the brain (i.e., body). Extra physiologic artifacts arise from outside the body (i.e., equipment, environment).

Electrical activities arising from muscle, also known as myogenic potentials are the most common artifacts. The frontalis and temporalis muscles (e.g., clenching of jaw muscles) are common sources. Generally, the potentials generated in the muscles are of shorter duration than those generated in the brain and are identified easily on the basis of duration, morphology, and rate of firing (i.e., frequency). Particular patterns of electromyogram (EMG) artifacts can occur in some movement disorders. Essential tremor and Parkinson disease can produce rhythmic 4 to 6 Hz sinusoidal artifacts that may mimic cerebral activity.

Table 2.1: Overview over some artifact types and their amplitude/frequency ranges. It should be noted, that those properties refer to measurements being taken as close as possible to the origin of the electrical activity, which is in the skin area closest to the skeletal muscle.

Signal	Amplitude Range		Frequency Range(Hz)	
	from	to	from	to
EEG	$2\,\mu V$	$100\,\mu V$	0.5	100
EEG(EP)	$0.1\,\mu V$	$20\,\mu V$	1	3,000
EOG	$10\,\mu V$	$5\,mV$	0	100
EMG	$50\,\mu V$	$5\,mV$	2	500
ECG	$1\,mV$	$10\,mV$	0.05	100

Source: [27]

Biological artifacts can be broadly classified into multiple categories which includes Eye-induced artifacts (eye blinks, eye movements and extra-ocular muscle activity), ECG artifacts, Muscle activity-induced artifacts and Glossokinetic artifact (artifacts are caused by the potential difference between the base and the tip of the tongue).

Eye movements are observed on all EEGs and are useful in identifying sleep stages [28]. The eyeball acts as a dipole with a positive pole oriented anteriorly (cornea) and a negative pole oriented posteriorly (retina). When the globe rotates about its axis, it generates a large-amplitude alternate current field, which is detectable by any electrodes near the eye (see Figure 2.2).
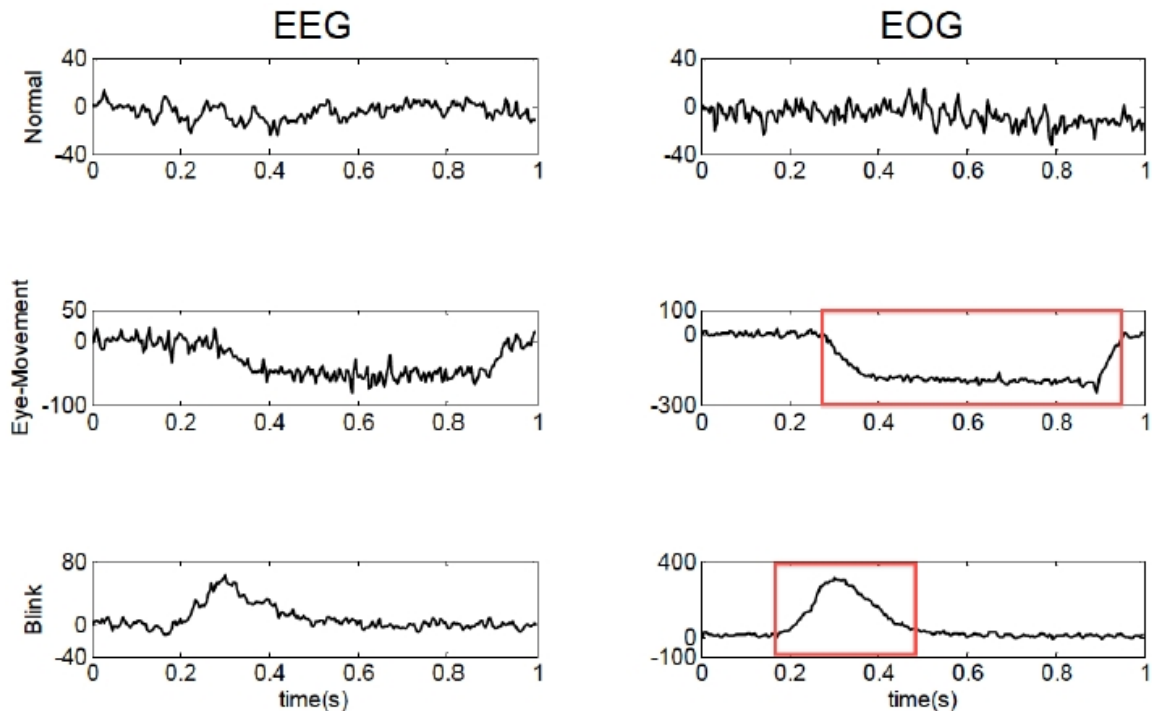
Figure 2.2: How eye-movements and blinks (right) influence the EEG recording (left). All y-axis scaling are in μV.

Source: [27]

The Electromyogram (EMG) measures electrical currents generated in muscles during its contraction representing neuromuscular activities. The EMG signal also influences the EEG recording as illustrated in figure 2.3. It is therefore important to inform the patient about it so that he can try to move as little as possible during the recording. Also EMG artifacts should be considered when designing an experiment: The patient should be seated comfortably and should not be required to move or turn his head

during the experiment. If possible, pauses might be built into the experiment that the patient can use to move.

Some individual variations in the amount and persistence of ECG artifact are related to the field of the heart potentials over the surface of the scalp. Generally, people with short and wide necks have the largest ECG artifacts on their EEGs. The voltage and apparent surface of the artifact vary from derivation to derivation. The artifact is observed best in referential montages using earlobe electrodes A1 and A2. ECG artifact is recognized easily by its rhythmicity/regularity and coincidence with the ECG tracing (each "sharp wave" equals artifact that synchronizes with each QRS complex of the ECG channel; see Figure 2.4). The situation becomes difficult when cerebral abnormal activity (e.g., sharp waves) appears intermixed with EEG artifact, and the former may be overlooked.
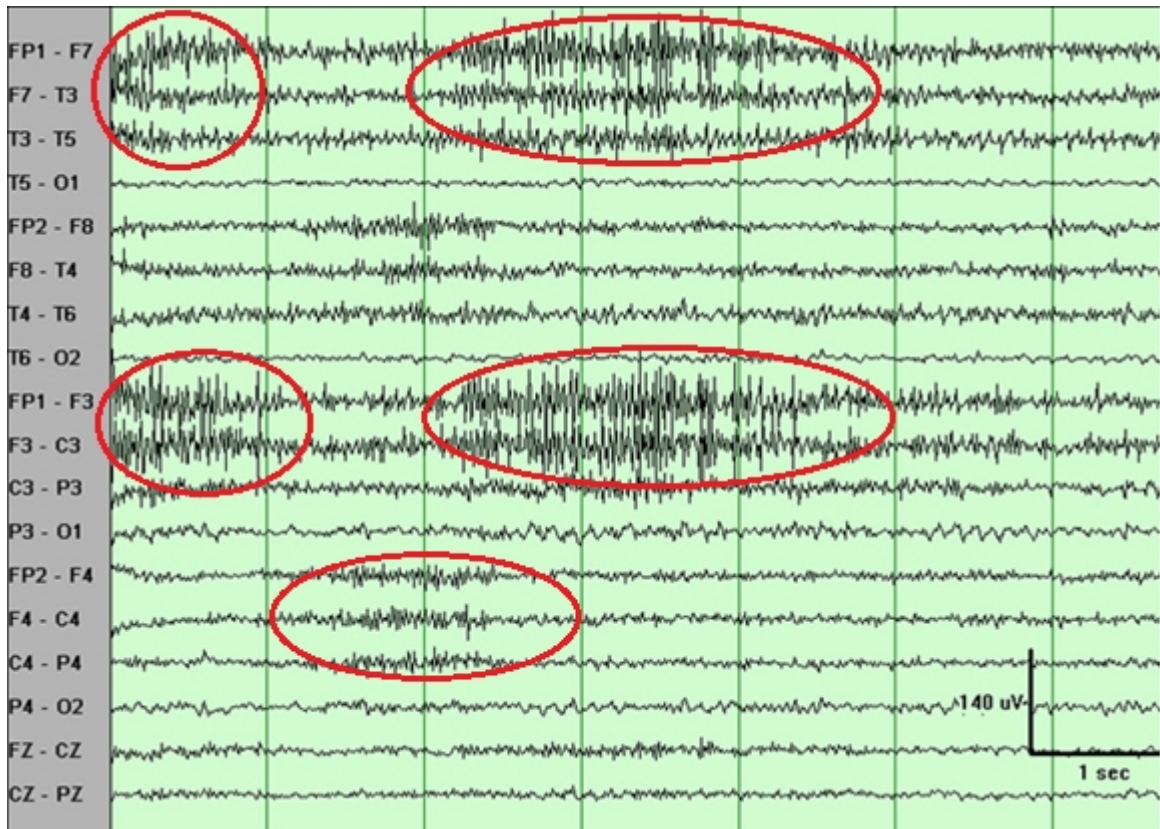
Figure 2.3: Electromyogram (muscle) artifact (marked in red). These waveforms represent motor unit potentials as typically observed on needle electrode examination during electromyogram, with a frequency of 20-100 Hz.

Source: [29]
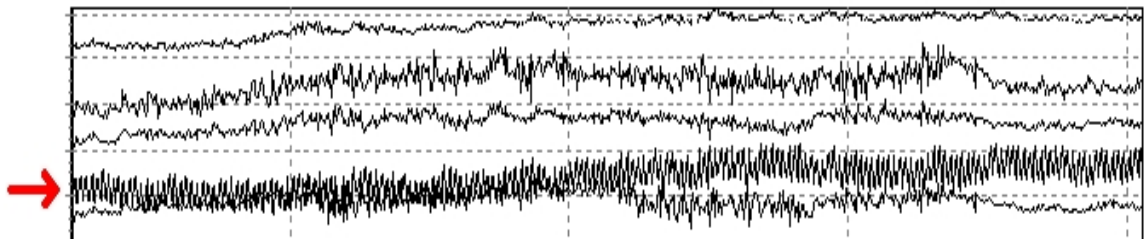
Figure 2.4: Artifacts due to power line interference. This figure shows an example for one signal channel (marked by the arrow) that is contaminated by regular high frequency (i.e., 60 Hz) noise.

Source: [30]
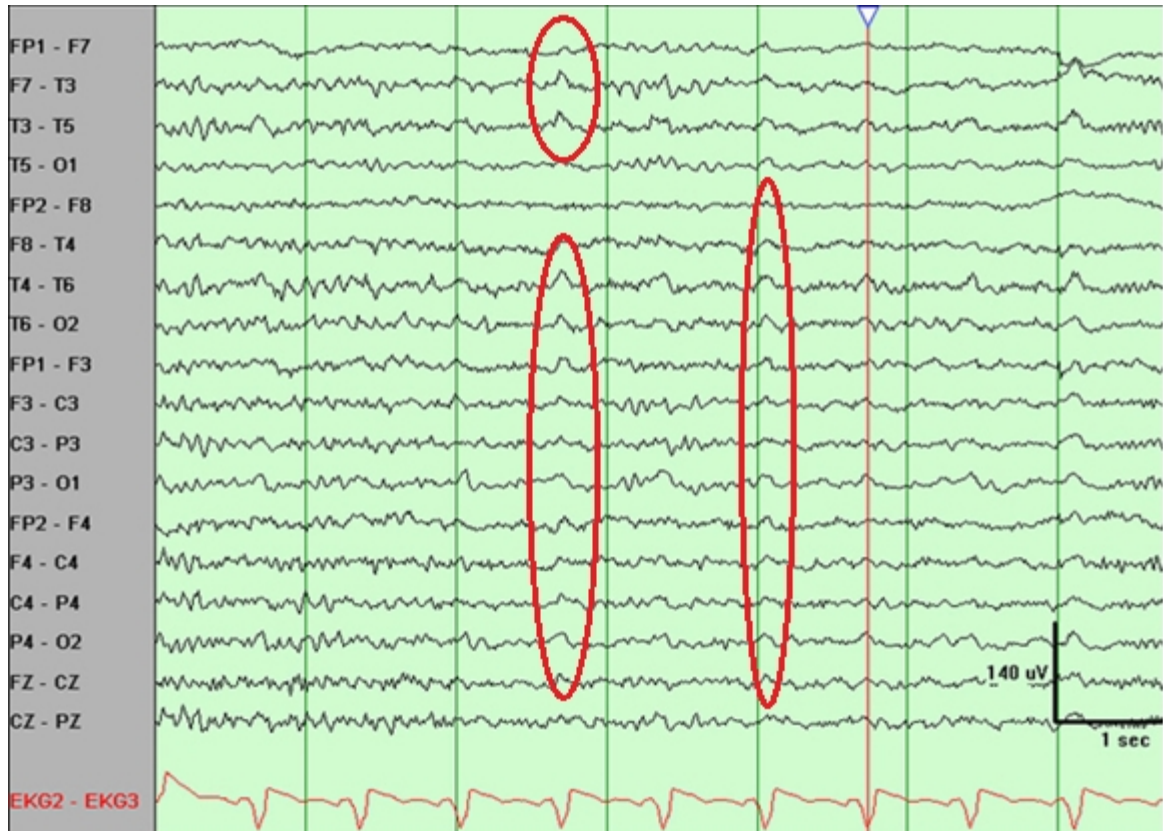
Figure 2.4: Regular (periodic) slow wave's best observed at mid temporal and posterior temporal electrodes T4-T6 and T3-T5 (shown in red). These clearly are related to ECG. The duration and morphology are those of pulse artifact, but as demonstrated by the marker, no delay occurs between the ECG and the artifact. Thus, this is an ECG artifact with broad QRS complexes.

Source: [29]

In addition to these artifacts, the tongue (like the eyeball) functions as a dipole, with the tip negative with respect to the base. In this case, the tip of the tongue is the most important part because it is more mobile. The artifact produced by the tongue has a broad potential field that drops from frontal to occipital areas, although it is less steep than that produced by eye movement artifacts. Chewing and sucking can produce similar artifacts. These are commonly observed in young patients. However, they also can be observed in patients with dementia or those who are uncooperative.

2.3 Event Related Potentials

Event-related potentials (ERPs) are very small voltages generated in the brain structures in response to specific events or stimuli [31]. They are EEG changes that are time locked to sensory, motor or cognitive events that provide safe and noninvasive approach to study psychophysiological correlates of mental processes. Event-related potentials can be elicited by a wide variety of sensory, cognitive or motor events. They are thought to reflect the summed activity of postsynaptic potentials produced when a large number of similarly oriented cortical pyramidal neurons (in the order of thousands or millions) fire in synchrony while processing information [32]. Positive and negative potential changes are commonly labeled with either "P" (for positive) or "N" (for negative) and a number corresponding to the time of their appearance relative to the event [21]. Consequently, N400 represents a negative peak 400ms after the event.

2.4 Event Related Synchronization and Desynchronization

An internally or externally paced event results not only in the generation of an event-related potential (ERP) but also in a change in the ongoing EEG/MEG in form of an event-related desynchronization (ERD) or event-related synchronization (ERS) (see Figure 2.5). The ERP on the one side and the ERD/ERS on the other side are different responses of neuronal structures in the brain. While the former is phase-locked, the latter is not phase-locked to the event. The most important difference between both phenomena is that the ERD/ERS is highly frequency band specific, whereby either the same or different locations on the scalp can display ERD and ERS simultaneously [33]. There are a couple of event-related phenomena which represent frequency specific changes of the

ongoing EEG activity (motor imagery being one of those) and may consist, in general terms, either of decreases or of increases of power in given frequency bands. This may be considered to be due to a decrease or an increase in synchrony of the underlying neuronal populations, respectively. The former case is called event-related desynchronization or ERD and the latter event-related synchronization (ERS) [33].
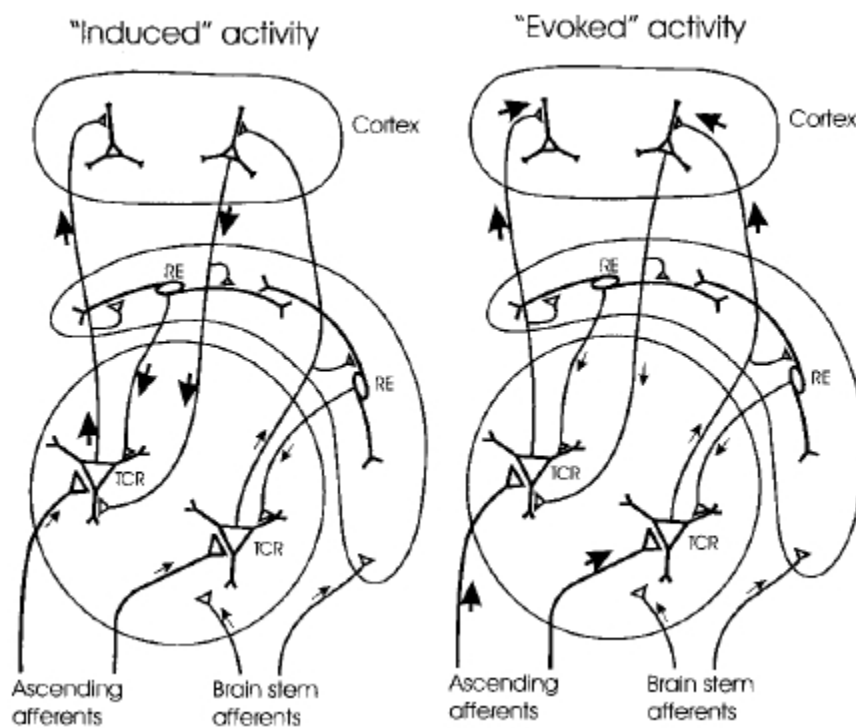
Figure 2.5: Schema for the generation of induced (ERD/ERS) and evoked (ERP) activity whereby the former is highly frequency-specific. TCR thalamic relay cells; RE reticular thalamic nucleus.

Source: [33]

Chapter 3

ELECTROENCEPHALOGRAPH HEADSET

3.1 Introduction and Comparison

An EEG has a very high time resolution, i.e. changes in electrical activity of the brain show up very quickly in the signal of the EEG (Also it is non-invasive and relatively user friendly). EEG headsets serve the purpose of acquiring these electrical activities from the scalp just like any other set of sophisticated electrode cap and amplifier. They measure voltage fluctuations resulting from ionic current flow within the brain. Compared to other professional EEG systems, performance of these headsets are low [34] and are completely subject dependent. But since it was never meant to be used as a medical device they serve the purpose of their manufacturers and users. It is very much capable of differentiating between brain states but subject needs to pay full attention and become familiar with what state of mind they are in. Such headset attracts hobbyists and may soon allow use of EEGs for the consumer. In a study, different low-cost EEG systems have been compared by price and functionality (see Table 3.1) and rated by usability (see Figure 3.1). In their findings, the Emotiv EPOC scored best in terms of usability and was ranged in the middle price segment [35].

Table 3.1: Low-cost EEG systems under $1000.

Price Range	Device	Data contents from device	Interface
0 − 200 $	ModularEEG	Raw EEG	RS232
	Neurosky, Mindset	Raw EEG/Classification Data	Bluetooth
$200 − $500	OCZ Tech., NIA	Classification Data	USB
	Emotiv, Epoc	Raw EEG/Classification Data	Wireless
$500 − $1000	Neurobit lite	Classification Data	Wireless IrDA
	Pocket Neurobics Pendant EEG	Raw EEG	Wireless
	Teunis van Beelen's openEEG	Raw EEG	RS232
	Psychlab EEG1	Raw EEG	USB

Source: [35]
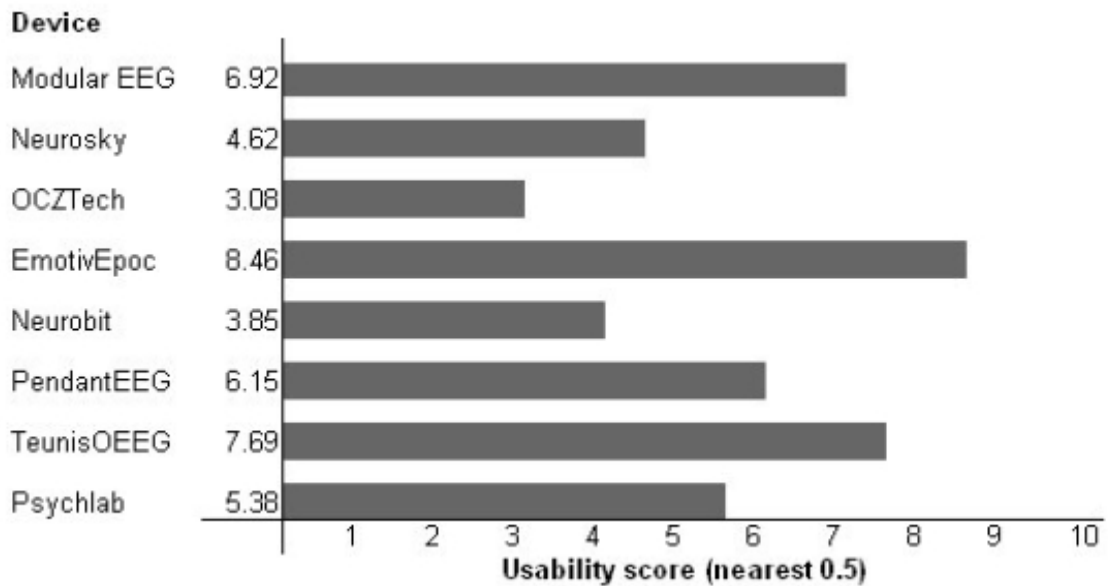
Figure 3.1: Usability rating of low budget EEG acquisition devices.

Source: [35]

3.2 Emotiv EPOC Headset

The Emotiv headset is an attempt to bring EEG capabilities to the masses. At $299.00 ($750.00 for the research SDK), the headset is relatively affordable. These "gaming EEG systems" use EEG activity to control the movement of characters or objects in games via headsets that comprise a small array of sensors that are:

- Wirelessly connected to software that runs on a laptop, the user maintains a full range of motion

- Require little adjustment of electrodes, so no need for long electrode placement procedures.

- Typically use small foam tipped felt sensors that are soaked in saline solution to connect each electrode to the scalp, so no need for messy gel, and hence no need for head washing.

The gaming EEG system (i.e., Emotiv EPOC®) used gold-plated contact-sensors that were fixed to flexible plastic arms of a wireless headset. The headset included 16 sites, aligned with the 10–20 system: AF3, F7, F3, FC5, T7, P7, O1, O2, P8, T8, FC6, F4, F8, FC4, M1, and M2. One mastoid (M1) sensor acted as a ground reference point to which the voltage of all other sensors was compared. The other mastoid (M2) was a feed-forward reference that reduced external electrical interference. The signals from the other 14 scalp sites (channels) were high-pass filtered with a 0.16 Hz cut-off, pre-amplified and low-pass filtered at an 83 Hz cut-off. The analogue signals are then digitized at 2048 Hz. The digitized signals are filtered using a 5th-order sinc notch filter (50–60 Hz), low-pass filtered and down-sampled to 128 Hz (specifications taken from the gaming EEG system web forum). The effective bandwidth is 0.16–43 Hz.

Figure 3.2: Emotiv EPOC$^{\text{TM}}$ EEG Headset. The black pads placed right behind the ears are non-conducive reference electrodes.

Source: [36]
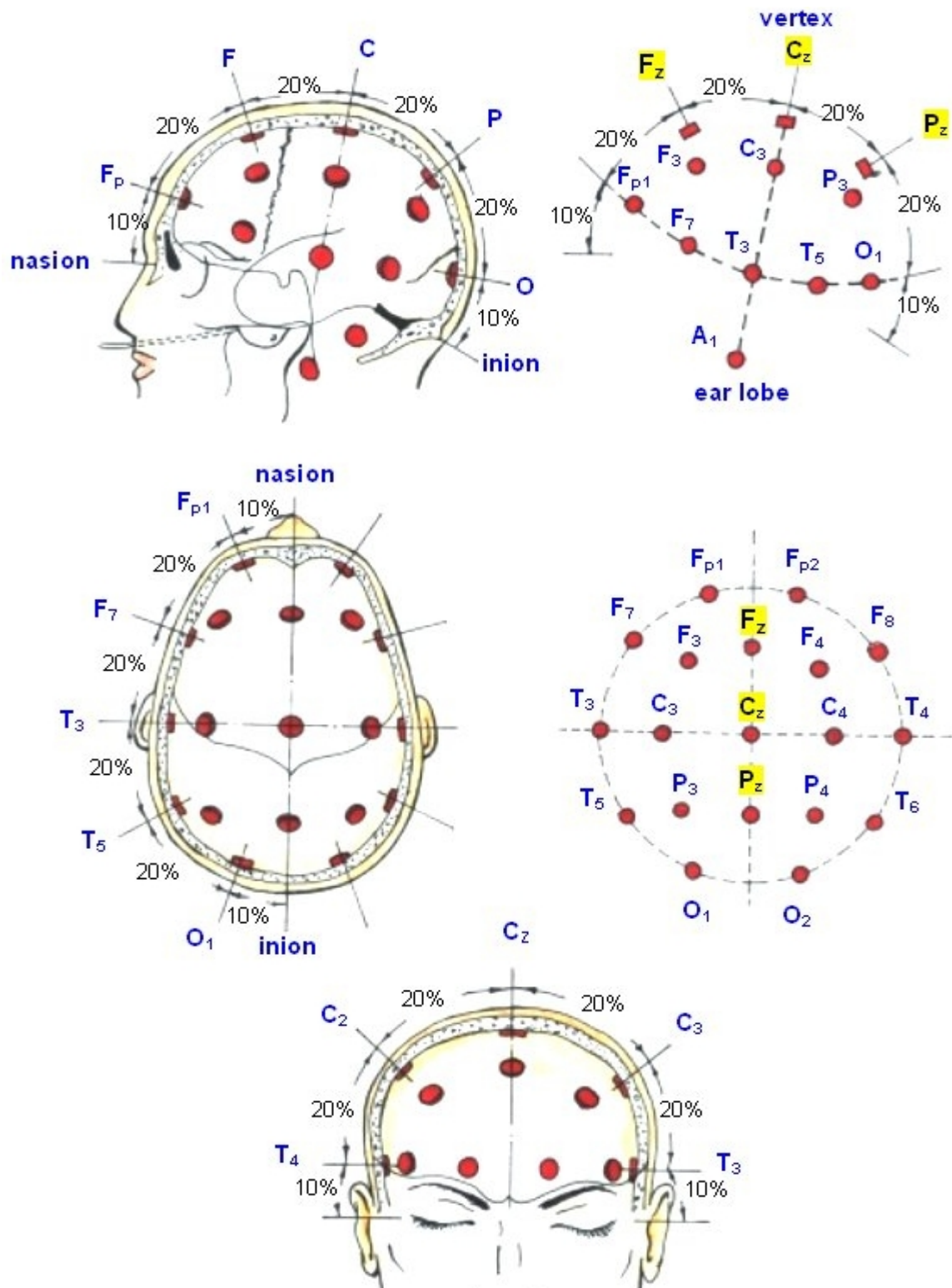
Figure 3.3: Points for EEG recording electrodes (international 10-20 electrode system).Electrode A1 is point for reference electrode connection.

Source: [37]
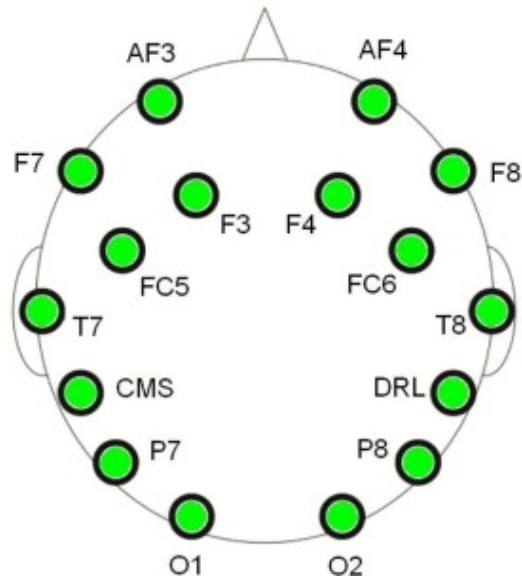
Figure 3.4: Electrodes placement of Emotiv EPOC Headset as per 10-20 placement system.

Source: [38]
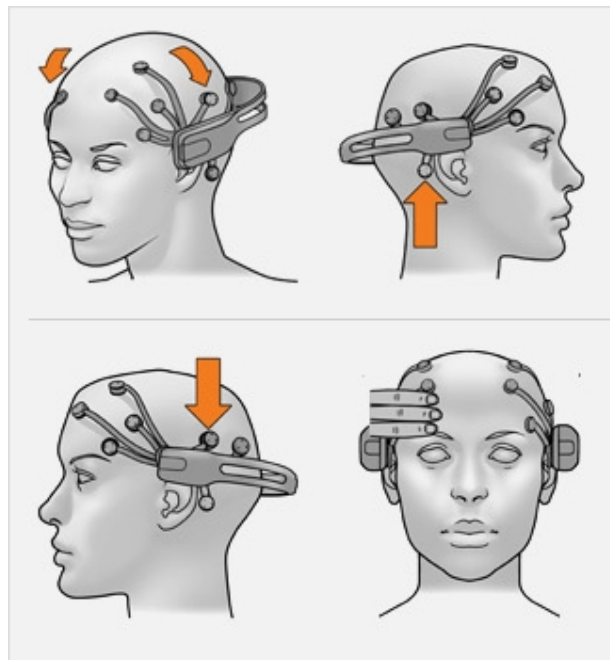
Figure 3.5: Emotiv EPOC Headset placement. Sensors with the black rubber should be placed on the bone just behind each ear lobe. Correct placement of the rubber sensor is critical for correct operation (Top). 2 front sensors should be approximately at the hairline or about the width of 3 fingers above your eyebrows. Press and hold the 2 reference sensors (located just above and behind the ears) for about 5-10 seconds (Bottom).

Source: [39]

CHAPTER 4

BCI2000 SOFTWARE

4.1 Introduction

As described in the previous chapters, many factors determine the performance of a BCI system. These factors include the brain signals measured, the signal processing methods that extract signal features, the algorithms that translate these features into device commands, the output devices that execute these commands, the feedback provided to the user, and the characteristics of the user. Thus, future progress requires systematic well-controlled studies that evaluate and compare alternative signals and combinations of signals, alternative feature extraction methods and translation algorithms, and alternative communication and control applications in different user populations. In consequence, a typical research and development program focused on human BCI research will usually run several studies at the same time, possibly even in different locations, and most often by different personnel. These requirements imply the need for a software tool that facilitates the implementation of any BCI system, and that facilitates the collaboration of multiple laboratories on algorithm design, experimental design, or data analysis. In other words, standardized software or procedural mechanisms for development of BCI methods and their components, for data exchange, and for the appropriate documentation of relevant configuration parameters are necessary. BCI2000 is a documented general-purpose BCI research and development platform. It can incorporate alone or in combination any brain signals, signal processing methods, output devices, and operating protocols. It is supported by a R01 grant by the NIH (NIBIB) to Gerwin Schalk and was

previously supported by a bioengineering research partnership (BRP) grant by the NIH (NIBIB/NINDS) to Jonathan Wolpaw. Studies have used BCI2000 to create BCI systems for a variety of brain signals, processing methods, and applications [40] [41]. The data show that these systems function well in online operation and that BCI2000 satisfies the stringent real-time requirements of BCI systems. By substantially reducing labor and cost, BCI2000 facilitates the implementation of different BCI systems and other psychophysiological experiments [30]. The goals of the BCI2000 project are 1) to create a system that can facilitate the implementation and collaborative use of any BCI system; 2) to incorporate into this system support for the most commonly used BCI methods; and 3) to disseminate the system and associated documentation to other laboratories. BCI2000 should thus facilitate progress in laboratory and clinical BCI research by reducing the time, effort, and expense of testing new BCI methods, by providing a standardized data format for offline analyses, and by allowing groups lacking high-level software expertise to engage in BCI research.

BCI2000 is based on a model that can describe any BCI system and that is similar to the one described in [42]. This model (see Figure 4.1 for a simplified diagram), consists of four modules that communicate with each other: Source (Data Acquisition and Storage), Signal Processing, User Application, and Operator Interface. The modules are separate programs that communicate through a TCP/IP-based protocol. This protocol can transmit all information (e.g., signals or variables) needed for operation. Thus, the protocol does not need to be changed when changes are made in a module. Brain signals are processed synchronously, in blocks containing a fixed number of samples that are acquired by the Source module. Synchronous processing is chosen over asynchronous

processing, because it makes it more practical to guarantee system performance, and it allows for a very generic mechanism to relate the timing of stimulus presentation to the timing of data acquisition. During system operation, each time a new block of data is acquired, the Source module sends it to Signal Processing, which extracts signal features, translates those features into control signals, and sends them on to the Application module. Finally, the Application module sends the resulting event markers back to the Source module where they and the raw signals are stored to disk. The contents of the data file thus allow for full reconstruction of an experimental session during offline analyses. The four modules and their communication protocol do not place constraints on the number of signal channels or their sampling rate, the number of system parameters or event markers, the complexity of signal processing, the timing of operation, or the number of signals that control the output device. Thus, these factors are limited only by the capacities of the hardware used.
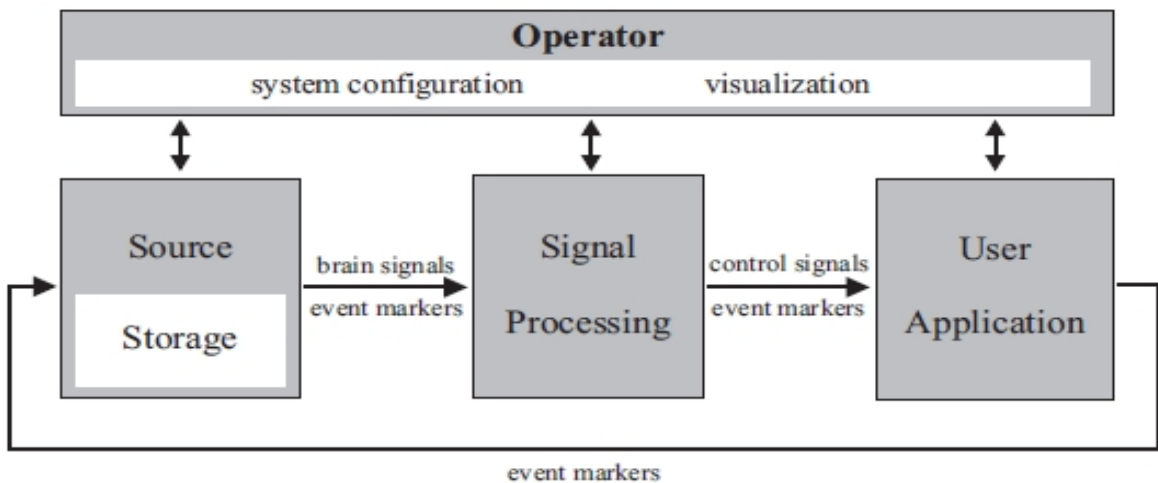
Figure 4.1: BCI2000 design. BCI2000 consists of four modules: Operator, Source, Signal Processing, and Application. The operator module acts as a central relay for system configuration and online presentation of results to the investigator. It also defines onset and offset of operation. During operation, information (i.e., signals, parameters, or event markers) is communicated from Source to Signal Processing to User Application and back to Source.

Source: [30]

4.2 Source Module

The source module digitizes and stores brain signals and passes them on without any further preprocessing to signal processing. It consists of a data acquisition and a data storage component. Data storage stores the acquired brain signal samples along with all relevant system variables (such as system parameters or all current event markers) in a data file. The documented file format consists of an ASCII header, followed by binary signal sample, and event marker values. The file format can accommodate any number of signal channels, system parameters, or event markers [30].

4.3 Signal Processing Module

The signal processing module converts signals from the brain into signals that control an output device. This conversion has two stages: feature extraction and feature translation. In the first stage, the digitized signal received from the source module is subjected to procedures that extract signal features (e.g., firing rate of a cortical neuron, amplitude of an evoked potential, etc.). In the second stage, a translation algorithm translates these signal features into control signals that are sent to the user application module.

Each of the two stages of signal processing consists of a cascade of signal operators, each of which transforms an input signal into an output signal. The individual signal operators (e.g., spatial filter, temporal filter, linear classifier) are themselves independent of each other and can, thus, be combined or interchanged without affecting others [30].

4.4 User Application Module

The User Application module receives control signals from Signal Processing and uses them to drive an application. In most present-day BCIs, the user application is presented visually on a computer screen and consists of the selection of targets, letters, or icons.

Existing User Application modules in BCI2000 implement very capable versions of popular feedback paradigms: a three-dimensional cursor movement paradigm (Cursor Task); a matrix spelling application based on P300 evoked potentials (P3Speller); and presentation of auditory and visual stimuli with optional feedback of evoked potential classification result (Stimulus Presentation). Fig. 4.2A-C shows the display to the user for these three applications, respectively.

4.5 Operator Module

The operator module defines the system parameters (e.g., the trial length in a specific application or a specific signal processing variable) and the onset and offset of operation. The system model does not specify how these definitions are made—they could come from an automated algorithm and/or from the investigator. In addition, operator can display information (e.g., a text message or a signal graph) sent to it from any other module without needing any prior information about the nature of this information. This allows an investigator to control an experiment and to receive real-time information about online events (e.g., display of unprocessed brain signals) using the same operator module, irrespective of the details of the experiment.
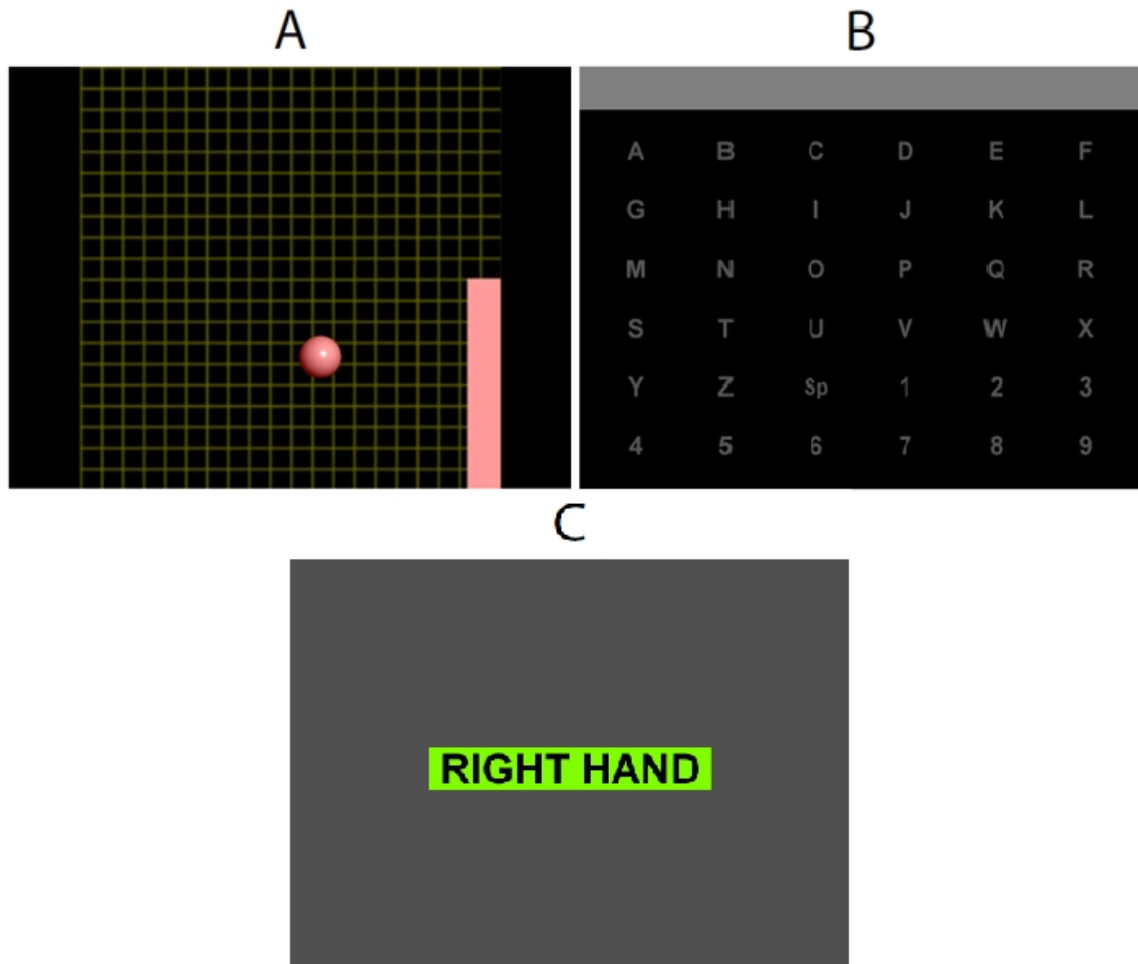
Figure 4.2: Displays for the three BCI2000 User Applications. A: Cursor movement to a variable number of targets (i.e., Cursor Task). B: A spelling application based on P300 evoked potentials (i.e., P3Speller). C: Auditory/visual stimulation program (i.e., Stimulus Presentation). In A, the cursor moves from a programmable location towards one of N programmable targets. In B, rows and columns of the matrix flash in a block-randomized fashion. In C, a series of programmable stimuli are presented in sequence.

Source: [43]

4.6 Interfacing Emotiv Headset with BCI2000

From this previous section on BCI2000, it is clear that there are multiple modules which are to be started up in a certain sequence with respect to the data acquisition device or amplifier. This is done by using scripts which are a batch files in BCI2000 and can be located under the installation directory (refer to figure 4.3). Emotiv EPOC headset is a

contributed source module, by Griffin Milsap, Graduate Student, Johns Hopkins University.
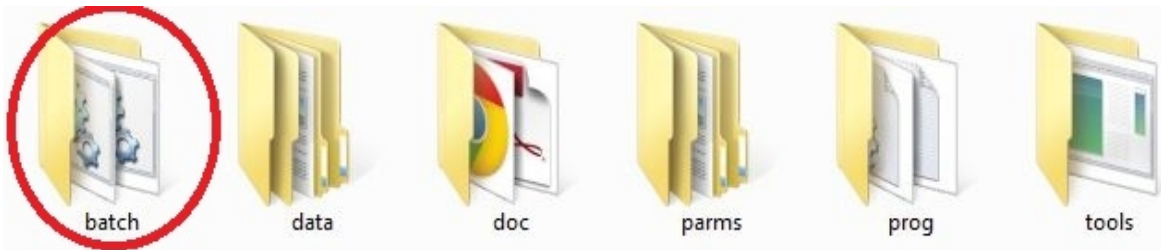
Figure 4.3: Batch file folder under the BCI2000 installation directory.

Following steps are needed to be followed to use contributed source module with a specific BCI paradigm.

- Identify the batch file in BCI2000/batch that provides the desired paradigm using the Signal Generator source module. For the cursor feedback paradigm, this would be CursorTask_SignalGenerator.bat.

- Create a copy of that batch file, and rename it to reflect the name of the source module you would like to use, e.g. CursorTask_Emotiv.bat.

- Open the newly created file in a text editor.

- Identify the line that refers to SignalGenerator.exe.

- There, replace SignalGenerator.exe with your source module's executable name, e.g. Emotiv.exe.

- Save the batch file, and run it to start BCI2000 in the desired configuration.

After creating the script/batch file, it is required to set it up as per respective amplifier which is Emotiv EPOC Headset in this case. Once, the script is executed it offers user to set parameter by clicking on 'Config' on the operator module. Configuration comprises the following fields: Visualize (to alter the visualization property of each of BCI2000 modules), System, Source (to set the properties as per the amplifier being used), Storage (to set the property of data management), Filtering (to set

the filtering, classifiers and other major properties useful), Connector (to set the communication property to export or import data) and Application (to set the application for the sessions, cursor task, normal triggering with imagination and rest etc.). Once all the parameters are entered we save it for easy configuration in future. The parameters for Emotiv EPOC are listed in figure 4.4.

By entering the correct parameters, the first step towards creating a Brain Computer Interface has been achieved. To create the cursor application, where the subject is controlling the cursor movements in one, two and three dimensions, application parameters are required to be set respectively. Application parameters includes, setting up the resolution and position of the application window, setting up the post-feedback, feedback and pre-feedback duration which decides the onset and offset of the cursor on the application window. Cursor task can be designed in any manner; it is completely on operator discretion. Operator can put the targets on any of the four sides of the application window and set the cursor parameters accordingly to check the accuracy (determined by the number of correct hits divided by the total number of targets), time taken to effectively switch brain state from imagination to rest or vice versa.

Figure 4.4: Parameters for Emotiv EPOC Headset.

CHAPTER 5

EXPERIMENTAL DESIGN

5.1 Design and Implementation

As described in the previous chapters, features extracted from EEG (imagination and rest) were used in sync with the biofeedback/visual feedback (further described in detail) to trigger neuroplasticity. But the first step towards developing this BCI rehabilitation is to train subjects to adapt to the system; Adaptation corresponds to the accuracy achieved in the cursor control task. The reason for choosing cursor task is to keep subjects motivated toward the task. Permission to recruit human subjects was acquired from the NJIT's Institutional Review Board (IRB) (refer to Appendix B). A total of five healthy human subjects were recruited from student population with a goal to achieve high adaptation and accuracy on these healthy subjects. Studies have shown that performance of the impaired subjects was found to be better than the healthy subjects [44]. Therefore, the idea was that if, healthy subjects could adapt successfully to the designed system it should work even better on the clinical population. The whole set up was divided into two halves; training phase, where all five subjects were given a maximum of eight sessions to adapt to the system and testing phase, where accuracy was determined post-training. Each session contained a maximum of eight trials having the target appear eighteen to twenty three times on an average; this number was varied for every subject as per their performance.

The designed system comprised of a PC/Laptop with an additional monitor or projector, Emotiv EPOC Headset and BCI2000 software. After setting up all the required

parameters in BCI2000, as discussed in previous chapter, the Emotiv EPOC headset was wirelessly connected to the software using the USB dongle. All the felt sensors were soaked with 0.4% to 0.9% saline solution in advance as shown in figure 5.1. Subjects were asked to comfortably get seated facing the video screen of a monitor or a projector. They were asked to put on the Emotiv EPOC EEG Headset and investigator arranged the electrodes properly on the scalp in order to get the best signal. The headset was needed to be placed in such a manner that F3 and F4 electrodes should come over the motor cortex rather than the frontal cortex. Subjects were instructed to minimize their body movements and eye blinks while data was being recorded. In the training phase, two targets were shown on the right side of the screen one after another in a pseudo random order; cursor appears after two seconds of the target appearance at the left center of the screen as shown in the figure 5.2. Feedback was available to the subject for three seconds and two seconds of post feedback duration was given to the subject before the onset of the new target. Cursor was programmed to move across the screen from left to right at a specific speed. Subjects were asked to imagine opening and closing their hand when the target appeared on the top right hand side of the screen and relax and not to imagine anything when the second target appeared in the bottom right hand side of the screen. Imagery output of the subject moved the cursor vertically towards the respective target. Horizontal distance and time were used in the training phase to allow subjects to train themselves to hold a brain state for a certain amount of time. The reason behind choosing the imagination task related to hand movement is because of its large representation on the homunculus (figure 5.3). Hands have the highest sensitivity and an imagination task related to the hands is expected to give a higher variance in the event related

synchronization and event related desynchronization. In the testing phase, subjects were assumed to be completely used to the task and therefore did not required time to switch state and could maintain the respective brain state for a significant amount of time. Therefore, they were given targets at other locations with the cursor appearing in the center of the screen moving unidirectional under complete control of the subjects.

Figure 5.1: Emotiv EPOC Headset, felt sensors highlighted in red with the saline solution. The white patch on the felt sensors is due to the deposited salt and needs to be washed off or changes after extensive usage.

Data acquired over the motor cortex were processed by the signal processing module. It was filtered using the Common Average Reference algorithm because it was found to be giving the best result compared to the Large Laplacian and Small Laplacian algorithm for the mu-rhythm based cursor control task (detail description is available further in the offline analysis part of this chapter). The magnitude of the spectra at the 10Hz frequency, via electrodes on both hemispheres of the brain over motor cortex, was used to control the cursor. Motor imagination triggered the event related synchronization leading to the increase in the power level whereas the relaxation triggers event related desynchronization leading to decrease in the power level over the motor cortex.
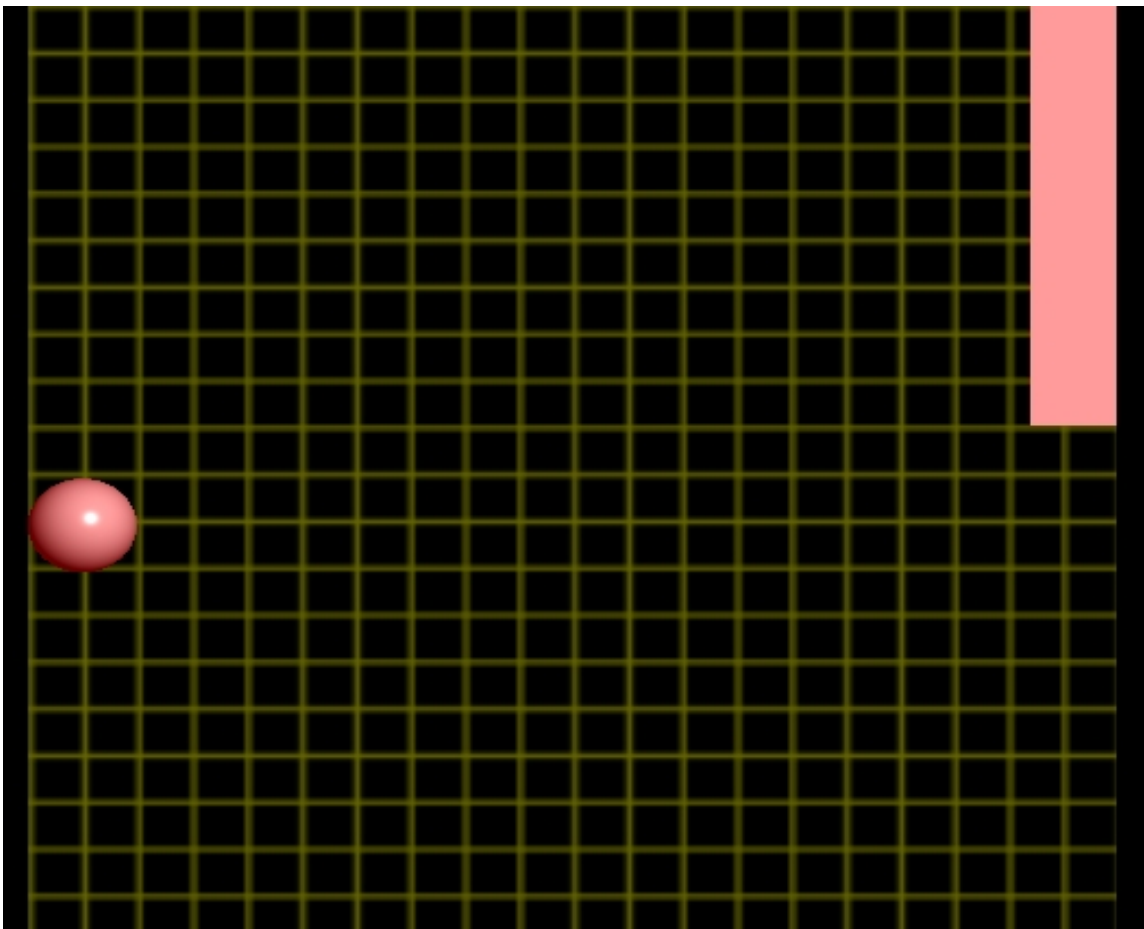
Figure 5.2: Training session application window. Target block appeared on the top right hand side of the screen and the cursor appeared on the center left hand side of the screen.
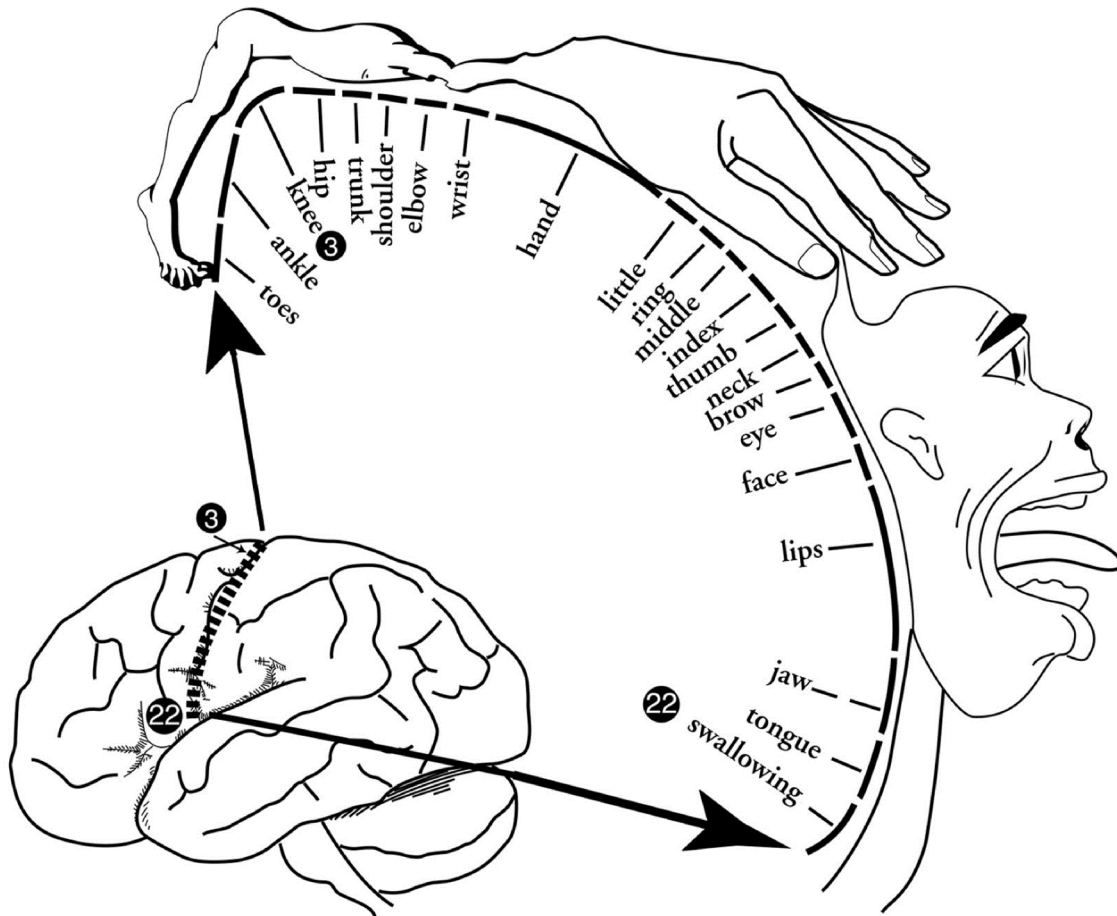
Figure 5.3: Homunculus of the motor area showing the enormousness of the hands.

Source: [45]

5.2 Test Run and Offline Analysis

Electrode position and control frequency both are the most important features of this BCI set up. Therefore, even before we begin with the training session one test run is conducted to extract the appropriate the feature from every subject. Application remains same to the one used in training session and subjects were asked to imagine instructed hand movement when the target bar appears at the top left hand side of the screen and relax when it appears at the bottom left hand side of the screen with no cursor as described for the training session. This test session consists of four to eight trials and data

collected (as shown in figure 5.4) from these trials is further analyzed using the BCI2000

Offline Analysis in MATLAB (figure 5.5).
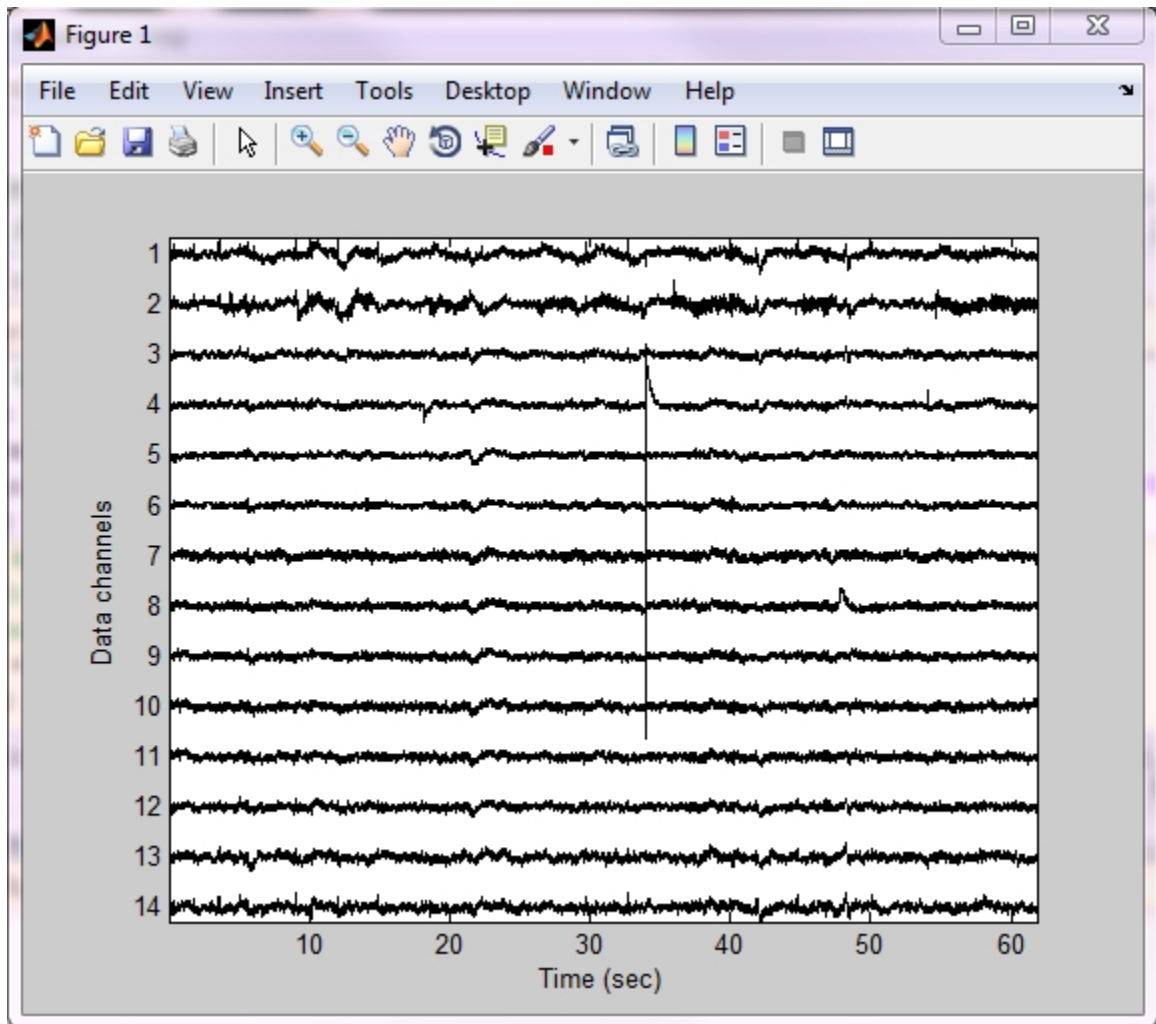
Figure 5.4: Data acquired via 14 channels of Emotiv EPOC Headset.

Result generates two plots, one containing the r-squared values, shown in figure 5.6 (with the y-axis as the channels and x-axis as the frequency) and the second comprising the spectra and the r-squared value at the selected frequency and the channel as shown in the figure 5.7. Using this result, we selected the channels and the frequency to be used as the classifiers in the cursor control task. Appropriate weight was given to each channel to decide whether we want to use mean activity or the difference of the

activity from the left and right hand area over motor cortex at 10 Hz to control the vertical cursor movement. A 3 Hertz bin is created about the selected frequency to account for the variability in the frequency band.
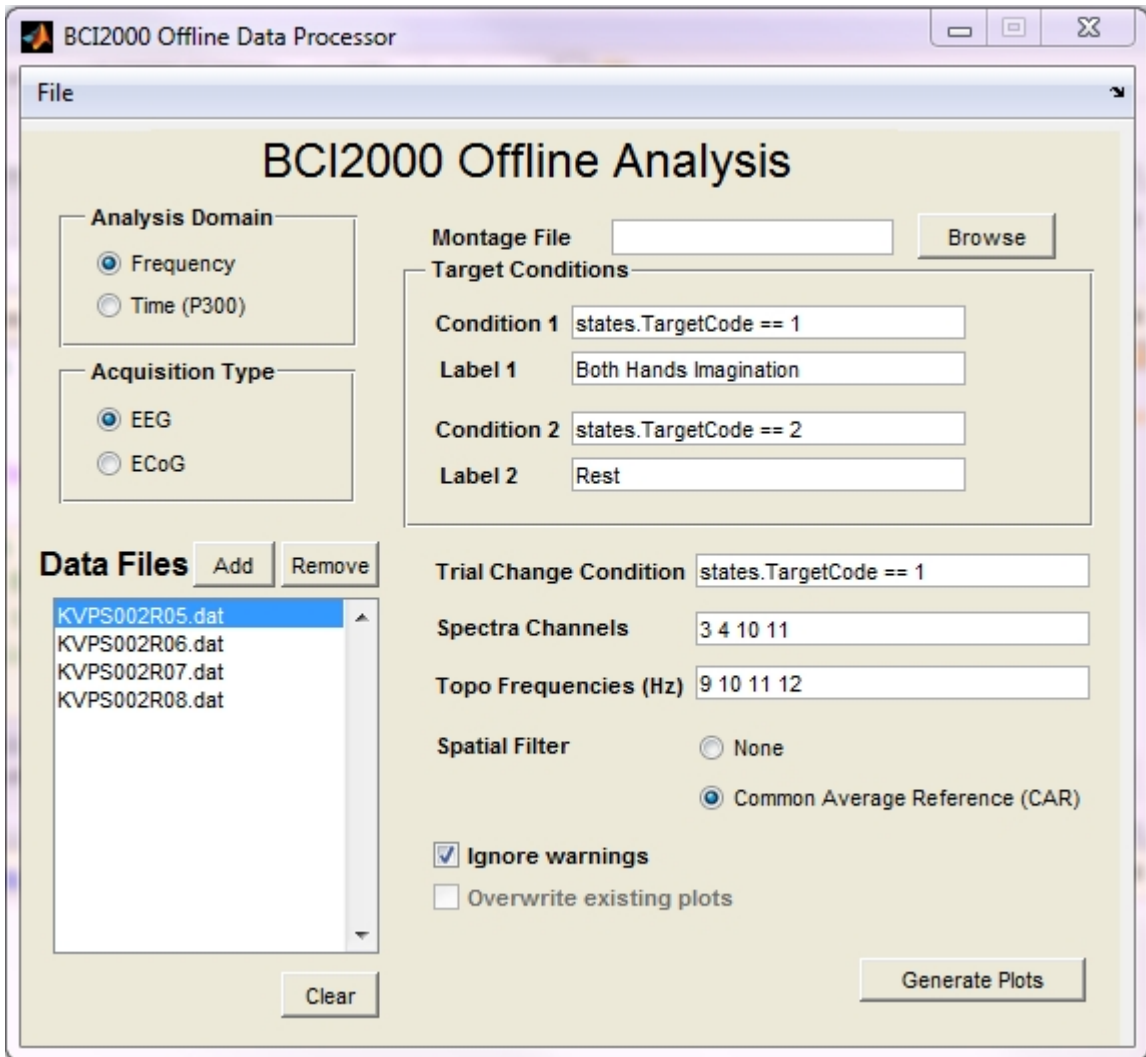
Figure 5.5: BCI2000 Offline Analysis Tool.
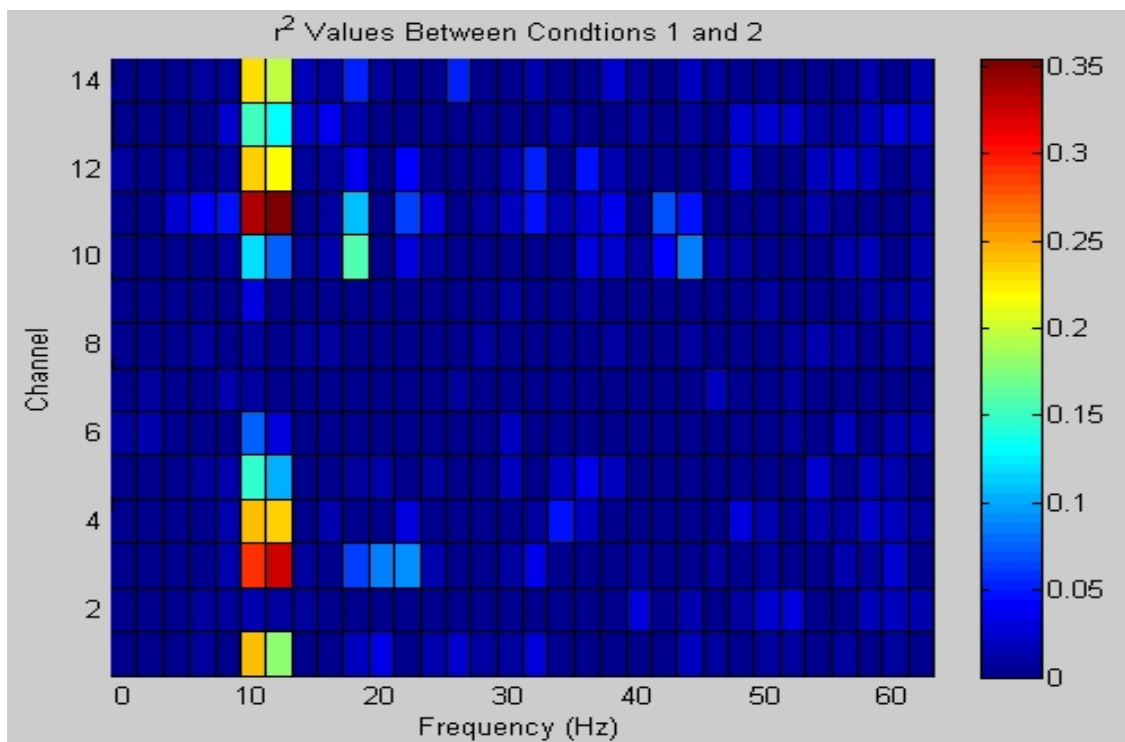
Figure 5.6: r-squared value between imagination and rest can be seen to be high (Red) at the electrodes over the motor cortex and at around 10 Hertz frequency.
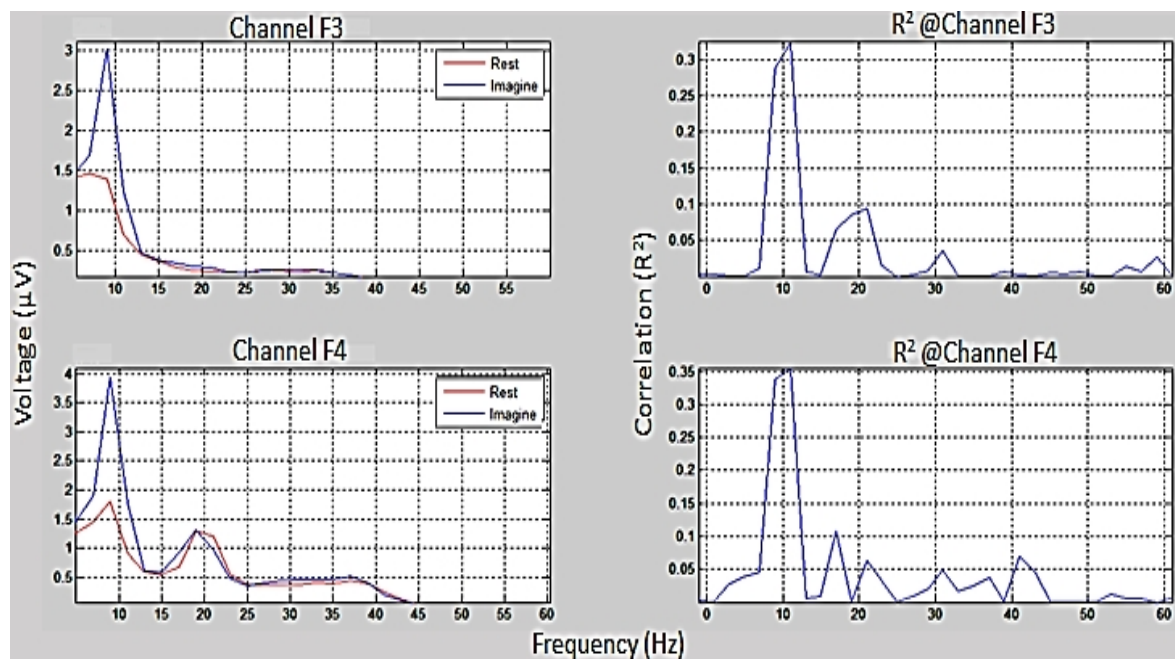
Figure 5.7: Spectra and the r-squared value at the selected channels. R-squared values were found to be significantly higher at 10 Hertz.

Apart from these two parameters there are other parameters like filtering. It plays a critical role when it comes to feature extraction from the data. BCI2000 provides the operator with a variety of filters to choose from; for e.g. Common Average Reference (CAR), Large Laplacian, Small Laplacian etc. To find out the effect of each of those filters and choose the one giving the best result programs, subroutines were written in Matlab (refer to the Appendix A for the programs and subroutines). Using the results, it was concluded that CAR filtering gives the better result than Laplacian filtering techniques, as shown in figure 5.8.
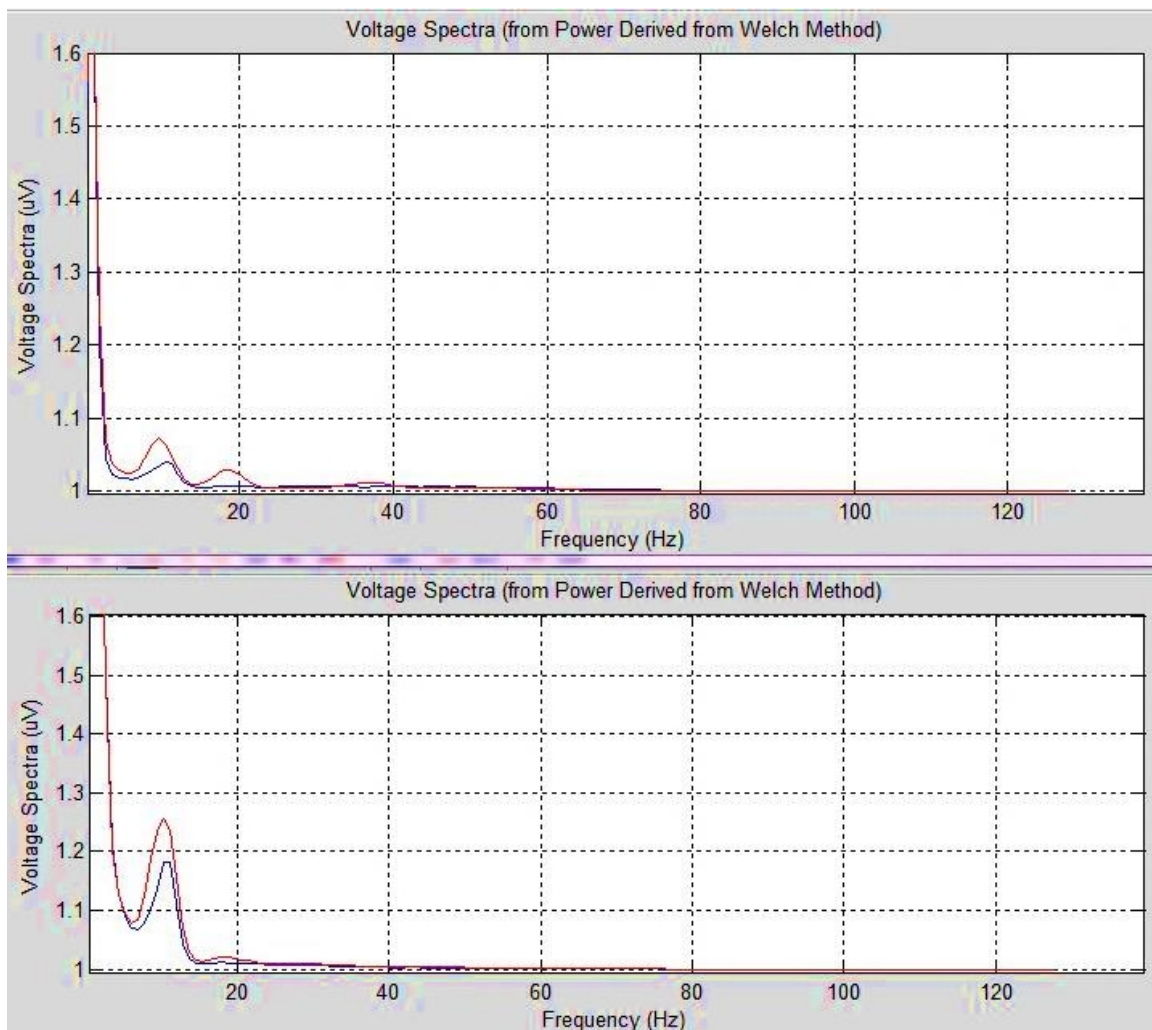
Figure 5.8: Differences in the spectra output after using Laplacian (Top) and CAR (Bottom) filtering techniques. Both the images are result of data collected from same electrode and same parameters used to find the spectra except the filtering technique.

5.3 Biofeedback and Neuroplasticity

An immersive virtual environment (as shown in figure 5.9) was created by using Virtual

Reality Modeling Language (VRML) and V-Realm Builder 2.0 where every node of the

environment was individually controlled by the program written in Matlab (refer to

Appendix A). V-Realm Builder is a powerful three dimensional authoring package for

the creation of 3D objects and "worlds" to be viewed with V-Realm Browser or any other

VRML 2.0 compliant browser.
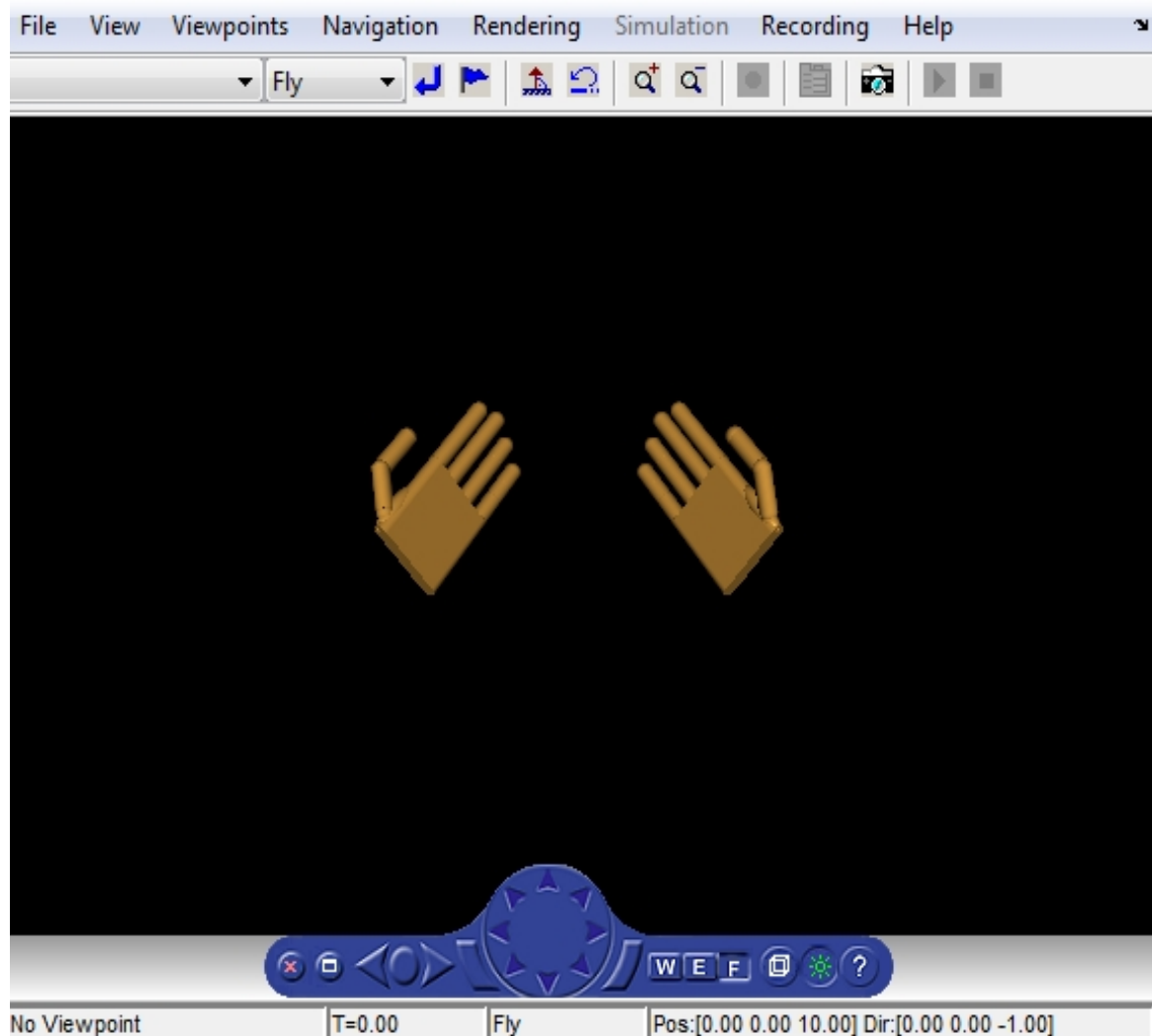
Figure 5.9: Virtual environment giving visual feedback of the hand opening and closing imagery task being performed.

Creating an interactive environment in the context of physical therapy increases subject motivation and engagement, leading to active participation and learning by the stroke survivor. This interactive feedback component of the system is also crucial to a) distancing the subject from the challenges of the physical task, b) intuitively communicating amplitude of error and direction for improvement and c) maintaining subject engagement in repetitive task-oriented therapy. In the designed virtual world, subject saw two hands which would open and close as the subject will perform the same motor imagery task and will remain open when they are in resting state.

In order to control the objects of virtual environment, a User Datagram Protocol (UDP) Communication was established between BCI2000 software and Matlab to transfer the control states being collected by BCI2000 via Emotiv EPOC Headset. UDP is within the Transmission Control Protocol/ Internet Protocol (TCP/IP) protocol suite that is used in place of TCP when a reliable delivery is not required. There is less processing of UDP packets than there is for TCP. UDP is widely used for streaming audio and video, voice over IP (VoIP) and videoconferencing, because there is no time to retransmit erroneous or dropped packets. Matlab program reading the server was written (refer to Appendix A) to use two out of all the states being received by the program; TargetCode and Signal(1,0). TargetCode values are the markers for the onset and offset of the targets being given to the subject and Signal(1,0) values are the control values used to control the cursor on the screen. In Signal state, 0, 1 and 2 referred to the direction of the cursor movement on the screen. (0,0) is the 1D movement in X-direction (left to right on screen), (1,0) is the 1D movement in Y-direction (top to bottom on screen) and (2,0) is 1D movement in Z-direction (in and out of the screen).

In the testing phase, this virtual environment can be controlled in two ways. We can trigger the opening and closing of hand using the TargetCode value which is 0, when none of the two targets are on the screen and is 1 and 2 with respect to the onset of each of two target blocks. Therefore, when the value of TargetCode is 1, hands will start opening and closing at the given frequency and will stop when the value reaches 2 or reverts back to 0. Values collected from the Signal state can also be used to control the hand in the virtual environment. Signal state values have got a range for each task which varies for every subject; therefore, an average of the range collected from the training phase has to be acquired. Using this has an advantage over using TargetCode. With this the overall grip of the hands can be manipulated as per the incoming Signal value. If the incoming value is close to the maximum value of the range, hands will grip fully making a fist and if it is close to the minimum rather than making a full fist fingers will flex slightly. Using this way, we are providing users with a feedback of their intensity of imagery performance. Therefore, if the event related synchronization yields a very high value of power then hands will grip completely, as shown in figure 5.10.

Virtual reality (VR) systems are novel and potentially useful technologies that allow users to interact in three dimensions with a computer-generated scenario (a virtual world). The implementation of conventional rehabilitation is resource-intensive and costly, usually requiring transportation of patients and affecting adherence. Immersive virtual environment with BCI system narrows down that gap and applies relevant concepts in rehabilitation (i.e. repetition, intensity, and task-oriented training of the paretic extremity) showing benefits in motor function improvement after stroke. Neuroplasticity can be triggered in the clinical population suffering from impairment in

their central or peripheral nervous system as per Hebbian Type Learning [46]. The general idea is an old one; that any two cells or systems of cells that are repeatedly active at the same time will tend to become 'associated', so that activity in one facilitates activity in the other. Therefore, the three modalities, Motor Imagery, Motor Observation and Motor Execution (which excite the same part of the motor cortex) were combined to generate the required rehabilitative effects.

CHAPTER 6

RESULTS AND CONCLUSIONS

Three out of five subjects, having no prior BCI experience were able to adapt to the system in the given training phase with an increase in their performance with time. Being a full time student, the remaining two did not completed all the training sessions and quit due to sudden increase in their work; their performance was also showing improvements like other three subjects but relatively slow. Detail of their performance is given in Table 6.1. Accuracy was determined using the following formula:

$$\text{Accuracy} = \sum_{k=1}^{8} \left(\text{Number of Correct Hits/ Total number of Targets}\right) \Big/ 8$$

'k' represents the trial number in the testing session.

Table 6.1: Performance of healthy subjects in the cursor control task.

#	Subjects	Total Sessions to Adapt	Accuracy (post-training)
1.	AXM	1	>85%
2.	KVP	1	>80%
3.	DIL	1	>90%
4.	UBS	Excluded	Excluded
5.	SXS	Excluded	Excluded

The result from healthy subjects was quite promising and opens up the possibility of using BCI in rehabilitation in a cost effective manner. Combined with Assistive Robotic and Virtual Reality, this system has the potential to provide rehabilitation to stroke survivors. The Signal state which was intended to be used in the virtual environment to open and close hand as per the power level of the motor imagery can also be used for a robot. Therefore, the resultant would be assistive movement in

synchronization with the intention to move. Subjects having no residual movement can imagine moving their impaired limb and the robot will move their limb on a pre-programmed trajectory. This also satisfies the top-bottom approach of rehabilitation where rather than using assistive therapy with little or no involvement of subject, system waits for the effort to be put in by the patient. This approach calls for a high level of subject involvement therefore can be called an active rehabilitation method rather than passive one.

Further work can be done to analyze the efficacy of this setup as a rehabilitation technique. Rather than testing it on healthy subjects, stroke patients who lost their ability to move can be recruited and if their motor cortex is affected the contralateral side of their motor cortex can be used to provide us with the motor imagery and rest state related values to control a robot or objects in the virtual environment. The Emotiv EPOC headset intended to be used as a gaming device by their originators, holds the capability to be used in a BCI setup to control simple applications like cursor control in one and two dimension. This is sufficient enough to acquaint the patients with their brain power to heel themselves.

APPENDIX A

MATLAB PROGRAMS

Program 1: Function to implement Common Average Filtering

```matlab
% This program is used to re-reference digitized EEG data
to a common average reference (CAR)
% Composed of 14 electrodes distributed over the entire
scalp (i.e. electrodes of 10-20 system).
% Channel data should be sent as an input
% Channel Numbering Convention should be the one provided
by Emotiv and BCI2000.
% Only two electrode locations (i.e. F3 & F4) are re-
referenced and returned.
% Ref: "Spatial filter selection for EEG-based
communication", McFarland DJ, 1997
% (C) Abhineet Mishra 2012-13
%       Graduate Student, NJIT
function [ret1, ret2] = epocCAR(data)

display('Applying Common Average Reference to C3 and C4');
EEG_FC5 = data(4,:);
EEG_FC6 = data(11,:);

% Channel Numbering is used as per the numbering used by
Wadsworth Center.
% Channels used are AF3 F7 F3 FC5 T7 P7 O1 O2 P8 T8 FC6 F4
F8 AF4
ret1 = EEG_FC5 - ((1/14)*(data(1,:) + data(2,:) + data(3,:)
+ data(4,:) + data(5,:) + data(6,:) + data(7,:) + data(8,:)
+ data(9,:) + data(10,:) + data(11,:) + data(12,:) +
data(13,:) + data(14,:)));

ret2 = EEG_FC6 - ((1/14)*(data(1,:) + data(2,:) + data(3,:)
+ data(4,:) + data(5,:) + data(6,:) + data(7,:) + data(8,:)
+ data(9,:) + data(10,:) + data(11,:) + data(12,:) +
data(13,:) + data(14,:)));
end
```

Program 2: Function to implement Laplacian Filtering

```matlab
% This program is used to re-reference digitized EEG data
to Laplacian Derivation (LARGE).
% 64 or more channel data should be sent as an input
% Channel Numbering Convention should be the one used by
Wadsworth Center.
% Only two electrode locations (i.e. C3 & C4) are re-
referenced and returned.
% Ref: "Spatial filter selection for EEG-based
communication", McFarland DJ, 1997
% (C) Abhineet Mishra 2012-13
%      Graduate Student, NJIT
function [ret1, ret2] = laplacian(data)

display('Applying Large Laplacian Derivation to Cp3 and
Cp4');
EEG_Cp3 = data(16,:);
EEG_Cp4 = data(20,:);
% Electrodes used for re-referencing were F3 Cz P3 T7
% 0.25 was calculated from the formula given in the paper
McFarland et al. 1997
ret1 = EEG_Cp3 - (0.25 .* data(2,:) + 0.25 .* data(18,:) +
0.25 .* data(57,:) + 0.25 .* data(45,:));

% Electrodes used for re-referencing were F4 Cz P4 T8
ret2 = EEG_Cp4 - (0.25 .* data(6,:) + 0.25 .* data(18,:) +
0.25 .* data(59,:) + 0.25 .* data(46,:));
end
```

Program 3: Program to perform Offline Analysis on the collected EEG Data

```matlab
% This program is to perform Offline Analysis on the EEG
data.
% It imports the data file from the given path, filter it
using either
% laplacian or CAR and calculated the Voltage spectra and
r-square value
% (C) Abhineet Mishra 2012-13
%     Graduate Student, NJIT
% -----------------------------------------------------
%% Importing Data
clc
clear all
importdata
('C:\Users\Abhineet\Desktop\Work\AXM001\AXMS001R14.ascii');
EEG = ans.data;
%% Spatial Filtering
Fs = 160; % Sampling Frequency of the EEG Data
EEG = EEG';
[EEG_c3, EEG_c4] = laplacian(EEG);
%% Program to extract the trial from the data. Data is
needed to be loaded in the workspace
j1=1;
c1=1;
j2=1;
c2=1;
TargetCode = EEG(71,:);

for i=1:length(EEG)
    if TargetCode(i) == 1
        Lx1(j1,c1) = EEG_c4(1,i);
        c1 = c1 + 1;
    else if TargetCode(i) == 2
        Rx1(j2,c2) = EEG_c4(1,i);
        c2 = c2 + 1;
        else if TargetCode(i) == 0 && (i-1 ~= 0)
                if TargetCode(i-1) == 1
                    j1 = j1+1;
                    c1=1;
                else if TargetCode(i-1) == 2
                        j2 = j2+1;
                        c2=1;
                    end
                end
            end
end
```

```matlab
        end
    end

end
clear c1 c2 j1 j2 i;

%% Finding Voltage and r2
len1 = size(Lx1);
len2 = size(Rx1);
for i=1:len1(1)
[PS1,f1] = pwelch(Lx1(i,:), triang(50),[ ],300,Fs);
Vs1 = sqrt(10.^(PS1./10));
X(1,:) = f1;
Y(1,:) = f1;
X(i+1,:) = Vs1;
Y(i+1,:) = -1;
end

for i=1:len2(1)
[PS2,f2] = pwelch(Rx1(i,:), triang(50),[ ],300,Fs);
Vs2 = sqrt(10.^(PS2./10));
X(i+12,:) = Vs2;
Y(i+12,:) = 1;
End

%% Working on FINAL MATRIX X and Y STYLE 1
for i=1:151
c = cov(X(2:22,i),Y(2:22,i));
varX = c(1,1);
varY = c(2,2);
covXY = c(1,2);
r2(i) = covXY^2/varX*varY;
end
r2 = r2';
hold on
plot(f1,r2,'r')
grid on
```

Program 4: Program to load the Virtual Environment designed in VRML using V-Realm

```
%% Hand.m is a script that loads handRAF.wrl that contains
left and
%  right hand articulated VRML models.  It opens the object
and allows it
%  to be viewed in the default SL3D viewer.
% R. Foulds  4/17/2013


% Open and view the object myhand
myhand = vrworld('handRAF.wrl');
open(myhand);
view(myhand);


% Rotate the right hand about the x and z axes to give a
perspective view
myhand.Handrot1.rotation=[0 1 0 -pi/4];
myhand.Handrot2.rotation=[0 0 1 pi/4];


% Rotate left hand so it appears as mirror image
myhand.LHandrot1.rotation=[0 1 0 -3*pi/4];
myhand.LHandrot2.rotation=[0 0 1 pi/4];
```

Program 5: Function to interact with the Virtual Environment

```
%% bendvr.m is a function that cycles the fingers and
%thumbs of the left and right hands of the VRML model from
%fully extended (0 rad of each finger joint) to a flexion
%angle that is between 0 and pi/2 rad, and back to 0 rad.

% R.Foulds 4/17/2013 edited by Abhineet Mishra to use it
with UDP Communication.

% The time for the cycling is determined by the second
pause value.

% The trajectory of flexion angles (an(i) is computed from
0 to the maximum flexion angle, an(max))

% The maximum angle of flexion is determined by the current
%value of the variable thinking. When thinking is negative,
%it is set to 0.  Otherwise the value of thinking (max of
%1)is used to scale the flexion angle,
%i.e. anmax=thinking*pi/2

% the increments in the trajectory are .1 rad scaled by
thinking
% i.e. .1*thinking

function bendvr(myhand,thinking)
%% Check if thinking is less than 0
if thinking<0
    thinking=0;
end

% Compute current flexion trajectory
an=0:0.1*thinking:pi/2*thinking;

%% Flex hands
for i=1:length(an)
    %PM of right hand fingers
    myhand.Indexbase2.rotation=[1 0 0 an(i)];
    myhand.Middlebase2.rotation=[1 0 0 an(i)];
    myhand.Ringbase2.rotation=[1 0 0 an(i)];
    myhand.Pinkybase2.rotation=[1 0 0 an(i)];

    %PIP right hand fingers
    myhand.IndexM.rotation=[1 0 0 an(i)];
    myhand.MiddleM.rotation=[1 0 0 an(i)];
```

```matlab
    myhand.RingM.rotation=[1 0 0 an(i)];
    myhand.PinkyM.rotation=[1 0 0 an(i)];

    %DIP Right hand fingers
    myhand.IndexD.rotation=[1 0 0 an(i)];
    myhand.MiddleD.rotation=[1 0 0 an(i)];
    myhand.RingD.rotation=[1 0 0 an(i)];
    myhand.PinkyD.rotation=[1 0 0 an(i)];

    %MC Left hand fingers
    myhand.LIndexbase2.rotation=[1 0 0 -an(i)];
    myhand.LMiddlebase2.rotation=[1 0 0 -an(i)];
    myhand.LRingbase2.rotation=[1 0 0 -an(i)];
    myhand.LPinkybase2.rotation=[1 0 0 -an(i)];

    %PIP left hand
    myhand.LIndexM.rotation=[1 0 0 -an(i)];
    myhand.LMiddleM.rotation=[1 0 0 -an(i)];
    myhand.LRingM.rotation=[1 0 0 -an(i)];
    myhand.LPinkyM.rotation=[1 0 0 -an(i)];

    %DIP left hand
    myhand.LIndexD.rotation=[1 0 0 -an(i)];
    myhand.LMiddleD.rotation=[1 0 0 -an(i)];
    myhand.LRingD.rotation=[1 0 0 -an(i)];
    myhand.LPinkyD.rotation=[1 0 0 -an(i)];


%     pause(.005) %pause to allow thumb to move after
finger flexion
    myhand.Side1.rotation=[0 1 0 -an(i)];
    myhand.LSide1.rotation=[0 1 0 an(i)];

    pause(.001) % Controls speed of flexion
end

%% Extension (move back to 0 rad)
% Follows reverse trajectory from an(max) to 0 rad
for i=length(an):-1:1
    % Right hand
    myhand.Indexbase2.rotation=[1 0 0 an(i)];
    myhand.Middlebase2.rotation=[1 0 0 an(i)];
    myhand.Ringbase2.rotation=[1 0 0 an(i)];
    myhand.Pinkybase2.rotation=[1 0 0 an(i)];

    myhand.IndexM.rotation=[1 0 0 an(i)];
    myhand.MiddleM.rotation=[1 0 0 an(i)];
```

```matlab
    myhand.RingM.rotation=[1 0 0 an(i)];
    myhand.PinkyM.rotation=[1 0 0 an(i)];

    myhand.IndexD.rotation=[1 0 0 an(i)];
    myhand.MiddleD.rotation=[1 0 0 an(i)];
    myhand.RingD.rotation=[1 0 0 an(i)];
    myhand.PinkyD.rotation=[1 0 0 an(i)];

    % Left hand
    myhand.LIndexbase2.rotation=[1 0 0 -an(i)];
    myhand.LMiddlebase2.rotation=[1 0 0 -an(i)];
    myhand.LRingbase2.rotation=[1 0 0 -an(i)];
    myhand.LPinkybase2.rotation=[1 0 0 -an(i)];

    myhand.LIndexM.rotation=[1 0 0 -an(i)];
    myhand.LMiddleM.rotation=[1 0 0 -an(i)];
    myhand.LRingM.rotation=[1 0 0 -an(i)];
    myhand.LPinkyM.rotation=[1 0 0 -an(i)];

    myhand.LIndexD.rotation=[1 0 0 -an(i)];
    myhand.LMiddleD.rotation=[1 0 0 -an(i)];
    myhand.LRingD.rotation=[1 0 0 -an(i)];
    myhand.LPinkyD.rotation=[1 0 0 -an(i)];

%     pause(.005)
    myhand.Side1.rotation=[0 1 0 -an(i)];
    myhand.LSide1.rotation=[0 1 0 an(i)];

    pause(.001) %Controls speed of extension
end
```

Program 5: Function to read data from BCI2000 using UDP Communication

```matlab
%% Program to read via UDP port
ip = 'localhost';
port = 20320;
% Create and open a UDP object that connects to BCI2000.
u = udp( ip, 20319, 'LocalPort', port, 'Terminator',
'CR/LF', 'Timeout', 10 );
fopen( u );

% Read data until timeout occurs.
s = fgetl( u );

while( s~=-1 )
    disp(s)
    s = fgetl( u );
end

% Close and delete the UDP object.
fclose( u );
delete( u );
```

APPENDIX B

INSTITUTIONAL REVIEW BOARD APPROVAL LETTER

N J I T.
New Jersey's Science & Technology University

Institutional Review Board: HHS FWA 00003246
Notice of Approval
IRB Protocol Number: F 141-13

Principal Investigators: Richard Foulds
        Abhineet Mishra
        Biomedical Engineering

Title: Brain Computer Interface Based Robotic Therapy
Performance Site(s): NJIT:

Type of Review: FULL [x]   EXPEDITED [ ]

Type of Approval: NEW [x]   RENEWAL [ ]   REVISION [ ]

Approval Date: December 20, 2012   Expiration Date: December 19, 2013

1. **ADVERSE EVENTS:** Any adverse event(s) or unexpected event(s) that occur in conjunction with this study must be reported to the IRB Office immediately (973) 596-5825.

2. **RENEWAL:** Approval is valid until the expiration date on the protocol. You are required to apply to the IRB for a renewal prior to your expiration date for as long as the study is active. It is your responsibility to ensure that you submit the renewal in a timely manner.

3. **CONSENT:** All subjects must receive a copy of the consent form as submitted. Copies of signed consent forms must be kept on file with the principal investigator.

4. **SUBJECTS:** Number of subjects approved: 5

5. The investigator(s) did not participate in the review, discussion, or vote of this protocol.

6. **APPROVAL IS GRANTED ON THE CONDITION THAT ANY DEVIATION FROM THE PROTOCOL WILL BE SUBMITTED, IN WRITING, TO THE IRB FOR SEPARATE REVIEW AND APPROVAL.**

Judith Sheft, IRB Chair,

REFERENCES

1. Wolpaw J.R., Birbaumer N., McFarland D.J., Pfurtscheller G., Vaughan T.M., *Brain Computer Interfaces for Communication and Control.* Clinical Neurophysiology, 2002, 113(6): 767-791.

2. Virani, Nathan D. Wong, Daniel Woo, Melanie B. Turner., *Heart Disease and Stroke Statistics-2013 Update.* American Heart Association, Dallas, Texas, 2013.

3. Murray C.J.L., Lopez A.D., *The Global Burden of Disease: A Comprehensive Assessment of Mortality and Disability from 1990 projected to 2000.* Harvard University Press, Cambridge, Massachusetts, 1996.

4. Nelles G. et al., *Arm Training Induced Brain Plasticity in Stroke Studied with Serial Positron Emission Tomography.* NeuroImage- Elsevier, 2001, 13(6): 1146–1154.

5. Liepert J. et al., *Motor Cortex Plasticity during Constraint-Induced Movement Therapy in Stroke Patients.* Neuroscience Letters, 1998, 250(1): 5-8.

6. National Institute of Neurological Disorders and Stroke, *Interagency Head Injury Task Force Report.* Maryland: Bethesda, 1989.

7. Belda-Lois et al., *Rehabilitation of Gait after Stroke: A Review towards a Top-Down Approach.* Journal of NeuroEngineering and Rehabilitation, 2011, 8(66).

8. Dohring M.E., Daly J.J., *Automatic Synchronization of Functional Electrical Stimulation and Robotic Assisted Treadmill Training.* IEEE Transactions on Neural Systems and Rehabilitation Engineering, 2008, 16: 310-313.

9. Fasoli S.E., Krebs H.I., Stein J., Frontera W.R., Hughes R., Hogan N., *Robotic Therapy for Chronic Motor Impairments after Stroke: Follow-up Results.* Archives of Physical Medicine and Rehabilitation, 2004, 85: 1106-1111.

10. Hidler J., Nichols D., Pelliccio M., Brady K., *Advances in the Understanding and Treatment of Stroke Impairment using Robotic Devices.* Topics in Stroke Rehabilitation, 2005, 12: 22-35.

11. Edwards D.J., *On the Understanding and Development of Modern Physical Neurorehabilitation Methods: Robotics and Non-Invasive Brain Stimulation.* Journal of Neuroengineering and Rehabilitation, 2009, 6(3).

12. Mirelman A. et al., *Effects of Robot-Virtual Reality Compared with Robot Alone Training on Gait Kinetics of Individuals Post Stroke.* Virtual Rehabilitation, 2007, 65-69.

13. Qiu Q., Adamovich S., Saleh S., Lafond I., Merians A.S., Fluet G.G., *A Comparison of Motor Adaptations to Robotically Facilitated Upper Extremity Task Practice Demonstrated by Children with Cerebral Palsy and Adults with Stroke.* IEEE International Conference of Rehabilitation Robot, 2011: 5975431.

14. Hand Randall, *Virtual Worlds for Patient Rehabilitation*. Vizworld Website. [Online] 2010. http://www.vizworld.com/2010/03/virtual-worlds-patient-rehabilitation/

15. Jeannerod M., *The Representing Brain: Neural Correlates of Motor Intention and Imagery.* Behavioral and Brain Sciences, 1994, 19: 187-245.

16. Gallese V. et al., *Action Recognition in the Premotor Cortex.* Brain, 1996, 119(2):593-609.

17. Rizzolatti, Giacomo and Arbib, Michael A., *Language within our grasp*. Trends in Neurosciences, 1998, 21(5): 188-194.

18. Schilder P., *The Image and Appearance of the Human Body.* Routledge & Kegan Paul, London, UK 1935.

19. Kosinski R. J., *A Literature Review on Reaction Time.* 1st ed., Clemson University, Clemson, South Carolina, 2008.

20. Kirschstein T., Köhling R., *What is the Source of the EEG?* Clinical EEG and Neuroscience, 2009, 40(3):146-149.

21. Ward J., *The Student's Guide to Cognitive Neuroscience.* 2nd ed., Psychology Press, New York, NY, 2010.

22. Hallez H., Vanrumste B., Grech R., *Review on Solving the Forward Problem in EEG Source Analysis.* Journal of Neuroengineering and Rehabilitation, 2007, 4: 4-46.

23. Chambers J. A., Saeid Sanei, *EEG Signal Processing.* 1st ed., Wiley-Interscience, New York, NY, 2007.

24. Fisch, Bruce. *Fisch and Spehlmann's EEG Primer: Basic Principles of Digital and Analog EEG.* 3rd ed., Elsevier, Amsterdam, Netherlands, 1999.

25. Proverbio A., Alberto Z., *The Cognitive Electrophysiology of Mind and Brain.* 1st ed., New York: Academic Press, 2002.

26. Olejniczak P., *Neurophysiologic Basis of EEG.* Journal of Clinical Neurophysiology, 2006, 23(3): 186-189.

27. Kierkels M., Johannes J., *Validating and Improving the Correction of Ocular Artifacts in Electro-encephalography.* Technische Universiteit Eindhoven, Netherlands, 2007.

28. Fraiwan L., Lweesy K., Khasawneh N., Wenz H., Dickhaus H., *Automated Sleep Stage Identification System based on Time–Frequency Analysis of a Single EEG Channel and Random Forest Classifier.* Computer Methods and Programs in Biomedicine, 2012, 108(1): 10-19.

29. Diego Rielo and Selim R. Benbadis, *EEG Artifacts.* [Online] April 2012.
http://emedicine.medscape.com/article/1140247-overview#showall

30. Schalk G., McFarland D.J., Hinterberger T., Birbaumer N. and Wolpaw J.R., *BCI2000: A General-Purpose Brain-Computer Interface (BCI) system.* IEEE Transactions on Biomedical Engineering, 2004, 51(6): 1034-1043.

31. Blackwood D. H., Muir W. J., *Cognitive Brain Potentials and their Application.* The British Journal of Psychiatry, 1990, 157(9): 96-101.

32. Peterson N.N., Schroeder C.E., Arezzo J.C. et. al., *Neural Generators of Early Cortical Somatosensory Evoked Potentials in the Awake Monkey.* Electroencephalogrphy and Clinical Neurophysiology, 1995, 96(3): 248-260.

33. Pfurtscheller G. and Silva F.H., *Event-related EEG/MEG Synchronization and Desynchronization: Basic Principles.* Clinical Neurophysiology, 1999, 110(11): 1842-1857.

34. Duvinage M. et al., *A P300-Based Quantitative Comparison between the Emotiv EPOC Headset and a Medical EEG Device.* Proceedings of the IASTED International Conference Biomedical Engineering, ACTA Press, Austria, 2012.

35. Stamps K. and Hamam Y., *Towards Inexpensive BCI Control for Wheelchair Navigation in the Enabled Environment– A Hardware Survey*. Brain Informatics, 2010, 6334: 336-345.

36. NeuroAudience, Inc., *NeuroAudience, Technology*. [Online] 2011. http://astrid.astida.com/neuroaudience/technology.html

37. Beitas K. et al., *Biological Measurements.* University of Kardeljeva, Comlab. [Online] 2010. http://www.pef.uni-lj.si/eprolab/comlab/sttop/sttop-bm/bm-elephy.htm

38. Khushaba R.N. et al., *Choice Modeling and the Brain: A Study on the Electroencephalogram (EEG) of Preferences.* Expert Systems with Applications, 2012, 39(16): 12378–12388.

39. Emotiv, Inc., *Emotiv EEG- Quick Set up.* Emotiv, Inc. [Online] 2013. http://www.emotiv.com/eeg/setup.php

40. McFarland D.J., Vaughan T.M. and Schalk G., *The Wadsworth Center brain-computer interface (BCI) research and development program.* Neural Systems and Rehabilitation Engineering, 2003, 11(2): 1-4.

41. Christian J Bell et al., *Control of a humanoid robot by a noninvasive brain computer interface in humans.* Journal of Neural Engineering, 2008, 5: 214.

42. Mason S.G. and Birch G.E., *A General Framework for Brain–Computer Interface Design.* IEEE Transactions on Neural Systems and Rehabilitation Engineering, 2003, 11(1): 70-85.

43. Mellinger J. and Schalk G., *A Practical Guide to Brain-Computer Interfacing Using BCI2000.* Springer, New York, NY, 2009.

44. Wolpaw J.R. and McFarland D.J., *Control of a two-dimensional movement signal by a noninvasive brain–computer interface in humans.* Proceedings of the National Academy of Sciences, Albany, NY, 2004, 101(51): 17849–17854.

45. Dewey R., [Online] 2011. http://www.intropsych.com/ch02_human_nervous_system/homunculus.html

46. Hebb D.O., *The Organization of Behavior: A Neurophysiological Theory.* New Ed. ed., Wiley & Sons, New York, NY, 1949.