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School of Computer Science, Engineering and Mathematics

Analysis of Potential Types of Brain-Computer Interface Technology for a Severely Locked-in Patient

Master of Engineering by Research
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Abstract

This study will assess a patient suffering from brain damage over decades to fit with a Brain Computer Interfacing (BCI) technology. These techniques will replace conventional muscle controls with direct brain control of outside assistive devices such as wheelchair. This would help people with severe impairments to live happier and more productive lives.

As part of this study, patient's clinical background was investigated. Considering patient's abilities and strengths, a protocol was designed. The protocol included all practised BCI techniques in literature to find feasibility of implementing a fitting the patient with BCI technology. This research studied auditory, visual and tactile steady state responses, auditory and visual evoked potentials and visual, audio and cross modal (audio-visual) oddball responses.

Results obtained suggested lesions in the brain interrupted the operation of some sensory systems. Techniques used to access BCI feasibility for this patient suggested presence of visual steady state response and possibly very weak respond to cross modal oddball tasks. None of the results in the other modalities of the steady state test response and oddball test indicated presence of response. The two sections with possibly positive results may be further investigated in order to find if the results found can be focus related and reliably reproduced.

Keywords: Brain Injury – paralysed – locked-in– consciousness – awareness – abilities – vision – hearing – sensory - current brain assessments for consciousness – BCI for diagnose and treatment - communication – mobility – control – assistive technologies – BCI as assistive technology

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I would like to thank my family for their ongoing support and encouragement during the course of this study.

Declaration

Except where sources have been acknowledged, the work submitted for this thesis is my own, and does not contain any materials previously written or published by another person.

Fatemeh Khazab

19th October 2014

Contents

1. Case Scenario

1.1 Patient History

This thesis is focused on assisting a patient with a severe traumatic brain injury as a result of a car accident two decades ago. As a result of this accident the patient has lost independent movement and communication and is dependent on his/her family and carers for all activities of daily living. The patient uses a powered wheelchair for mobility which he/she is unable to control independently. The patient appears to have very minimal movement on right hand fingers. This movement is currently of no functional use. The patient's parent communicates with him/her through facilitated writing. This is done by the parent holding a paper pad in one hand and holds the patient's right hand and a pen in the other and writes responses to questions.

The patient has been under treatment for over 20 years and has yet to be successfully fitted with an assistive device for communication and mobility and thus represents a major challenge and is being evaluated to see what kind of device could be developed for such a patient with severe and multifaceted disability. The Flinders Artificial Intelligence (FAI) team in the School of Computer Science, Engineering and Mathematics was contacted by both the patient's family and the patient's occupational therapist independently. Both the patient's family and occupational therapist heard about FAI work through public communications. They had a view of working with the team to adapt a Brain Computer Interface (BCI) technology to assist the patient in independent communication and mobility.

This study was approved by The Southern Adelaide Health Service / Flinders University Human Research Ethics Committee (SAFUHREC) for the period of 19th October 2010 to 19 October 2013.

1.2 Patient Current Abilities

Patient’s current health was studied using reports provided by clinical professionals that have previously examined or routinely assess the patient’s wellbeing. The reports were obtained from the patient’s Occupational Therapist, Neurologist, Optometrist and General Practitioner.

- **Visual Reports**

The optometrist has seen the patient for many years and used to interact with the patient by relying on responses mediated by the parent's. Patient exhibits variable alertness on different occasions as per the optometrist interactions with the patient. When drowsy, the right eye tends to close completely and the head and eyes tend leftwards.

According to the optometrist’s report, the patient was myopic (short sighted) prior to the accident and required glasses for distance viewing and had no difficulties with close work. However, as a consequence of the accident injuries the patient has Post Trauma Vision Syndrome. Post Trauma Vision syndrome usually manifest as reduced or poor near focusing ability and myopia. Moreover, the client has a difference in pupil size and adaption to changes in lighting levels. The patient can see quite normally for distance vision using glasses but requires a separate pair for close work especially for computer/music/reading tasks. Corrected acuity (clearness of sight) is estimated to be R 6/12 L 6/9 with glasses. Near vision is adequate, but for computer viewing the patient would benefit from a minimal size of 16pt type. This prescription assists with focusing for near work. Patient's visual acuity was tested by asking the patient to indicate via the parent whether the flashed letter was seen with a yes/no answer. When different lenses where applied patient was asked to write the actual letter through assistive writing. The optometrist reported that the patient responses got letters correct with expected good vision and did not see letters with expected poor vision. The left eye has good visual acuity; however, the optometrist is not confident about the right eye acuity.

The patient also has difficulty looking directly at objects and is better when objects are placed on midline or to the left of the patient's midline. Patient has been fitted with prism spectacles to correct his/her tendency to look left and bring the visual environment back to the centre of vision. Primary gaze (to the front) takes place when patient is alert. However, when drowsy, the head and eyes drift to the left and the right eyelid closes. The right eye is closed about 50% of the time. About 10% of the time and only when alert, patient can gaze to target, but this task is more difficult to the right. The visual field of the patient was not possible to assess. The optometrist is suspicious of a nasal defect in the right eye and a temporal defect in the left eye (right cerebral hemisphere lesion).

The optometrist did note at one visit, when the patient was more assessable, a very pale optic nerve in the patient's right eye, suggesting that the patient may in fact have optic nerve atrophy which would explain quite a few of clinical impressions.

- **Neurological Reports**

According to the assessment by neurologist in the year 2000, the patient was reported sleepy and hard to arouse during recording. The background EEG recording was dominated by beta frequencies around 15-17Hz mixed with occasional alpha rhythms at 12-13Hz of low amplitude. Intermittent 5-6Hz theta activity was reported in the left anterior temporal region and 2-5Hz components at times. A few focal sharp waves were recorded in the right mid to anterior temporal region. According to neurologist report the record was abnormal showing localized slow wave activity in the left anterior temporal region and focal sharp waves over the right mid to anterior temporal area.

The patients' current neurologist has studied this patient since 2003, having taken over since the patient's previous neurologist's retirement. According to the neurologist, the patient has a seizure disorder. In regards to mapping the patient's visual field the neurologist noted that the patient responds in all four quadrants to visual threat. However more detailed testing of visual fields is virtually impossible. Based on his report the patient's eyes do not move in response to verbal command in either the vertical or horizontal plane. The patient has occasionally shown to be able to track moving objects only in the horizontal plain in both directions although this is quite variable.

The patient displays the occasional facial grimacing but otherwise no controllable movements were detected. There is certainly no movement to verbal command. Furthermore, no controllable head movements were witnessed in either flexion extension or rotation. The patient has a left spastic hemiparesis with no movement in the left arm or leg. There are some non-purposeful movements in the distal right hand and foot which are not reproduced on verbal command. The regional and sensory loss was not examined or obtained for this patient.

According to the neurologist, the patient has remained quite stable in the past 9 years for both motor and communication functions. The neurologist was never able to communicate with the patient directly and the communication has indirectly occurred via writing pad and with the parent's assistance (assistive writing). In the scenario the patient is able to respond with written text although this is barely legible. The process induces purposeful movement by the parent which has been a contentious issue that has not been challenged by the neurologist as he has been primarily focused on the patient's seizure disorder. When the neurologist has taken on the role of supporting the patient's arm/hand to facilitate assistive writing no purposeful movement were detected to any specific questioning.

Based on the EEG monitoring report in 2008, abnormal localized slow wave activity in the left anterior temporal region and focal sharp waves over the right mid to anterior temporal area was reported. Few years ago patient has been through a video EEG monitoring. Few episodes of teeth clenching and one episode of staring were recorded with no abnormal EEG changes. Record was mildly asymmetrical. Right hemisphere contained alpha rhythms at 8Hz of moderate amplitude mixed with low voltage beta frequencies at 15-25 Hz and occasional irregular 2-5 Hz activity of higher amplitude. Left hemisphere, more prominently over the temporal region, contained a mixture of theta activity, beta frequencies and intermittent dysrhythmic irregular delta components. Abnormal EEG, slow wave activity was observed chiefly in the left hemisphere with emphasis over the left temporal region. Frank epileptic features were lacking in patient's EEG study.

The patient's brain CT scan in 2011 showed prominence of the ventricles and sulci is much greater than expected for the patient's age and consistent with atrophy. There is more focal gliosis in both frontal lobes and in the left parietotemporal region.

The patient's seizure frequency is obtained from the parent's who keeps a diary. According to that diary the patient had three brief generalized seizures in March and one on the 4th April 2012. The patient has not had any further seizures since that time (this report was obtained on 29th May 2012 from the neurologist). These occurred in the context of weaning from Carbamazepine as this has caused SIADH. The patient now appears stable on a combination of Lamotrigine 300mg b.d. and Levetiracetam 1 gm b.d.

- **EEG Reports**

The patient has gone through some EEG assessment previously at Brain Health Clinics Adelaide, in 2010. The EEG report indicated a relatively normal brain response to sensory stimulation; but there was evidence of excessive slow wave brain activity clearly marking some pathology with processes relevant to attention and memory. Moreover, excessive muscle activity was present in and around the scalp. Measures of averaged, event-related brain activity showed patient's brain to be responsive to the physical aspects of auditory stimuli (P1-N1-P2 complex) but were equivocal in relation to the attention-related (i.e. P3) response to such stimuli. The client's brain response to visual stimuli was equivocal in all regards. In order to improve the outcome for visual stimulation there might be a requirement for calibration of the head position for accurate orientation to visual stimuli, but only likely in relation to measurement of the brain's response to the physical properties of visual stimuli. Overall, the assessment did not provide strong evidence of the presence of a mentally determined, attention response by the brain during information processing. Detection of a mentally determined response such as this is required by the brain computer interface (BCI) under consideration.

The relative lack of success in the previous assessment might have been due to a number of uncontrolled factors. Firstly, high levels of spontaneous muscle activity may have masked the response, as there would a relatively low signal to noise ratio in the measures obtained. Secondly, it is possible that there was a high level of variability in the brain's attentional response to individual auditory and visual stimuli - if so, this would have markedly reduced the averaged measure of the response obtained. As such, this response may be better detected with BCI techniques that focus on single trial rather than an averaged brain response, and which obtain higher signal-to-noise in the EEG.

As the raw data from previous assessment is no longer available, no further signal processing techniques can be used in order to study the data further. Therefore, in order to confirm the client's mental activity new experiments need to be set up considering factors that were of concern for previous EEG study.

- **Rehabilitation Specialist Report**

The rehabilitation specialist has been involved with this patient since the 1990's. The patient's parents have a record of him in late 1990's reading Judith Wright's tender poetry to the patient in the early post-coma phase. There is also a copy of Channel 7 video in which the patient is writing and listening to music and poetry. The rehabilitation specialist believes that these are useful historical records, which even in the patient's early post-coma phase demonstrate awareness and understanding.

The rehabilitation specialist has visited the patient in May 2012. The following is what was observed during his time with the patient and parents:

The patient takes time to become accustomed to conversation with a person with whom he/she is not familiar. As soon as the specialist adjusted to the patient's response latency, the interaction flowed.

Patient's working memory is believed to be intact based on the rehabilitation specialist's report. Working memory flows once interaction has been established. Naturally the parents know instinctively how to initiate the patient's participation and he/she responds accordingly. Unless one is familiar with the patient it takes time to establish interaction.

The patient benefits from having a routine and known person who are part of that routine. While the rehabilitation specialist was present, the patient's regular caregiver arrived; the patient responded with obvious delight to his/her caregiver's presence.

The patient's sense of humour is intact and responds immediately to humour and absurdity. Based on the account of the rehabilitation specialist, the patient laughs easily and at one point his/her body was convulsed with laughter. Based on the specialist observation the patient displayed the conceptual knowledge necessary to understand absurd language and quickly put this into context. The reason for using absurdity is that it facilitates and/or demands attention.

The patient has 'pictures' in his/her brain of what is taking place around him/her. How he/she generates the sense that he/she is the 'owner' of these pictures and therefore is able to respond to them, is complex. The physiological mechanism to enable the patient to generate a speech production, or a gestural response is seriously impaired. However, during the rehabilitation specialist's short time with the patient, he/she produced audible sounds as he/she endeavoured to respond. The patient is trying every waking hour to respond and participate. The patient's severe difficulty with responding, accurately and immediately, influences if not compromise his/her awareness and grasp of receptive language 'pictures'.

The patient responds with comparative ease to music provided that there has been adequate preparation. The patient has a comprehensive 'auditory memory' particularly for classical music. However the patient's difficulty is in demonstrating his/her understanding. Nevertheless the patient's recent Master's thesis in Musicology from Adelaide University is testament to his/her academic attainment. The patient's grasp of music theory as well as his/her capacity to learn and respond is remarkable, if not outstanding.

The patient, given appropriate support, responds by writing short notes on a pad. This has the effect of shaping and reinforcing his/her graphic and acoustic language templates. The rehabilitation specialist has observed the patient writing on a pad and believed that the fact that the patient was supported by parent did not detract from the patient's successful participation and carefully reasoned written responses. The specialist also believed that this was an 'errorless activity' which is essential for someone who has experienced such a severe traumatic brain injury.

Based on the rehabilitation specialist's report the patient gets fatigued easily and when tiredness creeps up on him/her then his/her muscle tone can become even more rigid. Therefore, working and participating with the patient will be most successful in short time spans.

1.3 Past Assistive Technology Used

- **Switches used as Interfacing Devices**

The patient was referred to ASSIST Central (OT) to determine if he/she was consistently and reliably able to access a switch for the purpose of using and electronic communication device. The referral had been initiated by the patient's parents who wanted to explore options for the patient to communicate independently. The patient currently communicates through parent who uses facilitated writing. The parent requested an alternative to this in the event that the parent was not available to assist Airlie.

It was determined by the ASSIST Speech Pathology Department that in order for the patient to be able to use an electronic communication device successfully, a switch trial would need to be conducted that showed the patient to have at least 80 % accuracy. In order for the patient to achieve this goal, he/she would need to produce a controlled, consistent and reliable response during the trial. The patient would also need to time his/her switch press so that the correct selection was made. Because of the difficulties with the patient's vision, it would also be necessary for him/her to listen to the scanned choices and make the right selection.

Switch Options

Therapists in the past have looked at upper limb, lower limb and head activated switches without success. After exhaustive assessment by many therapists over the years, it was determined that a switch attached to the patient so that he/she did not need to reach for, would require less effort and give the patient the best opportunity to succeed. The patient trialled switches placed on his/her wheelchair arm rest and hard switches placed in his/her hand without success.

In this section the switches used for the patient so far are displayed in figures 1 to 6. They are using variety of different techniques and fingers or limbs to control. Using index finger control glove in figure 1, patient was able to control the wheelchair using only the index finger movements. Thumb control glove gives the same sort of single movement control but using thumb movement only as shown in figure 2. Micro switch displayed in figure 3 provided opportunity to use any finger or part of hand/arm to activate and figure 6 is based on the same concept of using any part of the hand but it does not required precise finger movement. Figure 4 displayed the glove that provide control by pressing the index finger and thumb together. Figure 5 displays a bigger switch that can be activated by pressing down any finger or combination of fingers. All however, have failed to provide a reliable and relatively independent controls.

Gloves with a variety of switches

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Figure 1: Glove Switch – Index Finger Control

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Figure 2: Glove Switch - Thumb Control

Micro Switch:

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Figure 3: Micro Switch

Thumb switch with flat bar:

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Figure 4: Thumb Switch - Thumb Press against Index Finger in Holder

Switches for Mobility Control

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Figure 5: Control Switch on the Wheelchair

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Figure 6: Bar Switch for Wheelchair Control

A new switch (Balloon Switch, figure 7) that the patient had not tried previously had been recommended for trial by a Speech Pathologist from Technical Solutions. This switch had been developed by the company for clients with similar functional ability to this patient and it had been very successful.

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Figure 7: Balloon Switch

Switching Skills

The initial trial of this switch indicated that the patient could hold it between the thumb and index finger of her right hand. The patient was unable to hold and activate it in his/her left hand and the patient is right hand dominant. The switch construction (a soft balloon with a foam insert) requires that it is held between something and pressed. The patient was able to hold the switch in his/her right hand and this was the site that was chosen.

During the assessment, it was determined that the patient preferred to have his/her right arm extended while holding the switch. OT set up the switch with the patient's radio so that the radio switched off every 30 seconds. OT observed that for 45 minutes, the patient was able to turn the radio on immediately when it went off. OT observed that the patient appeared motivated and alert while doing this.

OT observed that while the radio was on, there were very few activations and as soon as the radio went off, the activations increased significantly. During this 45 minute trial, OT observed that the patient was relaxed and sitting back in his/her wheelchair with a smile.

Timing of the Switch Press

In order to assess and train the patient's ability to time activation of the switch, a four location scanning device (Alpha Talker) was set up with four messages. Within the switching sessions the patient was asked to select specific messages, and also given the opportunity to answer questions spontaneously. The messages were "Yes", "No", "I don't know" and "Please ask Mum".

Ability to See or Hear the Scanned Choices

OT requested a visual assessment prior to proceeding and a report was obtained from Behavioural Ophthalmologist from the Vision and Learning Institute who determined that the patient had Post Trauma Vision Syndrome. As a result of the patient's brain injury, he/she experiences sensorimotor spatial disorganization. The symptoms associated with this include double vision, headaches, blurred vision, dizziness, light sensitivity, reading and comprehension difficulties and visual memory problems. For this reason, the balloon switch was set up with a pillow speaker (this is a small speaker that can be set up near the patient's ear so that he/she can hear the choices as they are scanned) so that the patient could hear the messages and select the one that he/she wanted.

This system (switch, Alpha Talker and Pillow Speaker) was set up for the patient and left in place for him/her to practice for some months over the Christmas Break of 2010/2011.

Switch Training/Intervention

An intensive switch training programme was commenced on 9th May 2011 and there were twelve sessions where an Allied Health Therapy Assistant (AHTA) from ASSIST Central attended at the patient's home to provide the training and collect the data.

The first part of the session involved the AHTA asking the patient to select one of the answers and the second part was asking questions that the patient needed to respond to. The questions were provided by the patient's parent along with the correct answers and they were as basic as "Is your name ---".

Results and Recommendations

The results from the switch training sessions were as follows.

Session	Accuracy in selecting the correct target:
Session 1	55%
Session 2	25%
Session 3	62.5%
Session 4	35%
Session 5	42.5%
Session 6	45%
Session 7	100%
Session 8	10%
Session 9	10%
Session 10	05%
Session 11	00%

Session 12 05%

The average accuracy per session is 32.9%. With the reported results, the patient has not demonstrated the ability to use a switch and scanning with the required accuracy to utilise an electronic communication device. There would be a very high likelihood of error in selection of messages for communication purposes using this method of access.

Consideration of an alternative system may be worthwhile investigating. At this time, it is recommended that a referral be put through to ASSIST Speech Pathology to determine alternative solutions to the patient's communication requirements.

- **Occupational Therapist Report**

Over the years since that accident, the patient has been seen by many therapists who have trialled a number of different switches and accessing systems. The result from these trials is that the patient does not have a functional, consistent or reliable accessing site that can be used to access any electronic device or environmental control system.

Based on the report from the last trial attempted, the patient could hold the switch in his/her right hand and activate it but could not control his/her activation time. The patient was not consistent or reliable in the use of this switch.

There is no evidence in any documentation either at Highgate Park or ASSIST Central that suggests the patient has the potential to use a single switch which is the minimum requirement for accessing electronic devices. The only switch type that we have not been able to trial with the patient, is a switch controlled by brain activity.

The occupational therapist believe that based on her assessment of the patient and according to all files reviewed relating to the patient's ability to access assistive technology, at this moment in time, there is nothing available that will increase the patient's functional ability in this area.

1.4 Conclusion

This case scenario has introduced the patient's abilities and considerations that need to be made during designing the experiments. Based on the reports from clinicians who assessed and worked with this patient, all the methods used so far has failed in terms of providing a solution for the patient to control wheelchair or a communication device independently. Patient's parents and few others who worked with the patient however claim that patient has awareness of the situation and might have the skills that can be utilized. There might also be skills that can be improved by a feedback system.

The patient has once gone through an EEG and Event-Related Response assessment. The report from that study however showed no promising evidence as to patient might have the ability to be fit with BCI technology. However there were few considerations that had to be made for this patient in regards to EEG/ERP type studies.

The lack of ability to communicate or a reliable assistive device has introduced some challenged to this study. This study is considering all techniques commonly used and takes advantage of the techniques that bypass the need for communication in order to investigate and adapt an assistive technology that can be reliably and practically used by the patient.

2. Review of Literature

2.1 Definition of Disability

In 2001 United Nation's World Health Organization (WHO) released a new definition of disability after years of deliberation and cooperation. The sentiment was approved by 191 member states. In the new definition, disability is an ordinary part of each person's experience. Most importantly, disability is defined as something occurring outside of a person. As per WHO's definition, variation in ability of an individual cannot be accommodated in physical, information, communication, and social and policy environment. Based on this definition, one's disability can be reduced by designing environment that accommodate varying functional ability. (Understanding Disability 2010) Nearly six hundred and fifty million people experience various types of disabilities worldwide. As a result of rise in chronic diseases, car accidents, injuries, violence, aging and etc. this number is increasing. Out of all, 80% are poor and have limited or no access to basic rehabilitative services and facilities. (Noncommunicable Diseases and Mental Health 2011)

Australian Bureau of Statistics (ABS) reported four million people in Australia have disability in 2009. This is according to the Survey of Disability, Aging and Carers (SDAC) results. In this survey, disability is defined as:

"Any limitation, restriction or impairment which restricts everyday activities and has lasted or is likely to last for at least six months"

Examples of these disabilities vary from vision loss that is not corrected by glasses to arthritis causing difficulty in dressing or to advanced dementia in which constant assistance and supervision is required. (DACA Summary 2010)

In this definition of disability cover terminology such as impairment, activity limitation and participation restrictions by the International Classification of Functioning, Disability and Health (ICF) whereas impairment is defined as loss or significant variation in body structure or physiological functions according to ICF.

Disability divided into four groups by SDAC based on their relation with mind, sensational, anatomy, or physiology functions. The groups named sensory, intellectual, physical and psychological. Sensory group includes loss or restricted sight, hearing and speech. Intellectual consist of difficulties related to learning and understanding. Physical disabilities contain breading difficulties, loss of consciousness, pain or discomfort which affects daily activities, deficient use of arms, fingers, feet or legs, deformity and any sort of restrictions for physical activity. The Psychological group includes brain damage or injury and any terms of emotional or mental condition that restricts ones daily activity and would require assistance or supervision. Overall any kind of long term condition which restricts everyday activities is considered as a disability.

Based on ABS report there are assistive technologies such mobility aids (e.g. wheelchair), hearing aids, speaking aids (i.e. synthesized speech device) and reading and writing aids (e.g. talking work processors) to support the individuals experiencing a disability.

2.2 History of Assistive Technology for People with Severe Disability

Assistive technologies are critical to elders and/or people with impairments for maintaining independence in daily activities. Adequate assessment of the patient's needs, the appropriateness of the device that need, and the patient's motivation to use of a device is required for successful outcomes. A team approach is needed to ensure that devices are correctly prescribed, and the patient is taught how to use it effectively. A wide range of devices is available to support activities of daily living, mobility, home management, and safety. The use of personal computers is significantly expanding the possibility of independent living through support systems, monitoring systems, and information resources. (Brummel-Smith & Dangiolo 2009) The use of current assistive technologies which are capable of ameliorating communication, house-environment management and mobility, based on user's motor abilities can improve the quality of life of people suffering from severe motor disabilities. (Cincotti et al. 2008)

- **Mobility Devices**

For individuals who suffer from limitations in gait abilities, mobility aid is their basic social need. Henceforth, selecting the best technology for an individual with mobility aid dependency is essential to the outcome of rehabilitation and successful integration of the individual into society and active life. Disabilities that require wheelchair use are mostly due to nervous and musculoskeletal systems diseases, traumatic accidents involving spine and cervical regions mainly or progressive physical malfunction as a result of diabetes or cardiovascular problems. (Karwowski 2001)

Based on the disability that an individual experiences, a different type of wheelchair would be suitable to be used as an assistive aid. Wheelchairs generally are in three main categories of manual, automatic and both manual and automatic combined. For people who have strong upper body and can control a wheelchair using their hands, manual wheelchair would be good option. However, people who are suffering from disabilities that limit most of their mobility on both upper body and lower body extremities would require an automatic or powered wheelchair. The wheelchair which has both manual and automatic features is for people who are marginal manual wheelchair users but may have upper extremity injury due to manual wheelchair propulsion. Therefore, they require some extra assistance for their mobility control.

This study involves a patient with limited and unreliable mobility. Thus, automatic (powered) wheelchair is the mobility technology that is to be considered and studied.

Since introducing microprocessor-controlled powered wheelchairs there was a rapid development in powered wheelchair designs, controls and range which allows customization of controls to meet user’s needs. The new smart wheelchairs provide more than just mobility assistance. Their designs are aimed to resemble a healthy person's mobility. They come with different controlling systems to control wheelchair directions and may also include controlling other devices within user's environment such as TV, computers, air conditioner and, etc.

In order to match an assistive technology to an individual with specific needs or abilities, different factors are to be considered. The stake holders in matching the need of an individual to the wheelchair technology would be mainly the client, his/her family, therapists, rehabilitation engineers and suppliers etc. information such as client's disability, prognosis, weight, body structure and capabilities, vision, ability to propel, occupation, age and roles that they have are important in order to choose the most appropriate assistive technology. The environment that the person would use the wheelchair mainly in is one of the other important considerations in order to select an appropriate design or feature. Other essential considerations in selecting a right wheelchair to ones abilities and needs are type of wheelchair controller and its essential features and complexity. (Karwowski 2001)

According to the case scenario in this study, a powered wheelchair with highly featured controller is required for independent or partially independent mobility control. In this case, patient has full upper and lower bodies’ limitation of movement. Old assistive technology for these cases is to use attendant control at the back of the seat for caregiver or assistance to drive the wheelchair or techniques such as sip and puff control. None of these techniques however, would give the user independence and would not be convenient way for the individual to interact with outside world.

A power wheelchair control system includes controller, battery, motor and wiring connection that interconnects electrical components. Controllers consist of two parts of inputs and outputs. The input part can be thought of as a control device through which the system would be controlled. The output part is to convert the user commands to outputs which would have desirable effects/actions. There are two types of controllers in general, integral and Modular/Remote. The integral controller has both a user control device and output functions integrated into a signal box. A modular controller has the control device remote from the output section. Both controllers have some inputs in common such as a proportional joystick to request variable speed and direction, an ON/OFF switch to power the system on and off, a control that sets maximum speed, a battery charger socket to recharge the battery and a programming socket to customize controller performance. The outputs that all controller types have are two high current outputs to drive the two motors, two lower current outputs to drive the two park brakes, a battery capacity gauge and controller ON indicator LED and a diagnostics/status display. The modular controllers have some benefits to integral ones for the purpose of this study and in general. Modular control box is compact and ergonomic as compared to integral control box which is large. Modular have high number of choices of controllers and can be expanded to control all chair functions and other devices such as communication aids and can work as environmental control, etc. Modular controllers disadvantages however to integral system is that they are more complex and require experience and training and they are more expensive to purchase. (United Spinal Association TechGuide 2004) The integral controller would be a good type of control for using as a basic mobility application with no additional control features. However, when it comes to interfacing and communicating with other devices that accept different inputs rather than joystick such as sip and puff system, head array system, chin control, or Electromyography (EMG) and Electroencephalography (EEG) signals, integral control would not be a suitable option.

The most common user interface to a wheelchair is a joystick. Joystick is an input device that enables four directional movements. Moving the joystick to any direction would manoeuvre the wheelchair to that direction and leaving the joystick in neutral position would stop the wheelchair if driving and stay in standby mode. For a wheelchair driver to be able to use joystick as an interfacing unit to a powered wheelchair, a relatively strong and precise movement skills in upper limbs is required. However, the case in this study experiences upper limbs limited and unreliable movements.

Alternative control systems to a powered wheelchair could be either proportional drive or switched drive. The proportional drive provides speed proportional to joystick displacement. The examples for this controlling system are chin control, remote joystick, touch pad, finger steering etc. The non-proportional drive systems consist of different types of switch interfacing to the wheelchair. There are two main types of non-proportional drive systems which are multi-switch systems or single switch systems. The multi-switch systems are such devices as head-array systems, wafer board switches and Penta switches. The single switches are like a trigger switch, a grip switch, micro-touch, tip switch etc. (Additional Electronics n.d.) which some has been used for the patient in this study by the Occupational Therapist. Moreover, there are different switch systems that can work either by single switch, multi-switches or some types of proportional drive systems. The most common examples of these systems are Dynamic and P&G Omni.

Integrated control devices are another type of user interfaces to wheelchairs. They enable a single control interface to operate two or more assistive technologies. They can be connected to other types of wheelchair controllers or systems such as chin control, sip and puff control etc. These Interfaces are designed for a large variety of input mechanisms corresponding to a large range of specific disabilities and degrees of incapacity. The integrated controls for powered wheelchairs that are available currently in Australia were studied. They include DX IRIS, WiseDX, SRS100/Q-Controls, ClickToGo, and Genie Joystick. These provide different features and different inputting to the controller. They also contain displays and visual feedback systems that give feedback to the person about the selections they made. For example the ClickToGo option contains scanning modes. This scanning mode results in a chair that can be driven in any direction by pressing and holding the primary switch till the desired direction arrow is illuminated. Then the primary switch is released for a selection to be made. This selection could be done via the scanning mode or by using other user interfacing devices such as switch inputs for this integrated control device. These devices are also able to control items other than just the wheelchair (both driving and seat actuators) such as switch operated environment control device and switch operated communication device. Most of these integrated control devices have built in environmental controls or can be interfaced to any switch controlled by IR control in order to provide a high level of control for the user. High-level controllers with a high degree of self control would be desirable for people experiencing severe disabilities and limitations. These controllers would accept complex inputs from the user but then act by themselves. Controllers with modular degree of autonomy would allow the user to switch between lower and higher levels of control and ensure that the user is always in control of the device but freed from the burden of controlling it continuously (Tonet et al. 2008). Moreover, the environmental controls (e.g. Infra Red sensors) that are built in these integrated control devices can be mounted on the wheelchair and connected to the control system in order to improve the outcome for users in controlling the wheelchair by means besides signals from the brain. This might also reduce the number of tasks that a brain signal would be responsible for.

- **Communication Devices**

Augmentative and alternative communication (AAC) is a term used for communications other than speech. The AAC System is used to enhance communication or replace speech using combination of methods such as eye pointing, vocalizations and symbols pointing. AAC is to help people who are experiencing limited or non-existent speech ability. The system could also be used for people whom speech development is slow or as a back-up when their speech is difficult to be understood. Furthermore AAC can be used as an enhancing method to help develop understanding of delayed language. Therefore AAC systems or devices can be used for a short term or long-term solutions. (Novita, 2013)

Based on the patient’s ability and age there are different types of AAC. (AAC&Autism 2009) AAC methods available according to Novita’s Children Services organization are:

- Signing
- Object symbols
- Photo, drawings, symbols
- Communication boards and displays
- Pragmatic Organization Dynamic Display (PODD) communication books (a way of organizing world or symbol vocabulary in a communication book or speech generating device to provide immersion and modeling for learning). (Novita, 2013)
- Chat books
- Speech generating devices

Speech generating devices have two main benefits over other communication systems mentioned above. By using speech generating derives, the person can communicate by way of a spoken voice. This would enable the user to grab attention of a person that is further away or in another room, talk over the phone, talk with children/people who cannot read the symbols/words on a communication board, and give a speech to a group of people. This method has the advantage of messages being put together independently and then spoken out when ready.

There are two main types of speech generating devices, digitised (recorded) speech and synthesised (electric) speech. Digitised speech generating devices have the advantages of being able to suit the user's gender and age. They also can be in any language. Moreover, they can include any of the noises and sounds that are specific to the child or adult and make it more customised to the user. On the other hand by using digitised speech generating devices, the user is not able to put messages they want into devices themself and are dependent on a same person to be available to record messages as they are needed. Moreover, they have to record every message since commercial sets are generally not available. Furthermore they are not able to spell words to create messages.

Synthesised (electronic) speech generating device has an electronic voice similar to the ones used in automated telephone systems. Using synthesised speech enables the user who can spell, and their carers to store their own messages.

Messages on speech generating devices can be selected using one switch. Once a person is able to activate a switch can control their communication device. Then the user needs the motivation and language skills to be able to use the device for communication.

There are different ways of selecting messages that are direct selection and scanning. In direct selection user is able to activate the device using finger, fist, toe; a pointer on their hand or in their mouth; eyes (by looking at the item they want); a head-pointer (something attached to a headband or to the chin to point with); and a light beam to highlight the chosen messages.

Scanning selection is helpful for people who are not able to point directly to things or whom find point to be too hard or tiring. Scanning can be presented differently to suit the user's need, i.e., in straight lines, circular patterns, groups and then once at a time, once the group has been selected.

Moreover, the type of selection can be customized to the user's need for example one might light to activate scanning by pressing a switch and select the required command using another switch or another user might want the scanning to be started automatically and then when the desired one is highlighted then by pressing a switch it is selected. These are customized prior to use for the user by the authorized professionals.

There are different types of switches based on that can control a speech generating device. They can be customized to the user's ability. Switches can work with pressing, squeezing, pulling, making a noise, interrupting light beam, sucking/blowing, and etc.

Messages on a speech generating devices can be organized in four different ways, which are by topics (i.e. places, jokes, animals, etc.), by grammar (i.e. verbs, nouns, adjective etc.), by situation (i.e. words used in a restaurant situation, or in a birthday situation etc.), by pragmatics (i.e. the way a message is communicated e.g. requesting action or protesting).

Wide range of messages is communicated each day by a person and this makes it impractical to display messages in one page only. Speech generating devices organize stored messages in four mains ways.

One of the ways is to store messages on multiple pages or levels. These pages may be paper overlays or electronic displays that can be changed on the screen. The other way is to store messages using a type of code or sequence of pictures which represent a group of words. Letter encoding is another way to represent messages. For example using N to represent name and P to represent places. Morse code is another way of storing messages. Dots and dashes can be used to represent letters or alphabets. Using one switch which can be activated for short and long time or two switches one for dots and one for dashes can be used to facilitate Morse code.

Spelling is the most familiar way of communicating a message other than speech. It allows all words to be communicated easily without the need of programming or organizational methods to store words. (Novita 2011) It is very effective method of communication. However, the disadvantage of spelling is that in many people with disabilities there is difficulty in learning how to spell. Moreover, it is slow way of putting messages together especially if one cannot point to the letters directly. However features like message prediction, which can be installed in some of these speech generating devices, can speed up the process of typing the words and overall can improve speed of communication. (Novita 2013)

2.3 BCI as an Assistive Technology

People experiencing certain types of Tetraplegia or Amyotrophic lateral sclerosis (ALS) or brain injury have complete cessation of muscle movements. For those who are experiencing severe neuromuscular disabilities, conventional assistive technologies, all of which require some measure of consistent voluntary muscle control, are not satisfactory options. (Wolpaw 2009) Recent advancements in human-computer interfacing have endorsed the possibility of development of a new assistive technology for completely paralysed patients. (Wolpaw et al., 2000) A brain-computer interface is a technology that bypasses brain's normal output pathways of peripheral nerves and muscles. (Wolpaw et al. 2000) That is, as long as patients retain a conscious brain, access to the surrounding environment may be achieved through brain-computer interfacing. A brain-computer interface (BCI) device is a tool by which those unable to interact with the world through conventional pathways of the nervous system can regain the ability to do so. Brain-computer interfacing is the field concerned with establishing an alternative connection between the brain and the outside world without requiring a healthy peripheral nervous system. BCI system translates brain activity into signals which can be used to control external devices. Therefore, it is the only technology for severely paralysed patients to increase or maintain their communication and control options. (Cincotti et al. 2008)

Patients with cerebral palsy who experience lack of useful muscle control, patients with brain stem strokes who have no movement but minimal eye movement control, ALS patients with disease advancement, people with severe muscular dystrophies or peripheral neuropathies and possibly people with acute disorders, can all benefit from this technology. Even for those people who are experience slightly less severe disabilities and are currently using an assistive communication/control method, BCI technology might be preferable as compared to their conventional assistive technology that use their remaining muscle control abilities such as eye gaze or facial muscles. This preference, however, would depend highly on the speed, precision of control, reliability, and convenient of using BCI systems. (Wolpaw 2009)

Each individual need to be analysed separately for BCI technology implemented, depending on the patient condition the BCI method used would vary. Some of the BCI methods are useful in certain cases as supposed to other methods. Patient condition might have affected certain part of the brain and functions, for instance, in patients with CNS deficits, control of certain brain signals are impaired and not others. In ALS patients, the motor cortex is damaged but they appear to retain control of signals from some other regions of brains such as sensory-motor cortex. In the case of severe cerebral palsy subcortical damage would impair generation or control of sensory-motor rhythms. Therefore, the signals from these parts of the brain in patients with above mentioned diseases are non-existent or not reliable. All these information and patient history should be analysed and assessed prior to implementing a right BCI method. Furthermore, the practicality of BCI applications for each individual depends on factors such as steps required for donning and doffing electrodes, accessing BCI application, and user's appearance during operation of BCI system. These factors would greatly affect number and characteristics of people adapting BCI system and the extent of usability of the system in their daily lives. (Wolpaw 2009)

Practical applications of BCIs can vary from very simple to very complex systems. BCI applications can include systems to manage environmental control, orthosis movement control, computer control, speech devices and mobility devices controls such as wheelchairs. These would improve the quality of life for people with disability and would help them to have more productive life and would decrease the chance of depression due to limitations that people face as a result of their disability. (Wolpaw 2009)

More complex BCI systems are the ones used to control motorized wheelchair, robotic arm, neuroprosthesis. Present technology focus on invasive BCI systems development whereas non-invasive EEG based BCIs would make such control a possibility. The practicality of a BCI system will depend on its reliability, accessibility by the specific user, the extent to which it has more advantages over previous methodologies. Great degree of evaluation is required to establish a BCI application's clinical value and practicality. These evaluations consider long-term reliability, long-term usability and beneficial effects such as mood, quality of life, and productivity of an individual. Therefore, it is very important to consider each individual's unique needs, desires and physical ability and social environment. This will help in setting up an application that would suit and match that specific individual. The application would require ongoing assessment and evaluation especially when individual's physical ability and needs are changing. Despite the cost of BCI equipment being moderate, the cost associated with ongoing and expert oversight would be very expensive. As a result there are less people who can adapt BCI system as their assistive technology. In order to have more people benefiting from BCIs, the need for ongoing technical support should be minimized. For BCI as assistive technology to have significant practical impact on improving lives of people with severe disabilities, it must be easy to set up, easy to use, and easy to maintain. (Wolpaw 2009)

Brain-computer interfacing procedures include three main sections which are extracting brain signals, signal processing and interfacing to output device. In the signals processing stage, signals undergo thorough processing including amplification and filtering. Other signal processing steps include feature extraction for emphasizing frequency or spatial content of the data and classification for determining the final output or class of the data. The interfacing stage establishes the necessary connection between the classified results and the final output device. The instrument at the end of the system is thus controlled by the brain signals and could be a neuroprosthesis device or a control unit to vary local parameters in the living environment such as opening or closing doors and switching lights on and off. With regard to signal processing via software, spatial or frequency extractors are the common algorithms used for feature extraction. In the same sense, linear classifiers often provide results of suitable accuracy. Once the controls are distinguished, interfacing these commands to the device of interest will be specific to and depend heavily on the hardware used by the output device (i.e. the wheelchair or communication aid), which is in turn heavily dependent on the purpose of the BCI system.

2.4 Signal Extraction

Brain activities can be detected and recorded using variety of different methodologies. These include methods for recording electrical or magnetic fields i.e electromagnetic measures (such as Event Related Potentials (ERPs) and Event Related Magnetic Fields (ERMFs)), hemodynamic measurement methods such as functional magnetic resonance imaging (fMRI), positron emission tomography (PET), and functional near-infrared (fNIR) imaging; and microelectrode measurement methods (for example, single-unit and local field potential recordings). (Wolpaw 2009)

Electrical fields from brain activity can be recorded at scalp using electroencephalography (EEG), cortical surfaced using electrocorticography (ECoG) or within the brain using local field potentials (LFPs) or neuronal action potentials (spikes). These recording locations are displayed in following figure.

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Figure 8: Different sites of recording electrophysiological signals used for BCI purposes. EEG recorded on the scalp. ECoG recorded on the cortical surface. Neuronal action potentials or LFPs recorded inside of the cortex. (Wolpaw 2009)

Electromagnetic measures (ERPs and ERMFs) have high temporal resolution and low spatial resolution. Hemodynamic measures (fMRI, PET and fNIR) on the other hand have low temporal resolution and high spatial resolution. Under optimal conditions, ERPs have a temporal resolution of 1ms or better but hemodynamic measures due to their slow nature of response have resolution limited to several seconds. Hemodynamic measures' spatial resolution range is in millimetre. In the ERP technique, spatial resolution range is not defined due to the fact that there are infinitely internal ERP generators that result in the ERP response and there is no specific margin of error for ERP localizations. In ERP technique the voltage recorded from a single electrode at any moment is the contribution of many different ERP generator sources, that each reflects a different neuro-congnitive process. (Luke 2005)

ERPs are much less expensive than any of other techniques mentioned. The costs associated to the lab, accessories required, techniques or devices for recording and analysing the data are minimal for ERPs. These costs have dropped down due to the decreased cost and availability of computing equipment. In hemodynamic measurement techniques, PET is exorbitantly expensive, due to the need for radioactive isotopes with short half-lives and medical personnel. FMRI is fairly expensive too and its major cost is associated to the personnel and amortization of the machine. In techniques for microelectrode measures, single-unit recordings are also very expensive due to the cost of surgery and high level of expertise required for recording electrophysiological data. (Luke 2005)

Brain signal extraction methods vary in the location where electrodes are placed or recording sites. Microelectrode measures are performed by inserting an electrode into the brain. Those methods where the electrodes need to be inserted into the tissue/scalp are invasive methods whereas the methods such as placing electrodes on the skin are non-invasive methods. The advantages and disadvantages of different recording sites will be explained below.

PET method does not use any invasive probe but there will be a limitation as to how much a subject can be exposed to radiation, therefore, there would be only a small number of test/trials that each subject can go through. In contrast, other extraction methods such as ERP or fMRI do not have any restriction in regards to how much trails can be run for one subject and how long the subject can be exposed to those environments. (Luke 2005)

- **Invasive**

Invasive method of brain signal extraction started from the realization that thought-relevant brain activity could be clearly detected via a direct contact between an electrode and the brain. Some common types of invasive brain signal extraction are Intracortical recording and Electrocochleography (ECoG). The invasive procedures offer much clearer signals with amplitudes as large as 10mV. These methods are less prone to artefacts and lead to pleasing results. They may also provide more accurate access points for brain-regions of interest. For example in the non-invasive method, it is often difficult to relate an acquired signal to its original source, whereas by placing depth electrodes into the brain, the area of interest related to the specific thought or action under examination can be separately access. There are, on the other hand, several disadvantages related to invasive signal extraction methods. First is the usual complication associated with all invasive procedures. Beside the surgical hurdles there are issues with infection. If electrodes permeate the skull for long periods, an environment for bacterial growth and their access into the body is created. On the other hand, due to the constant flow of blood to the brain, white blood cells carried by the blood which are responsible for the body's immune system continuously cleanse the surroundings of the electrode to help prevent build-up of infection. Another issue with placing foreign objects into the body is scarring as talked about earlier. This could result in the weakening of the signals received by the electrodes. Signal extraction via the invasive approach is further restricted to only a small region of the brain. Thus, different areas of the brain and functionality would not be possible to be studied at the same time.

- **Non-Invasive**

Non-invasive method started after robust signal processing methods revealed that different brain signals attributing to thought were still detectable even after being extracted from regions beyond the skull. There are many techniques used to non-invasively measure thought relating to brain activity. These include functional magnetic resonance imaging, near infrared spectroscopy and magneto-encephalography. Although these techniques may successfully detect and differentiate control thoughts from the brain, the required size and weight associated with their equipment in developing suitable BCI devices for everyday use is beyond consideration. A much more suitable and common method for non-invasive brain signal extraction is the electroencephalogram (EEG). The EEG device is basically composed of a series of scalp electrodes, an amplification unit and recording software. The EEG is an ideal candidate for a brain-controlled wheelchair as it is small, safe, commercially available and comparatively inexpensive and has superior temporal resolution. The method for the placement of scalp electrodes has improved since its conceptualization to the point that today it is simply only required to put on a head-wear with the configured electrodes. An applicable gel may be used to bridge the connection of the electrodes to the scalp, but it is no longer required to shave the head for collecting these signals. The most common type of scalp electrode placement configuration is known as the International Federation 10-20 System which uses anatomical landmarks to standardize electrode placement. The connection between the individual electrodes has three forms, namely bipolar (connection between pairs), mono-polar (individual connections to a reference electrode) and averaging (connection between a single electrode and the average of the rest). The bipolar method offers the advantage of having a high common-mode rejection ratio, minimizing artefacts common to the electrode pair and mainly picking up the differential signal between the two electrodes (Webster & Clark 1998).

The amplitude of the signals in the non-invasive method is considerably low, resulting in small signal-to-noise ratios as compared to invasive procedures. These signals are in the range of 100μV. However, given the immense progress in non-invasive signal processing techniques within the last five years, it is reasonable to say that non-invasive methods may well become the dominating branch of BCI technologies in the near future. There is also recent publication in support of this argument by concluding that there are comparable results between invasive and non-invasive extraction of brain signals (McFarland & Wolpaw 2008). In addition, placement of an electrode array over the entire surface of the head brings about the advantage of collecting signals from all brain regions and not just a single point.

- **Invasive vs. Non-invasive**

Each of the methods mentioned may be beneficial depending on the situation, subject of study and range of applications they can support. However, magnetoencephalography, fMRI, and PET are not currently suited for everyday use due to their intricate technical demands, high expense and/or limited real-time capability.

Intracortical recording or recording within other brain areas can result in highest resolution signals but it requires insertion of multi-electrode arrays within brain tissues. Like any other BCI system, a system based on intracortical recording needs adaptation to consider for the improvements in the user and system's performance. These methods face unresolved problems in accordance to tissue damage and scarring and in achieving long-term recording stability and capabilities in practical applications. There are some studies that indicate that a non-invasive EEG-based BCI system have produced control performance comparable in speed and accuracy to that achievable by intracortical methods. (Wolpaw 2009)

ECoG recording has better topographical resolution and frequency range and they are much less susceptible to contamination by EMG or EOG signals. ECoG encompasses gamma rhythms beside mu and beta rhythms. Gamma rhythms are very small or completely missing in EEG recordings. ECoG can be used in tasks limited to a few square millimetres of cortical surface recording, if the inter-electrodes are appropriately spaced. Using ECoG technique the subjects can be trained to control cursor movement using motor imagery in only few minutes. This speed is much faster than the speed of learning for sensory-motor rhythms of scalp- recorded EEG technique. ECoG has an invasive recording method. Therefore, it requires electrodes arrays to be implanted on the cortical surface. According to literature this method has only been tested on limited people and the implant was there only for a short period i.e. a few days or weeks. (Wolpaw 2009) Besides the risks associated with invasive methods, widespread clinical use of BCI based on ECoG technique requires a fully implanted system to be developed and to be surely confirmed that the system will provide safe and stable recording for years without any need for variation or re-calibration of the implanted system. This method is not feasible to be a clinical BCI adaption testing method for wide community due to its cost, invasiveness, not being flexible or adjustable, and clinical expertise required. Therefore, it would not be a practical technique to use for assessing the patient for the right BCI technique adaptation.

EEG recording is a non-invasive method and easily available. It is not expensive to have these recordings done and it can be a portable system for recording. However it has limited topographical resolution and frequency range and can have noises from electromyography (EMG) signals produced by cranical muscles or from electro-oculographic (EOG), eye muscles activity. (Wolpaw 2009)

Human BCI to date has been based largely on non-invasive EEG-based research. Reports show a few short-term ECoG studies and limited data from few individuals with intra-cortical implants.

Three kinds of EEG-based BCIs have been evaluated which are distinguished by the type of EEG features derived and used as a control signal. (Wolpaw 2009)

2.5 Brain Signals

There are different types of EEG-based BCIs that have been evaluated on people based on literature. Each are distinguished based on their EEG features that they use to derive the person's intent.

- **Brain Waves**

The oscillating property of electrical signals produced by the brain has been studied. Although most of the time the perceived waveforms seem irregular, at certain times, specific patterns with characteristic frequencies may be identified. Each frequency of oscillation is attributed to a particular task or level of consciousness. Generally each of the frequencies that form these waves is between 0.5 to 100Hz (Webster 1997). The four types of brains waves are as following:

Delta waves

Delta waves are slowest but loudest brainwave activity that ranges from 1 to 3 Hz. This brainwave is found during deep, dreamless sleep and sometimes in deepest meditation. This state is when healing and regeneration are stimulated. It can be observed every 2 or 3 seconds as a result of brain disease (Webster 1997)

Theta waves

Theta brainwaves occur when brain activity slows almost to the point of sleep or in deep meditation. Theta brainwaves range from 4 to 8Hz. In this state senses are withdrawn eternal world and focused on signal originating from within. In theta state are dreamlike imagery, intuition are receptiveness to information beyond ones normal conscious awareness. It is also where fears, long-forgotten memories, troubled history and nightmares are stored. Theta waves can also appear in adults due to emotional stress such as frustration and disappointment. (Webster 1997)

Alpha waves

Alpha brain waves range from 9 to 14Hz. Alpha waves are present when one is truly relaxed but not quite in meditation state. This state is when one is resting but awake. (Webster 1997) This state is gateway to deeper states of consciousness. Alpha waves are involved for mental coordination, calmness, alertness, mind/body integration and learning. (Meditations UK n.d.)

Beta waves

Beta brain waves have activity of 15 to 30 Hz. Beta waves are present when one is in normal wakeful and alert state. This brain activity is associated with mental activity such as thinking, conscious problem solving and active attention directed towards cognitive tasks and the outside world. (Meditations UK n.d.) Beta brain activity is divided into three groups, low beta can be thought of as a fast idle or musing, medium beta as high engagement and high beta is highly complex thought, high anxiety or excitement.

Gamma waves

The fastest brain waves are Gamma waves. This occurs when information is processed simultaneously from different brains areas. During this state information is passed rapidly within the brain areas. However the mind needs to be quiet in order to access that information. Gamma was found to be highly active when the person is in states of universal love, altruism and higher virtues. (Meditations UK n.d.) Gamma rhythms modulate perception and consciousness and they disappear during anaesthesia. (Brainworks n.d.)

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Figure 9: Brain Waves (Episode 4 - Brain Waves 2014)

2.6 Brain Signal Features

Other than sinusoidal waves of different frequencies, there are features that emanate from the higher brain areas including slow cortical potentials, evoked potentials, movement-related potentials and event-related potential. Brain Computer Interfacing (BCI) techniques are categorized based on these EEG brain activity patterns. (Amiri, et al. 2013) Control signals from imagined movements and actions (sensory-motor rhythms) as well as mental tasks such as relaxation, multiplication and geometric rotation would also result in features in brain signals that may be used in BCI (Fitzgibbon 2007). This study focuses on features of EEG brain activity patterns, Event Related Potentials, Steady State Responses and Oddball/P300 responses.

- **Event Related Potential**

Event Related Potentials (ERPs) were originally named as Evoked Potentials (EPs). Evoked Potential (EP) is the electrical potential which is evoked by stimuli as compared to spontaneous EEG rhythms. This term was first used by Herb Vaughan in 1969. According to Vaughan, 1969, the term "evoked potential" is not sufficiently general to apply to all EEG phenomena related to sensory-motor processes, since cerebral processes could be related to voluntary movement and relatively stimulus-independent psychological processes. In addition to stimuli and motor responses sufficiently prominent or distinctive psychological events may serve as time references for averaging. ERP defines a general class of potentials that display stable time relationships to a definable reference event. Most of the research use the term ERP but there are some others that use other terms such as Evoked Response (i.e. Evoked Potential) and Evoked Response Potential (i.e. an accidental miscombination of terms evoked response and event related potential). (Luke 2005)

Evoked potential responses can be classified based on monitoring and measuring electrical activity in certain location of the brain in response to the stimulation of specific sensor nerve pathways. (AnaesthesiaUK 2005)

- **Visual Evoked Potential**

The terms Visually Evoked Potential (VEP), Visually Evoked Response (VER) and Visually Evoked Cortical Potential (VECP) are equivalent. (Creel n.d) They all clinically refer to ERPs elicited by visual stimuli. (Luke 2005) VEP test measures the conduction of the visual pathways from optic nerve, optic chiasm, and optic radiations to the occipital cortex. (Evans, et al 2014) These measurements provide information about functional integrity of visual pathways from retina to visual cortex of brain via optic nerves. Functional integrity of optic pathways is better quantified using VEPs rather than scanning techniques such as magnetic resonance imaging (MRI).

Visual stimuli stimulate both primary visual cortices and secondary areas. VEP recording is from occipital scalp overlying the calcarine fissure. This location is the closest to primary visual cortex. According to the common electrode placement system, i.e. "10-20 International System", mid-occipital electrode location (Oz) is on the midline which is located 10% of the distance between inion and nasion above inion. There are also two other locations where the lateral occipital electrodes located with a similar distance off the midline (i.e. O1 and O2).

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Figure 10: Electrode Locations over Occipital Cortex based on 10-20 International System (Creel n.d)

Common techniques used to present visual stimuli are strobe, Light Emitting Diodes (LEDs), transient and steady state pattern reversal and pattern onset/offset. For VEP, the most common stimulus used is a checker board pattern that reverses every half a second. Since pattern reversal has more inter-subject VEP reliability as compared with flash or pattern onset stimuli, it is a preferred stimulus. (Creel n.d)

Visual sensory response in VEP result will include different components. C1 is the first major visual ERP component which is the largest wave at posterior midline electrode sites. C1 can have varying polarity so it is never labelled as positive (P) or Negative (N). C1 wave appears to be generated in primary visual cortex (V1) area. V1 area is folded into the calcarine fissure in human brains. The part of V1 which is located on the upper bank of the fissure codes the lower visual field and the part that is located on the lower bank codes the upper visual field. Therefore, the recorded voltage on the scalp above calcarine fissure is positive for stimuli in the lower visual filed and negative for stimuli in the upper visual field. For the stimuli on the horizontal midline, the C1 wave is small or positive, causing it to add up with the P1 wave and result into a single wave. As a result, unless upper field stimuli are used to generate a negative C1 wave a distinct C1 wave would not usually be observed. The C1 wave typically starts 40-60 ms after stimulus presented and peaks around the 80-100 ms post stimulus. C1 wave is highly affected by stimulus parameters such as contrast and spatial frequency. (Luke 2005)

Followed by C1 wave, is P1 wave which is the largest at lateral occipital areas and typically onsets 60-90 ms after stimulus with a the peak being between 100 – 130 ms. Due to the overlap between the P1 and C1, it is usually difficult to assess P1 onset time. The onset of P1 is also dependant on the stimulus contrast. Based on literature, there are at least thirty distinct visual areas that are activated within the first 100 ms of visual stimulus' onset and many of those areas would contribute to C1 and P1 characteristics and latencies. P1 is sensitive to variations in stimulus parameters such as direction of spatial attention and subject's state of arousal. (Luke 2005)

After P1 waver, the N1 wave appears which includes several visual subcomponents. The earliest subcomponent peaks occurs between 100-150 ms post-stimulus on scalp's anterior site. Moreover, there are at least two posterior N1 components which peak 150 -200 ms post-stimulus which arise from parietal cortex and lateral occipital cortex. Studies have shown that these components are influenced by spatial attention. It is also found that lateral occipital N1 subcomponent appears larger when subject is performing discrimination tasks as compared to detection tasks. (Luke 2005)

Followed by N1 is a distinct P2 wave at anterior and central scalp sites. This component is larger when stimuli with target features are present and this effect is enhanced when the targets appear infrequently. This feature of P2 wave is similar to P3 wave. However, this effect in anterior P2 occurs for simple stimulus but P3 effects can occur for arbitrarily complex target categories. On the posterior site though, P2 is difficult to find due to overlapping N1, N2 and P3 waves. (Luke 2005)

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Figure 11: Normal Visual Evoked Potential Features (AnaesthesiaUK 2005)

N170 is a response to stimuli with face perception rather than any other visual stimuli. It elicits a negative potential at lateral occipital electrode sites and especially over the right hemisphere which peaks at approximately 170ms. N170 is found to be later and/or larger for inverted faces as compared to upright faces. However, for non-face stimuli with an inversion effect, N170 response elicits if the subject has extensive experience viewing the stimuli in and upright orientation. (Luke 2005)

Abnormalities in the visual pathways or cortex can affect VEP. For example the amplitude of the wave peaks is reduced when optic pathways are compressed due to hydrocephalus or tumour for instance. Moreover, speed of VEP wave peaks is slowed due to myelin plaques common in multiple sclerosis. (Creel n.d)

VEP performance varies when different simulator generating devices used. Visual evoked potentials elicited by reversal of checkerboard pattern (square), red light-emitting diodes (LEDs) were compared with black and white pattern on a TV. Longer latencies were observed in responses elicited by LED stimulation while amplitudes of various components were differently altered. Moreover, the frequency of abnormal responses among the patients was higher with LED stimulation than with TV stimulation, but the highest diagnostic yield was obtained when both methods were combined. (Andersson & Siden 1994)

- **Auditory Evoked Potential**

The event related potentials elicited in the first 10 ms post auditory stimuli is called brainstem evoked responses (BERs) or Auditory Brainstem Responses (ABRs). These peaks arise from various stages along the brainstem auditory pathways. Therefore, BERs is a very useful technique in order to assess one's auditory pathology. (Luke 2005)

Followed by BERs are the auditory sensory responses starting from the Middle Latency Auditory Evoked Potential (MAEP), which are the component responses between 10 and 50 ms. The mid-latency components arise from medial geniculate nucleus and the primary auditory cortex. (Luke S, 2005) These potentials reflect activities in thalamal-cortical region and auditory cortex when involving in listening, including primary listening skills (such as recognition, discrimination, and figure-ground) and non-primary skills (i.e. selective attention, auditory sequence and audio-visual integration). (Romero et al. 2012)

MAEP is used as the most promising objective tests for examining alterations in central auditory nervous systems (CANS). MAEP consist of waves that occur in between 10 to 50 milliseconds after initial auditory stimulus. Na, Pa, Pb and Nb are positive (P) and negative (N) peak waves during MAEP. Pa is the wave most frequently used in diagnosis, due to its amplitude being visualized easily as compared to brainstem evoked response component, V. In MAEP, the first wave is Na with latency of 12 to 15ms and then Pa with latency of 25ms followed by Nb and Pb.

Na pathway is constant therefore, deflection analysis of Na is very important. (Romero et al. 2012)

MAEPs are not dependant on subject's response therefore; it has the clinically acceptable accuracy and objectivity to be used to study auditory processing disorder. The latency and amplitude in the response is analyzed to study auditory pathway dysfunctions. Decrease in intensity of stimuli provokes an increase in latency and decrease in amplitude of the response. (Romero et al. 2012)

Following mid-latency components are auditory P1 wave. P1 wave is the largest response at frontocentral electrodes sites. Auditory N1 wave includes several distinct subcomponents like the visual N1 wave. One the subcomponents are a frontocentral component with a peak around 75 ms. This subcomponent is generated in auditory cortex on the dorsal surface of the temporal lobes. A vertex-maximum potential with a peak around 100 ms is another subcomponent of visual N1 wave. A more laterally distributed component with a peak around 150 ms is also a subcomponent of visual N1 wave, which is generated in the superior temporal gyrus. N1 wave is sensitive to attention and N1 latency can be influenced by attention. (Luke 2005)

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Figure 12: Auditory Evoked Responses including Auditory Brainstem Response, Middle Latency Response, and Late Latency Response (Lamoré 2009)

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Table 1: Expected Latencies of the Middle Latency Responses (MLR) in Auditory Evoked Response (Lamoré 2009)

The responses elicited by a Somatosensory stimulus begins with an ERP component called N10 which reflects action potentials rather than postsynaptic potentials, arising from peripheral nerves. Following this is a set of subcomponents which peaks in 10 to 20 ms range and a set of short and medium latency cortical components with peaks in 20 to 100 ms. N1 wave is then observed in 150ms approximately and is followed by P2 wave with peak at 200 ms. N1 and P2 peaks are sometimes called together as vertex potential. (Luke 2005)

Repetitive non-target stimuli are found to elicit N2 deflection. Studies show that there are clearly different components in the N2 time range. If the other stimuli which are called deviants are presented in a repetitive train, amplitude in N2 latency range is found to be larger. If deviants are task irrelevant then mismatch negativity (sometimes is called N2a) is also elicited. However, visual mismatches do not seem to produce these automatic MMN responses. If the deviants are task-related then a later N2 effect called N2b is also observed. N2b is larger for less frequent targets and is thought as a sign for stimulus categorization process. (Luke 2005) Both visual and auditory deviants, if task-related, produce an N2b component but this effect is largest over central sites for auditory stimuli and over posterior sites for visual stimuli.

In the visual case, deviance is often studied spatially rather than temporally. This will help to compare the ERP waveform elicited by simultaneous array of homogeneous items to the ERP waveform elicited by a simultaneous array that contains several identical items plus one deviant item. This will identify the three N2 components. The first component is a bilateral, anterior response that is elicited even when the deviant is not a target. This however is not as automatic the MMN and the subject is supposed to be looking for deviant targets of some sort. Following the first response is two posterior N2 subcomponents that are present only if the deviant item is a target. One of these components is N2b which is bilateral and probability sensitive. The second one of those components is N2pc, where 'pc' represent 'posterior contralateral', noting the fact that this component is observed over posterior electrode sites contralateral to the location of the target. The N2pc is not probability sensitive and it reflects the focusing of spatial attention onto the target location. (Luke 2005) A contralateral negativity is also elicited during visual working memory tasks but it has a more parietally focused scalp distribution and appears to reflect some aspect of working memory maintenance.

- **Language-Related ERP Components**

Language-Related ERP has a component called N400. N400 is elicited as a response to violations of semantic expectancies. For example, when a sentence is presented on a monitor as following "While I was visiting my home town, I had lunch with several old shirts"; a large N400 will be observed. N400 activity would have been little if the past sentence was ended with a world "friends" rather than "shirts". Moreover, a large N400 response is elicited with observing/hearing an irrelevant pair of words for example, "tire ... sugar" as compared to "flour ... sugar" which would result in small N400 response. Furthermore, large N400 response will be elicited when hearing/reading infrequently used words such as "monocle" as compared to frequent words such as "milk". Studies found that non-linguistic stimuli would also elicit N400 or N400-like response as long as they are meaningful. For instance, a line drawing that is inconsistent with the semantic context created by a preceding sequence of words or line drawings will elicit an N400 response. (Luke 2005) However, this response could be due to the fact that the subject named the stimuli sub-vocally, thus N400 component is possibly reflecting language- specific brain activity.

N400 response is a negative-going wave that is mainly largest over central and parietal electrode sites and slightly larger amplitude over right hemisphere as compared to left hemisphere. Although, the response is found to be large in right hemisphere than left one but N400 appears to be generated primarily in the left temporal lobe. This could be explained that the generator dipole near the base of left hemisphere points almost medially rather than straight upward. In split-brain or lesion patients, N400 depends on left-hemisphere activity. The recording from cortical surface in neurosurgery patients has also indicated that N400-like activity occurs in the left anterior medial temporal lobe. (Luke 2005)

Syntactic variations will result in distinctive ERP response which is called P600 response. For example, when a word “to”, is presented in the sentence “The broker persuaded to sell the stock” a large P600 response will be elicited. However, if the word “to”, is used in the sentence “The broker hoped to sell the stock” the P600 response is not as large. This effect can also elicit a left frontal negativity in the range of 300 to 500 ms. The effect may also be elicited when a wh-question (e.g. “what is ...”) is presented as compared to yes-no questions (e.g., “Is the ...”). Words that are primarily syntactic elicit a different ERP activity as compared to the ones with rich semantics. The function words (e.g.,to, with) specially elicit N280 component at left anterior electrode sites, this component however, is absent for content words such as nouns and verbs. Content words on the other hand elicit N400 response which is absent for function words. (Luke 2005)

- **Steady State Responses**

Steady State Visual Evoked Potential (SSVEP)

Steady state visual evoked potential (SSVEP) is a brain response elicited as a result of gazing at repetitive visual stimuli with a constant frequency. (Amiri et al. 2013) Due to these stimuli, EEG activity with corresponding frequencies will be detected over occipital areas. (Allison et al. 2008) This response is a powerful technique for diagnosing visual pathway functions and for brain mapping visual imperfections in patients experiencing cerebral lesions, loss of multifocal sensitivity due to multiple sclerosis disease, and neurological abnormalities in schizophrenia patients and other clinical diagnosis. (Amiri et al. 2013)

Moreover, SSVEP is used as a BCI technique. In a BCI application that requires large number of commands, high recognition reliability, minimum or no training, and self-paced performance, SSVEP is the perfect technique to apply.

The amplitude parameters of responses to different frequencies indicate that SSVEP performance peaks at 15Hz stimuli. SSVEP detection is more accurate for low-frequency stimulations. However, stimulations in the range between 15 to 25Hz are more likely to induce photo epileptic seizures.

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Figure 13: Relationship between visual stimulation and SSVEP-evoked amplitudes. Amplitude of SSVEPs peaks at 15 Hz, forms a lower plateau at 27 Hz, and declines further at frequencies above 30 Hz. (Amiri et al. 2013)

Subject's selective attention modulates SSVEP response. SSVEP directly depends on visual stimulation frequency and the user's attended target is identified by analysing the frequency contents in the induced SSVEP. (Amiri et al. 2013)

SSVEP can be measured in terms of its amplitude and phase. The phase is a joint function of the stimulus frequency and the time delay between stimulus and brain response. The apparent latency of SSVEP is calculated from slope of the function relating phase to stimulation frequency. In control experiments, effect of varying stimulus eccentricity on SSVEP amplitude and latency was measured and it was found that amplitude was dramatically increased with eccentricity reducing, but latency was little affected. This ruled out the possibility that the attention effect on SSVEP latency was an artefact of the subjects' shifting their gaze toward the stimulus. (Russo et al. 2002)

Classical stimulators used to elicit SSVEP are cathode-ray tube (CRT) monitors, Light Emitting Diodes (LEDs), and liquid crystal display (LCD). LEDs arranged in arrays, or flashes stimulators are suitable options for single flickers, since their stimuli's brightness can be controlled. Moreover, when luminance and modulation depth are the same, the fundamental frequency amplitude in the SSVEP evoked by the LED flicker is significantly larger than that evoked by other flickers, whereas there is no significant difference between the SSVEP evoked by the Cathode-Ray Tube (CRT) and the Liquid Crystal Display (LCD) flickers. (Wu et al. 2008)

LEDs may also be attractive alternatives to LCD screens, especially for high-frequency stimuli, since LCD screens usually have low refresh rates (60–70 Hz). On the other hand, LCD and CRT screens provide more options in terms of stimulus shape, and also they are more convenient for generating more complex stimuli, such as checkerboard stimuli. CRT refreshing rates can be high (>200 Hz), but SSVEP amplitude drops for high refresh rates. (Vialatte et al. 2010)

Therefore, the selection of stimulator mainly depends on the complexity of the BCI system, although other parameters such as frequency can also influence this selection. (Wu et al. 2008) For example:

- For low complexity BCI (less than 10 commands), LCD screens are optimal, as they induce less eye-tiredness than CRT screens.
- For medium complexity BCI (10–20 commands), LCD or CRT screens are optimal
- For high complexity BCI (more than 20 commands), LED are to be preferred: provided that they have a short rising and descending time, they outperform LCD or CRT stimulators. (Vialatte et al. 2010)

Visual methods for BCI system have one major drawback which is the requirement for voluntary gaze control. Patients experiencing locked-in syndrome, lose volitional control of their eye. Patients in late stages of amyotrophic lateral sclerosis (ALS) lose their subtle vibrating movements of their eye balls and even lose the ability to lift the eyelid. In this stage somatosensory system however, would still be functional. In order to avoid the limitations due to eye muscle control loss other modalities may be used for generating a steady state evoked potential or response such as auditory or tactile. (Müller-Putz et al. 2006)

Audio Steady State Response (ASSR)

Auditory steady-state responses (ASSRs) elicited by selective attention to a specific sound source as an EEG based BCI paradigm. ASSR is a brain electrical response elicited when one is hearing periodic amplitude modulated sinusoidal tones or click sound trains. ASSR generally shows increased spectral density around the modulation frequency of the sound stream. The optimal modulation frequency has been reported as values ranging from 30 Hz to 50 Hz, peaking around 40 Hz. (Kim et al. 2011)

Kim's study (2011) demonstrated the possibility of materializing a totally vision-free BCI system using online ASSR-based BCI system. This would be an alternative system to BCIs with visual stimuli for people with severe disability resulted in lack of vision or eye movement required to perceived visual stimuli, especially when the stimuli change rapidly. (Wolpaw 2009)

Steady State Somatosensory or Tactile Evoked Potential (SSSEP)

Vibrating stimuli on, for example, a finger tip elicit SSSEP. Literature suggests that attending to a vibration on a finger would enlarge the amplitude of the frequency coded SSSEP as compared to the frequency of vibration at non attended finger. SSSEP amplitude augmentation suggests an enhancement of neural responses to spatially discrete flutter vibration when being attended. (Giabbiconi et al., 2004) SSSEP can be recorded from electrodes over fronto-central locations of the scalp. The side of the scalp activated is contalateral to the stimulated hand. (Victor & Mast 1991)

- **Mismatch negativity (MMN)**

Mismatch negativity (MMN) is eliminated when subject is presented with a repetitive train of identical stimuli with occasional mismatching stimuli. This will elicit a negative-going wave with a peak typically between 160 and 220 ms and is largest at central midline scalp sites. There are other components that are sensitive to mismatches if they are task-relevant. However, the MMN is elicited even when the subjects are not using the stimulus stream for a task. For example, MMN can be eliminated for stimuli presented in one ear when the subject is attending very strongly on completion of sequence of stimuli in the other ear. The MMN is an automatic process that compares the incoming stimuli to a sensory memory trace of preceding stimuli. (Luke 2005)

- **P300 Response**

P300 is a major peak and the mostly used component of an ERP. (Amiri et al. 2013) Auditory, visual, or somatosensory stimuli presented infrequently while interspersed with frequent or routine stimuli result in a positive peak about 300ms after stimulus which is called P300 or P3 response. (Bashashati et al. 2007) This is a response to task-related stimuli in a series of task-irrelevant stimuli.

P300 response is typically recorded from electrodes shown in following picture based on 10-20 system. (Amiri et al. 2013) largest amplitudes for P300 responses are at frontal and centroparietal (Fz, Pz) recordings. The amplitude difference between target and rare/frequent non-target was significant at centroparietal cortex (Pz). (Klostermann et al. 2006)

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Figure 14: Electrode Locations typically used for P300 (Amiri et al. 2013)

The ERP components in the P3 wave range are the frontal maximal P3a component and a parietally maximal P3b component. P3a and P3b are both elicited by unpredictable, infrequent stimuli. For example, a shift in tone pitch or intensity for audio stimuli can result in P3 wave but P3b would be present only when the shift is task-related. P3b elicits also when the target stimulus is awaited for or in some sense expected. When most of the researches, including this study, refer to P3, or P300 component they mean P3b component. Frontal P3 component only presents when the stimulus is unexpected and surprising. Moreover, some studies has shown that when an unexpected task –irrelevant stimulus is presented within an attended train of stimuli a frontal P3 like component will be elicited but it is not clear if that relates to the P3a component. (Luke 2005)

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Figure 15: P300 BCI. A matrix of possible selections displayed on a screen. Once the selection desired by the user appears a large P300 Potential is detected from Electrode Pz over the Scalp. (Wolpaw 2009)

There are factors that influence P3 amplitude and latency. P3 amplitude is larger when target probability is smaller. It is not the overall probability that only affect the P3 amplitude but also, the local probability would have influence on P3 wave characteristics. When a target is presented after large number of non-target presentation, the P3 amplitude is then larger.

Furthermore, it is the probability of the task-defined stimulus that influences P3 wave performance not the probability of any stimulus. For instance, if an experiment is designed to press button when a male name is presented in a sequence of male and female names with all individual males and females names occurring only once, the portion of males names occurring as compared to female's names is the factor that influence P3 amplitude. Moreover, in an experiment where letter E occurring 10 percent of the times and non-targets are presented randomly from rest of alphabetic letters, although the probability of present the target is four times more than each of other non-targets but there would be a very lager P3 wave elicited when letter E is presented. (Luke 2005)

When a subject devotes more effort to a task, P3 amplitude is larger. Therefore, P3 can be used as a measure of resource allocation. P3 is smaller when a subject is uncertain of the stimulus presented being target or non-target. Therefore, for larger amplitude in a P3 response in complicated tasks, it is important to encourage the subject to devote more effort to the task. However, if the subject is not clear enough about the tasks, this would decrease amplitude of subject's P3 response. (Luke 2005) Therefore, a combination of probability, uncertainty and resource allocation would influence P3 amplitude.

P3 wave latency depends on the time required to categorize the stimuli but it is not dependant on the time required to select and execute a response once a stimulus has been categorized. For example, the P3 response latency is the same for when a subject is required to press a button with left hand when a left sign is presented with when a subject is required to make left hand response with the same sign being present. In the cases where the stimuli are degraded perceptually, P3 latency is delayed. (Luke 2005) Therefore, P3 latency may be used to determine an experiment's degree of manipulation required for processes leading up to categorization of stimulus or selection and execution responses.

P300-based BCI focuses on P300 component of brain signal in an event-related potential. P300 is a brain reaction to an attended stimulus which appears in EEG about 300 ms after stimulus is presented. The stimulus for P300 BCI could be visual, audio and/or tactile. However the visual stimulus has been the most commonly practices stimuli for P300 BCI to date. A matrix including number, letters and/or signs can be set up which has each column and row highlighted. P300 feature will be activated when the column and row which contains the desired number/letter or sign is highlighted. (Wolpaw 2009)

BCI system can determine the user's intent by detection P300 potentials. This method can be used to control operation of a simple word-processing device which gives the user a way of communication at a rate of several words per minute. (Wolpaw 2009) This performance can be enhanced using different signal analysis.

- **Slow Cortical Potential**

SCPs are slow, non-movement potential variations that are generated by the subject. They are elicited from cortical areas and last from 300ms up to several seconds. (Bashashati et al. 2007) SCPs have voltage changes in negative and positive shifts ranges. In normal brain function, negative SCPs are associated with movement and other cortical activated functions and positive SCPs reflect cortical disfacilitation or inhibition. With appropriate training subject can learn to voluntarily produce positive and negative shifts. SCP can be used to perform basic word-processing and some other simple control tasks like accessing internet. (Wolpaw 2009)

- **Sensory & Motor Rhythms**

Electrophysiological activities of brain can be categorized based on signal features and/or brain area of activation. Brain waves are also characterized by their region of origin. This is the case for sensory-motor rhythms.

Both mu rhythms (ranging from 8 to 12 Hz) and beta rhythms (ranging from 13 to 30 Hz) originate in sensory-motor cortex. Mu and beta rhythms amplitudes changes are associated with movement, sensation and motor imagery. They are mostly prominent in frontal and parietal locations. A voluntary movement leads to a circumscribed desynchronization in the mu and lower beta bands. This desynchronization is called event-related desynchronization (ERD). ERD begins in the contralateral rolandic region about 2s prior to the onset of a movement. Immediately before execution of movement, ERD becomes bilaterally symmetrical. After a voluntary movement, the power in the brain rhythms increases. This phenomenon is called event-related synchronization (ERS). ERS is dominant over the contralateral sensorimotor area. It reaches a maximum around 600ms after movement offset. Gamma rhythm is a high-frequency rhythm in the EEG. Upon the occurrence of a movement, the amplitude of gamma rhythm increases. Gamma rhythms are usually more prominent in the primary sensory area. (Bashashati et al. 2007)

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Figure 16: Sensory-Motor Rhythm Recorded on the Scalp over Sensory-Motor Cortex. User controls the amplitude of Mu (8-12Hz) or Beta (18-26Hz) Rhythms to Generate Control Signals. Frequency Spectra Illustrates Users Control Signals are focused on Mu-Rhythms Frequency Band. (Wolpaw 2009)

Studies show that subjects can be trained to learn to control mu or beta rhythm amplitudes when there is no physical movement or sensation. This way of control can be used to move a cursor or select letters/icons on a monitor or even to operate a simple orthotic device and a basic word-processing device. Sensory-motor BCI method can support one and multi-dimensional controls such as controlling movements of a neuroprothesis or a robotic arm. (Wolpaw 2009)

- **Movement Related Potential (MRP)**

Movement related potentials (MRPs) are low-frequency potentials. MRPs start about 1-1.5 s before a movement. They have bilateral distribution and present maximum amplitude at the vertex. Close to the movement, they become contralaterally preponderant. (Bashashati et al. 2007)

- **Error Detection**

ERP studies has demonstrated that when a subject response incorrectly to the stimuli, a negative-going deflection at frontal and central electrode sites are observed. This deflection is called error-related negativity (ERN). According to literature a negative feedback to an incorrect response would elicit ERN as well. Moreover, ERN is elicited while a person observing someone else while making an incorrect response. ERN represents the system in brain that monitors response and is sensitive to conflict between intended and actual responses. Recordings from fMRI and single-unit demonstrate that ERNs are elicited in the anterior cingulated cortex. Moreover, dipole source modelling studies also demonstrated that the scalp distribution of ERN is consistent with a generator source in the anterior cingulated. However, it would be difficult to confirm the location of widely distributed component such as the ERN. In a study that involved an intracranial recording, ERN-like response was found in anterior cingulated but this kind of responses was also found at many other cortical sites. (Luke 2009) Therefore, location of ERN generator is not yet confirmed.

- **Response-Related ERP Components**

When a person is instructed to perform a series of occasional manual responses while there is no eliciting stimulus, the response is preceded by a slow negative shift at frontal and central electrode sites which starts about a second prior to the actual response. This effect s called readiness potential (RP).

Readiness potential depends on effectors that were involved for the response, considering the differences between two sides of the body and differences with each side. The readiness potential that is related to lateralization of brain function is called lateralized readiness potential (LRP). LRP can be easily isolated from other ERPs due to it being lateralized based on the limb involved in the response whereas other ERPs are not lateralized. Therefore, it is easy to find the effects of an experimental manipulation on LRP time or amplitude. On the other hand, it is challenging to confirm that an experimental manipulation has affected a P3 component or other overlapping components. This is one of the reasons that make it difficult to determine the cognitive process that P3 component reflects. The LRP is generated in motor cortex. Therefore, LRP preceding a foot movement is opposite to the hand movement one due to the fact that motor cortex representation of the hand is on lateral surface of brain, but the foot representation is on the opposed mesial surface. The LRP performance demonstrates key aspects of response preparation. When LRP is larger at the time stimulus onset, the responses are faster. A response will be triggered inexorably when the amplitude of LRP has passed the threshold level. The RP and LRP components elicited hundreds of milliseconds prior to the response whereas other components are more closely synchronized to the response.
Contingent negative variation (CNV) is a negative deflection between warning stimulus and target stimulus and relates to motor preparation. If the warning and target stimuli period is lengthen, then it is observed that CNV consists of negativity after the warning stimulus and a return to baseline and then preceding the target stimulus is negativity. (Luke 2009) The first negative deflection reflects warning stimulus process and the second negative phase regarded as readiness potential due to the subject preparation for responding to the target.

- **Overview**

Comparing different modalities in various BCI approaches such as P300-based, SCP-based and SSVEP-based BCI, latest one have higher accuracy and information transfer rate. Moreover, there is no need for training or if any required short training times would be sufficient for a SSVEP-based BCI system. Moreover, fewer EEG channels are required in SSVEP method.

Information transfer rate and training time are the two important features of any BCI system. Following figure shows comparison of different BCI approaches in regards to the two important features mentioned. (Amiri et al. 2013)

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Figure 17: Comparison of BCI Techniques in Training Time and Information Transfer Rate (Amiri et al. 2013)

2.7 Signal Processing

A brain signal extracted using any of the methods mentioned above is then recorded and analysed to find the features and brain signal components to derive assistive technology/device commands. Detecting patterns in EEG signals involves three steps: signal pre-processing, feature extraction and classification. In the pre-processing step noise and artefacts are removed and filtered. The most common filtering techniques used in EEG signal filtering are band-pass and notch filters. (Amiri et al. 2013)

Feature extraction is another part in brain signal processing. Feature extraction is measurement of signal's features that encode intent of the user. Brain signal features are parameters such as information about signals' amplitudes or latency of particular evoked potential (such as P300), amplitudes or frequencies of a specific rhythms (such as sensory-motor rhythms), or cortical neuron's firing rate. Signal features may also include more complex measurements such as spectral coherences or weighted combination of any of above mentioned measures. In order to have a reliable and productive system, the feature extraction part need to emphasis on features that for sure encode the intent of the user and the features need to be detected and extracted accurately. (Wolpaw 2009) In the absence of any algorithmic calculations, the raw data contains voltage features. In order to find the feature of the signal in frequency content, the signal is transformed into frequency domain using absolute discrete Fourier transform. Spatial feature extraction considers the difference in electrical activity of each between electrodes based on spatial location of each electrode. For example, in the case of motor-imaginary thoughts, each side of the body is activated by a thought from different hemisphere of the brain. Examples of most common feature extraction methods are Autoregressive Modelling, Common Spatial Patterns, Cepstrum, Shannon Entropy, Fourier Transform, and Wavelet Transform.

The next part in brain signal processing is translation of the extracted features into device control commands. Features like rhythm amplitude or frequency can be translated into commands that control outputs such as cursor movements, item selection, or prosthesis device operation. Algorithms required in order to enable the system to translate these brain features into control commands. Translation algorithms can be as simple as linear equations or as complex as neural networks, support vector machines, and etc. (Wolpaw 2009)

Translation algorithms classify and categorize signals into control commands. The classifier algorithm or method used is dependent on feature extraction method used and control signal that is carried by the dataset. There are different categories of classifiers, namely 'linear classifiers' (LC), 'artificial neural networks' (NN), 'nonlinear Bayesian classifiers' (NBC), 'nearest neighbour classifiers' (NNC) and 'combinations of classifiers' (CC) or 'fusion techniques'. (Lotte et al. 2006) In fusion technique different algorithms are fused together. In fusion technique different feature extraction or classifiers are run parallel results are combined with a particular rule in order to achieve highest accuracy. The list of the different classifiers is lengthy, however, some examples are Linear Discriminant Analysis (LC), Support Vector Machine (LC), Multilayer Perceptron (NN), Bayes Quadratic (NBC), Hidden Markov Model (NBC), K Nearest Neighbours (NNC), Mahalanobis Distance (NNC), Boosting (CC), Voting (CC), and Stacking (CC).

Translation algorithm with a successful performance ensures a full range of device commands selections achieved with the user's range of control of the chosen features. For example, in moving a cursor, user needs to be able to move the cursor to both right and left edges of the screen at a rate that is consistent with user's brain rhythms rapidity and maximum duration. Moreover, the algorithm needs to accommodate for any spontaneous variations in users control range due to diurnal change, fatigue or any other factors. (Wolpaw 2009)

Moreover, based on the type of BCI system, features in feature extraction step and the type of classifier is selected. For example, in P300 BCI with time domain or time frequency domain features, algorithms such as wavelets are appropriate feature extraction method. In the case of SSVEP BCIs frequency features are more appropriate. For P300 BCI classifiers such as Fischer's Linear Discriminant Analysis (FLDA), Bayesian linear Discriminant Analysis (BLDA), Stepwise Linear Discriminant Analysis (SWLDA), and support vector machine (SVM) are utilized. For SSVEP feature extraction and classification, different methods such as the Fast Fourier transform (FFT), the canonical correlation analysis (CCA), stimulus-locked inter-trace correlation (SLIC), and the common special patterns (CSPs) have been mostly used in the literature. (Amiri et al. 2013)

recent study are on investigating ways to improve accuracy, reliability, information transfer rate, and user acceptability of a BCI system by search into different feature extraction methods, classification techniques. There are also methods of combining different types of BCIs in order to improve the system and make a reliable and practical system as an assistive technology. This combining of different BCI techniques is called Hybrid BCI. (Amiri et al. 2013)

The translation algorithm needs to be able to adapt and even encourage user's control improvements. Any improvement in user's range of control need to take advantage by translation algorithm for improving the speed and precision of the control the algorithm should go through ongoing adaptation in order to accommodate for spontaneous or gradual changes in signal features. The ongoing system and user adaptation needs not only off-line analysis but it requires online analysis for finding the effects of the adaptive interactions. (Wolpaw 2009)

The advantage of using simple algorithms such as linear equations is they are easier to go through variations and adaptations. (Wolpaw 2009) More complex algorithms should only be used when both online and offline analysis confirmed that by using that complex algorithm the system no longer will alternate in performance or require recalibration.

2.8 Conclusion

The BCI techniques mostly practiced and studied in literature to date are considered and implemented in this study. Evoked potentials were checked in the patient to confirm patient's brain functions and abilities. Steady state evoked responses and oddball technique are used to find the possibility of implementing a BCI system for a person experiencing severe brain damage over long time. There are considerations to be made while working with a patient. Patient abilities would affect the type of BCI selected in this study. Thorough understanding of the patient's condition and strength would assist in analysing patient's ability and possibility of adapting of a BCI technique as an assistive technology. The main purpose of this study is to find if any of the existing BCI techniques sound promising with the current patient. Further studies and investigations required if the first set of test shows reliable results. BCI technique with a feedback system can be a treatment method for correcting a response such as gaze direction or muscle movement.

3. Experimental Design

The patient's cognitive abilities for the purpose of BCI system is examined by measuring electrical responses of patient's brain to sensory stimuli. Different set of tests are conducted in order to find the feasibility of implementing a BCI system for the patient in this study. The experiments are designed with the intention to lead to a solution pathway for the concern explained in the case scenario, i.e. to find a solution which possibly enables the patient to communicate and a feasible assistive technology that can be used by the patient almost independently. Overall this study aimed to find possibility of implementing a BCI technology as an assistive technology to improve the quality of life for the patients who are experiencing severe disability and impairments in mobility and communication.

Therefore, a complete set of tests which give an indication of a person's cognitive ability and indicates possible implementation of a BCI technique, has been designed and implemented. These set of tests include evoked potential responses, steady state responses and oddball task. Evoked potential test is to measure the times it takes for nerves to respond to stimulation. Steady state response test and oddball test are also studied to examine the feasibility of fitting a BCI system to the patient.

The techniques are considered and the experiments are designed with the patient's ability and condition in mind. For example, in the first set of tests such as evoked potential responses and steady state response, a factor such as attending to stimulus i.e. attention is not taken into account. This study is examining the patient's brain state and cognitive ability which can be used later to be trained and accommodated for controlling an assistive device.

The experiment components are all designed to be run in one session and give an overall understanding of the patient's brain responses and activities during the experiment. Due to mobility impairments of the patient, having only one session for assessing the patient's ability for BCI to minimize the number of times the patient needs to attend the lab, is desirable.

All the techniques and procedures conducted in this study present a preliminary study of the patient's cognitive ability and offer a baseline protocol for assessing and examining any individual's brain cognitive ability and BCI feasibility.

3.1 Apparatus

The system used for recording EEG signals was a 16-channel g.USBamp + g.GAMMAsys (g.tec, Austria) active EEG system; a portable EEG instrument that was manufactured by Guger Technologies. The recording has a resolution of 24 bits for amplitude and a sampling frequency of up to 38.4 Hz per channel. The amplifier can be connected to a computer via the USB port. The amplifier contains 16 analogue to digital converters, which operate simultaneously to achieve the aforementioned sampling rate. After connection to the computer, and as long as a USB software key is inserted into another port of the computer, the bio-signal recording software can be executed and after setting recording preferences, the EEG data can be collected and recorded.

For the purpose of this study, 16 electrodes on the EEG cap based on the International 10-20 System (Sharbrough et al. 1991) are placed over the occipital, temporal, parietal and frontal cortices. This would give an idea of each different cortex's activity during various ranges of stimuli and will cover the areas in which we expected to see activation due to the presented stimuli.

Electrode positions of O1, O2, P7, P3, Pz, P4, P8, T7, C3, C4, T8, F7, F3, Fz, F4, and F8, are selected for electrode locations. The right earlobe was the reference and the right mastoid was grounded. Electrode to skin impedance was measured below 5 kOhms. Data were captured with a sampling rate of 1000Hz for the trial experiment. The sampling rate in the patient session was 1200Hz. The data were filtered with a band pass filter of 0.1Hz to 100 Hz, using a built in analogue filter in g.USBamp.

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Figure 18: EEG Electrode Locations based on 10-20 System. Modified Version (WIKIPEDIA 2014)

The experiment was performed in a sound-attenuated Faraday cage (R.F.I. Industries, Bayswater, Victoria, Australia). The cage was designed to minimize electromagnetic interference from external sources. A ramp was designed by Biomedical Engineering Department at Flinders Medical Centre (FMC) in order for the wheelchair to be driven into the Faraday cage. Moreover, the strobe used in this experiment to present visual stimuli was designed by Flinders Biomedical Engineering Laboratory (FMC, Bedford Park, Australia).

Visual and Audio stimuli were programmed and presented using the Presentation® software from Neurobehavioral Systems Inc., which is a stimulus delivery and experimental control program to run neuroscience experiments and studies. Each experiment was programmed as a separate experimental script in Presentation. Tasks were programmed so that in case of patient's being uncomfortable to continue the experiment can be immediately stopped. Moreover, at the beginning of each task subject was presented with visual feedback related to the experiments.

3.2 Trial Experiment

Prior to a session with the patient, steady state response experiments were designed and tested on a healthy subject. This trial experiment is to help in preparation for when the patient is present. Experimental set-up such as strobe location, feedback to the patient or parents, laboratory situation and conditions are considered during the trial session. This result will indicate the appropriateness of the design and set-up for a subject with impairments. In the trial experiment the two commonly used steady-state sensor evoked potentials i.e. audio and visual, are designed and examined.

The set of tests which are studied for the patient while they were not tested during the trial session were due to the facilities not being available at that stage of study.

- **Trial Subject**

In the trial session subject is a male in 60 to 70 years range of age. The subject is not experiencing any mobility or speech disability. Subject has corrected vision.

- **Trial Method**

Visual Steady-State Evoked Responses

Experiment for Visual Steady State Response starts after 6 seconds delay. Stimuli of 16Hz is presented for 60 seconds and then stops for 6 seconds and is repeated for four times.

Auditory Steady-State Evoked Responses

Stimulus was presented using foam-protected air-tube earphones and with the same intensity on both (left & right) ears. Experiment starts with 6 seconds delay. Auditory stimuli consisted of sinusoidal, amplitude modulated tone with a carrier frequency of 2000Hz. The message frequency was 42Hz. The auditory stimulus was presented for 60 seconds. The stimulus was off for 6 seconds and then this procedure repeated for twelve times.

3.3 Patient Experiment

As discussed in detail in chapter 1, the subject is a patient with brain injury that occurred 20 years ago and resulted in the patient losing all movement and speech control. There are some non-purposeful movements in the distal right hand and foot which are not reproduced on verbal command.

Three modalities, visual, audio and tactile, were considered for this study. Since a clear and reliable response from a patient could not be obtained for the threshold of tactile stimulations, assessment of sensory pathway integrity was clinically performed at Flinders Medical Centre, Neurophysiology Laboratory.

Considering subject has epilepsy, photosensitivity testing has been performed in wide range of frequencies before undertaking any other tests. If the patient is epileptic to any of the frequencies presented, then the operator will withdraw that specific frequency and any that involves visual frequency in that range.

Based on the patient's abilities, two modalities of visual and audio have been examined further in this study. Experiment designs and set-up considerations are discussed in this chapter.

3.4 Procedure

- **Photosensitivity Test**

A strobe is positioned 10 cm away from the subject's eye to ensure that entire visual field is covered. Prior to visual steady-state response analysis, subject's photo sensitivity was examined by going through a set of frequencies starting from 2 Hz then 3Hz and increasing in Fibonacci sequence up to 55Hz. These prime numbers were selected to avoid harmonics and cover range of frequencies that are going to be studied in this case. Each frequency is presented for 10 seconds. There is a delay of 3 seconds between each stimulus presentation.

- **Steady-State Responses**

Visual

Based on literature, largest Visual Steady State Responses (VSSR) has been observed near 10Hz and 16-18Hz frequencies. (Zhu et al. 2010) Therefore, 16 Hz frequencies were selected as the frequency for VSSR tests in this study.

Experiment for Visual Steady State Response starts after 6 seconds delay. Stimuli of 16Hz is presented for 60 seconds and then stops for 6 seconds and is repeated for four times. The overall VSSR experiment is repeated twice. Details of this experimental protocol can be seen in table 1.

Audio

Audio Steady State Response (ASSR) is a brain electrical response elicited when one is hearing periodic amplitude modulated sinusoidal tones or click sound trains. The optimal modulation frequency has been reported as values ranging from 30 Hz to 50 Hz, peaking around 40 Hz. (Kim et al. 2011) Therefore a frequency modulation of 42 Hz was selected for ASSR test.

Stimuli were presented to the subjects using foam-protected air-tube earphones on both ears (left & right) with the same intensity. Experiment starts with 6 seconds delay. Auditory stimuli consisted of sinusoidal, amplitude modulated tone with a carrier frequency of 2000Hz. The message frequency was 42Hz. The auditory stimulus was presented for 60 seconds. The stimulus was off for 6 seconds and then this procedure repeated for four times as illustrated below. Overall, this ASSR protocol was repeated twice.

Tactile

Tactile Steady State Response was originally included in the set of experiment for the patient. However due to limitation in communication with the patient the threshold for tactile stimulus could not be confirmed, the experiment was conducted by Neurophysiology Laboratory Flinders Medical Centre, Bedford Park, South Australia. This modality is not the focus of this study at this stage unless all other modalities fail.

- **Event-Related Potential**

Auditory Evoked Potential

Sound presented to patient through earplugs with 1Hz stimuli on a carrier of 1000Hz. 1Hz stimuli presented for 5 seconds and stopped for a random period of 0.75 to 1 seconds. This procedure was repeated 10 times. Upon completion which took almost 60 seconds there was a 60 seconds rest time. Each trial was repeated for four times.

Visual Evoked Potential

Strobe presents 1 Hz stimuli for 5 seconds with a random delay of 0.75 s to 1second after. This was repeated for 10 times. After completion that lasted for almost 60 seconds there was a 60 seconds rest time. This was repeated for four times.

- **P300**

Visual Oddball

The oddball task includes target and non-target stimuli. The non-target stimulus is illustrated below and the target stimulus is 45 degree rotation of the non-target stimuli with 20% probability. Visual oddball experiment started with 5 seconds count down. The non-target stimulus is presented for 5 seconds with a black screen afterwards for 3 seconds. This procedure is performed at the beginning so that a baseline is formed for the subject to detect the target stimuli easier. The non-target stimuli presentation is repeated at a variable rate of 3 to 10 times before a target stimulus is presented for five seconds. This procedure is repeated 10 times for each trial. There are four trials for visual oddball test.

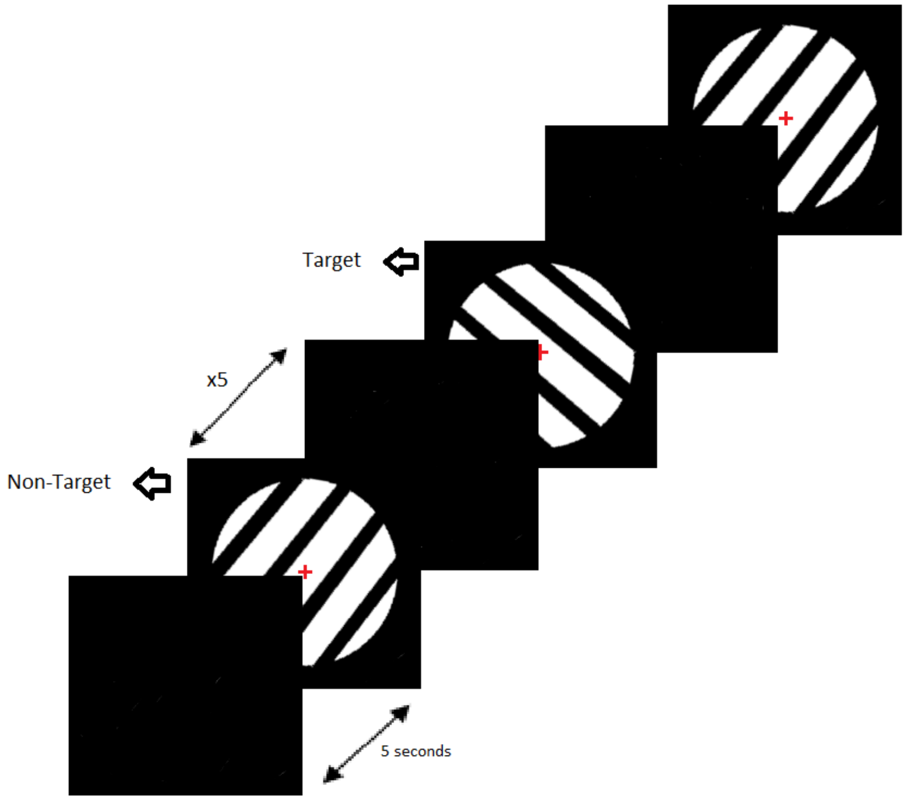

Figure 19: Visual Oddball Task Presentation

Audio Oddball

The non-target stimuli consisted of a tone at 1000 Hz. In the easy difficulty condition, the target stimuli was a tone at 2000 Hz. Tones were presented at 70 dB above hearing threshold and at a stimulation length of 70 ms with rise and fall time of 10 ms included. The non-target stimuli presented for 10 times and then target stimulus was presented and then repeated with variable number of 3 to 12 more non-target stimuli. This was repeated for 10 trials. The presentation of target and non-target stimuli is as illustrated below.

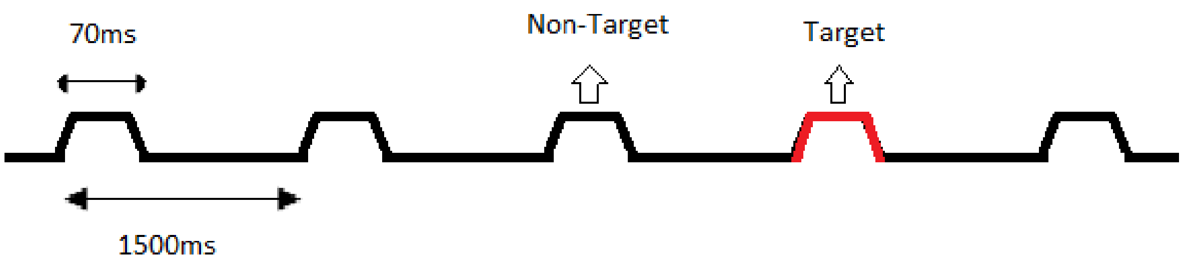

Figure 20: Audio Oddball Task Presentation

Cross-Modal (Audio-Visual) Oddball

Based on Campanella et al. (2010) cross-modal (e.g. audio-visual) stimuli can increase the clinical sensitivity of P3b modulations. Therefore, a cross-modal oddball was designed which included both visual and auditory modalities.

In the Audio-visual oddball task, an audio stimulus was combined to visual stimulus. 1000Hz tone was presented with the non-target visual stimuli illustrated in Visual Oddball section above and 2000Hz tone was presented when target visual stimuli was presented. Each stimulus was presented for 700 ms with randomized 500 to 1000 ms delay until the next stimulus. A non-target stimulus was presented 10 times before target stimulus was presented in order to form a baseline for the subject to detect the target stimulus easier. The target stimulus was presented and then followed by non-target stimulus for a variable number of 3 to 9 times. This was repeated for 10 trials.

3.5 Conclusion

Overall, experiments including all different tasks add up to 41 minutes of recording. This is divided to 5-10 minute-long experiments blocks with 5 minutes of resting in between. The protocol of the experiments is in the following table. The parameters in the protocol are subject to change considering the subject's well being and willingness to continue the tasks.

	Photosensitivity Test	VSSR	Auditory Threshold test	ASSR	VER	AER	VOB	AOB	A/V OB
Stimulus (f)	Strobe at 1 – 2 – 8 – 10 – 15 – 18 – 20 – 25 – 40 – 50 – 60 Hz	16Hz, 50% duty cycle	Patient/Parents judges loudness	Sinusoidal tone at 42 Hz on 2000Hz	Strobe approx. 1/sec	Click approx. 1/sec	Count the stripe (+45') with 20% targets approx.1/sec	Tones 1000 and 2000Hz	Combines VOB and AOB
Stimulus (t)	~10% (f) ms	~31 ms	Tones of 1500 of increasing intensity	n/a	Rise and fall of 10 with 50 ms at max	Rise and fall of 10 with 50 ms at max	Rise and fall of 10 with 50 ms at max	Rise and fall of 10 with 50 ms at max	Rise and fall of 10 with 50 ms at max
Protocol	Pause or stop stimulation during any of the 10 seconds blocks, up to 10 sec in duration. Break of 5 sec	4x60 sec blocks with 5 sec between	Choose level selected by the patient/parents	4x60 sec blocks with 5 sec between	4x60 sec blocks with 5 sec between	4x60 sec blocks with 5 sec between	4x60 sec blocks with 5 sec between Possibly 1 or 2 more blocks if the patient is OK	4x60 sec blocks with 5 sec between. Possibly 1 or 2 more blocks if the patient is OK	4x60 sec blocks with 5 sec between. Possibly 1 or 2 more blocks if the patient is OK

Table 2: Experimental Protocol for Analysing Feasibility of BCI for the Patient Studied

4. Results and Analysis

This chapter assesses the possibility of implementing BCI technology for the patient studied in this research. The results from a normal subject and the patient are both presented in this chapter. The normal subject trial included only steady state responses, whereas during the patient session, the main BCI technologies that are commonly studied in literature had been considered and implemented.

Techniques designed and implemented in this study included visual and auditory evoked potentials, steady-state visual, audio and tactile responses, and visual, audio and audio-visual oddballs. ERPs will give indication of the person's cognitive ability and intact visual and auditory pathways in the brain. The steady-state and oddball tests give indication of feasibility of applying BCI as an assistive technology for control of external devices such as a wheelchair or AAC.

These results were interpreted in a way to provide a clear understanding of the state of the patient's cognitive ability with a view of identifying potential BCI technology for development of an assistive technology that allows the subject to gain independence in control and/or communication.

Signal processing of the results was undertaken offline. MATLAB® software revision R2012b (version 8.0) has been used for the signal processing in this study. Processing techniques such as Fast Fourier Transform had been used for analysing steady-state evoked responses. Averaging technique was used for data in time domain to improve signal to noise ratio, i.e. to increase the strength of signal compared to the noise which obscures the target signal. The epochs containing the signal after each stimulus onset in time domain were averaged.

4.1 Normal Subject:

Steady-state evoked responses were analysed for the subject's data. Audio and visual modalities were studied. Responses to steady state stimuli were averaged for each channel and each modality and presented in this section. The data indicated presence of responses in both modalities.

- **Steady State Responses**

Visual

A visual stimulus of 16Hz was presented to the subject using strobe. The recordings of brain signals after each onset of the stimulus were averaged over 16 trials and analysed in frequency domain using absolute Discrete Fourier Transform.

According to MathWorks (n.d.) the Discrete Fourier Transform (DFT) of a vector x of length *n* is another vector of length *n:*

$$y_{P+1} = \sum_{j=0}^{n-1} \omega^{\mathrm{jp}} \mathrm{x}_{\mathrm{j+1}}$$

Equation 1: Discrete Fourier Transform

In which ω is a complex *n*th root of unity: $\omega = e^{-2\pi i/n}$

As illustrated, the response to visual stimuli was best observed in electrodes positioned over O1, Oz and O2 scalp locations. These electrode positions were located over occipital scalp area. The visual cortex is expected to be activated from visual stimuli according to literature. The electrodes over occipital area are indicators of visual cortex function.

According to these graphs, other than occipital areas, temporal and central electrodes and frontal areas of cortex exhibited a 16Hz response, but with smaller magnitudes compared to the occipital area.

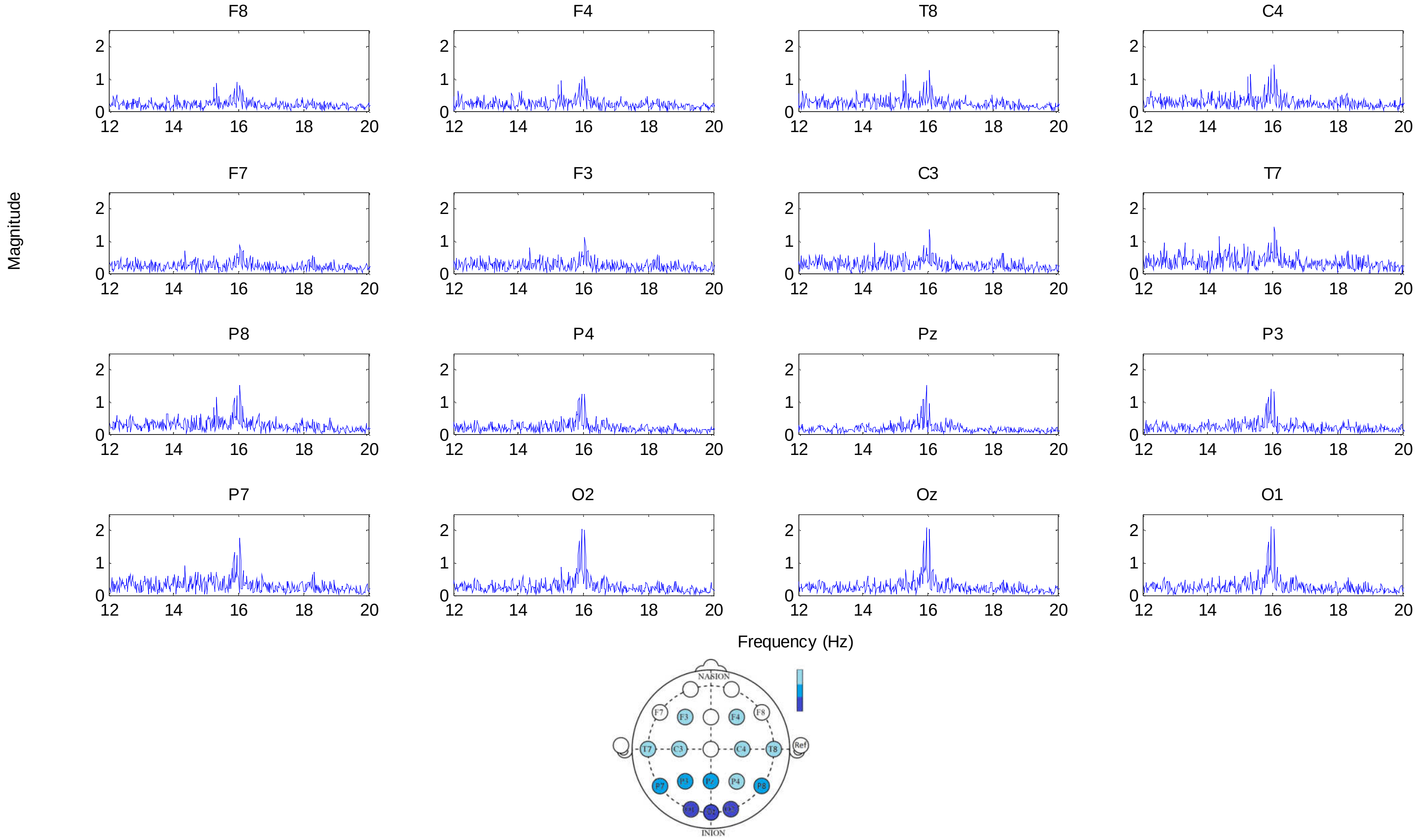

Figure 21: Normal Subject's Visual Steady-State Response to 16Hz Stimuli

Audio

Auditory Steady State Response was tested by presenting 42Hz audio stimuli over carrier of 2000 Hz. The subject's EEG response to 42Hz Steady-State Auditory Response was studied in frequency domain using DFT (Equation 1). Responses for each channel were averaged over 8 trials and presented in the following figure.

According to the plotted graph of auditory response in all 16 channels, audio response with were observed in cortical locations of C4, F3, F4, T8, F8, C3 P8 , F7 and P4. The largest magnitude responses were found in electrode locations C4, F3, F4, and T8 respectively. Therefore, the largest responses were observed over central, frontal and temporal area of cortex.

The temporal lobe is responsible for receiving auditory signals and processing the language. Therefore, electrode locations T7 and T8 which are over temporal lobe are expected to exhibit the 42Hz response Electrode T7 shows a noisy signal which makes it unclear if 42Hz frequency is present in the response. Electrode T8 however, has a clear indication of the presence of a 42Hz response. The front lobe is responsible for conducting functions such as motor activity and integration of muscle activity, speech and thought processes. (UIC The Body n.d.) Electrode locations on the frontal lobe, F3 and F4, have also indicated the presence of a 42Hz response. Electrodes over central cortex or somatosensory cortex, such as C4 and C3, are responsible for sensory-motor integration.

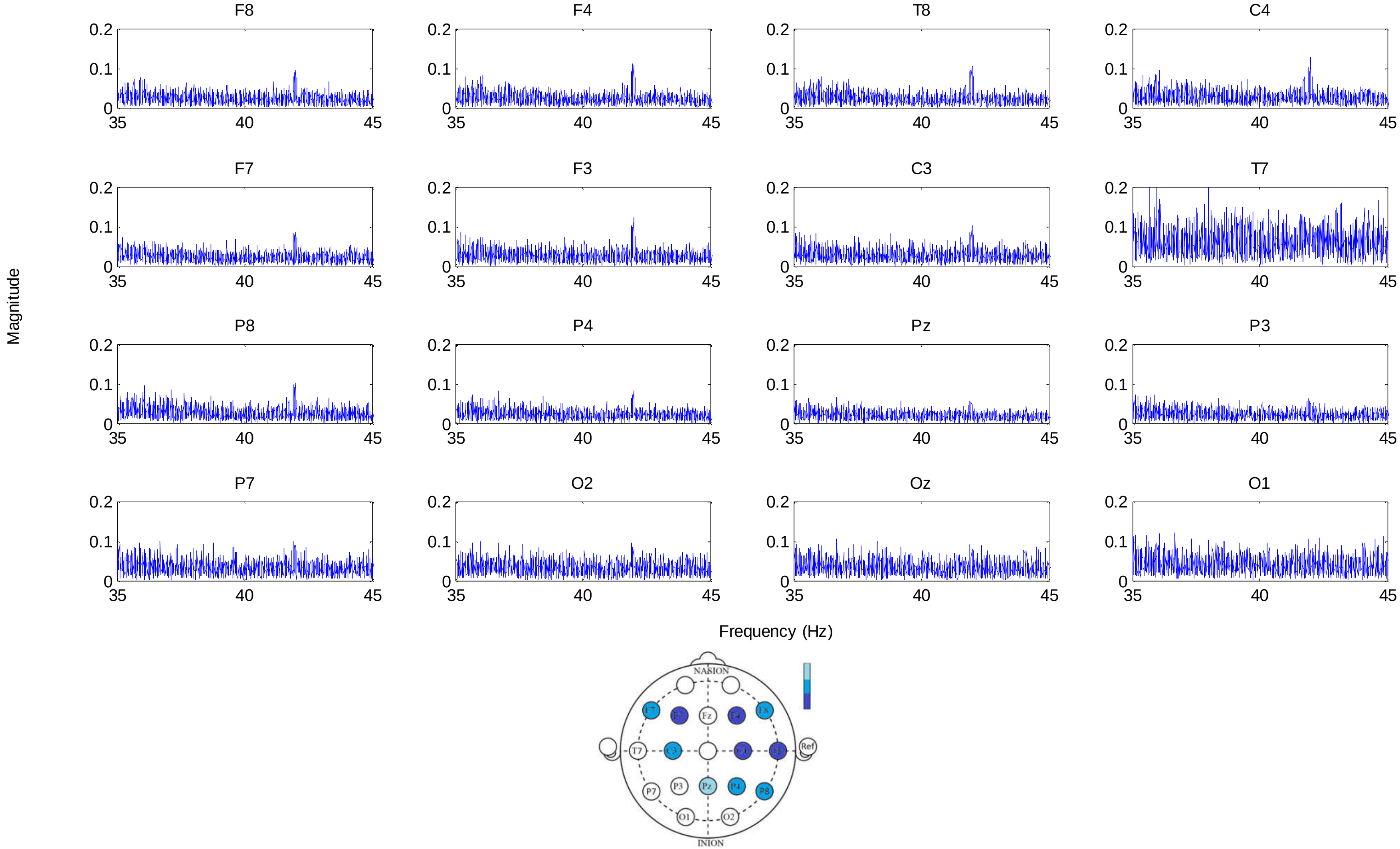

Figure 22: Normal Subject's Auditory Steady State Response to 42Hz Stimuli

4.2 Patient results:

In this study, the following types of BCI principles were studied: ERPs, SSRs and P300. The steady state response tests were performed in three sensory modalities: visual, auditory and tactile. The rest of the tests were performed in two sensory modalities: auditory and visual. In the oddball (P300) test, combination of visual and auditory modalities was checked in order to enhance subject's performance by presenting stimuli in both visual and auditory modalities.

- **Steady State Responses**

Visual

The visual SSR test was designed by flashing 16Hz frequency stimuli. The brain response is recorded and displayed in magnitude versus frequency using DFT (Equation1) in the following graph. According to the brain signal captured and processed 16Hz stimuli response was detected in most of the electrodes recording. This feature was observed in electrodes T8, F4, O2, C4, P7, O1, F3, and C3. Electrode locations T8, F4, O2, and C4 had the more prominent responses respectively. O2, O1 and Oz are electrode locations over the occipital area of cortex. The occipital area is associated with vision and visual cortex. The two main sources of VSSR are the primary visual cortex (V1) and a secondary source in the motion sensitive areas (MT/V5). (De Jong et al. 2010) Therefore, the 16Hz response in O2 and O1 are expected. However, larger responses were detected in temporal area (T8) and Frontal (F4) as illustrated in the graph.

Comparing this result to the result from normal subject indicated that in normal subject the best visual steady state performance was obtained from electrode locations over occipital area, as expected from literature. However, in the patient study visual steady state response was best observed in the temporal area. This could be due to the lesion to that part of brain due to the brain damage. This feature might have been adapted in another part of the brain which could be the temporal area.

Response from electrode location Pz was very noisy and therefore, was not included in the study. This might have been due to the electrode miss-location during the experiment which resulted to electrode not making enough contact with the skin.

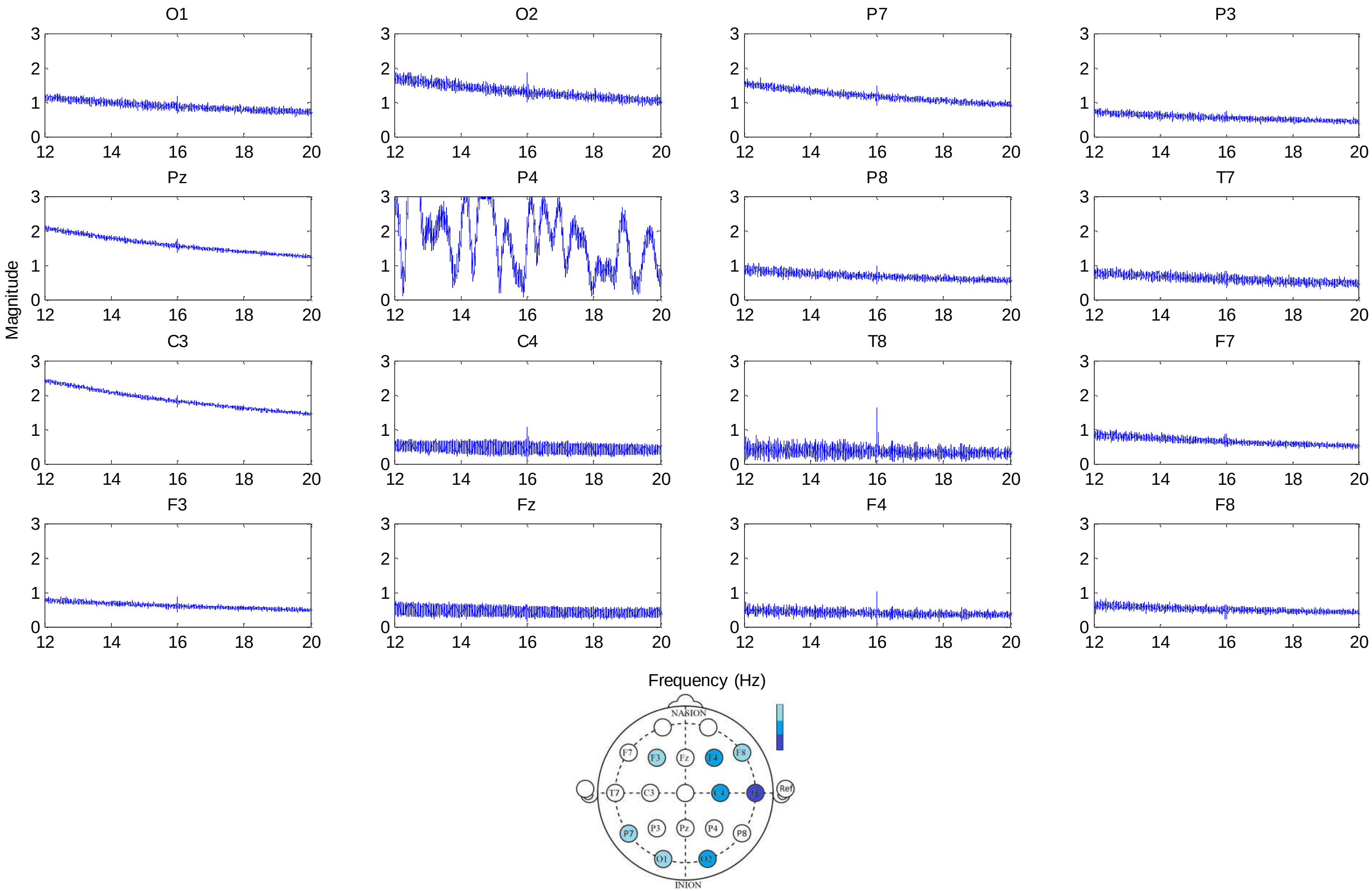

Figure 23: Patient's Visual Steady State Response to 16Hz Stimuli

Audio

Patient's Auditory Steady State Response was checked by presenting 42Hz auditory stimuli on the carrier of 2000 Hz. Patient's response for all 16 channels recorded over the scalp is illustrated in the following figure. The graph presents magnitude of response for each channel averaged over 23 trials. A peak is expected at 42Hz frequency over the temporal scalp location. (UIC The Body n.d.)

Results for Audio Steady State Response were converted to frequency domain using DFT (Equation 1) in order to detect the 42Hz Stimuli presented during the experiment. However, no significant auditory 42 Hz stimulus was observed in the brain recording of any of the electrodes.

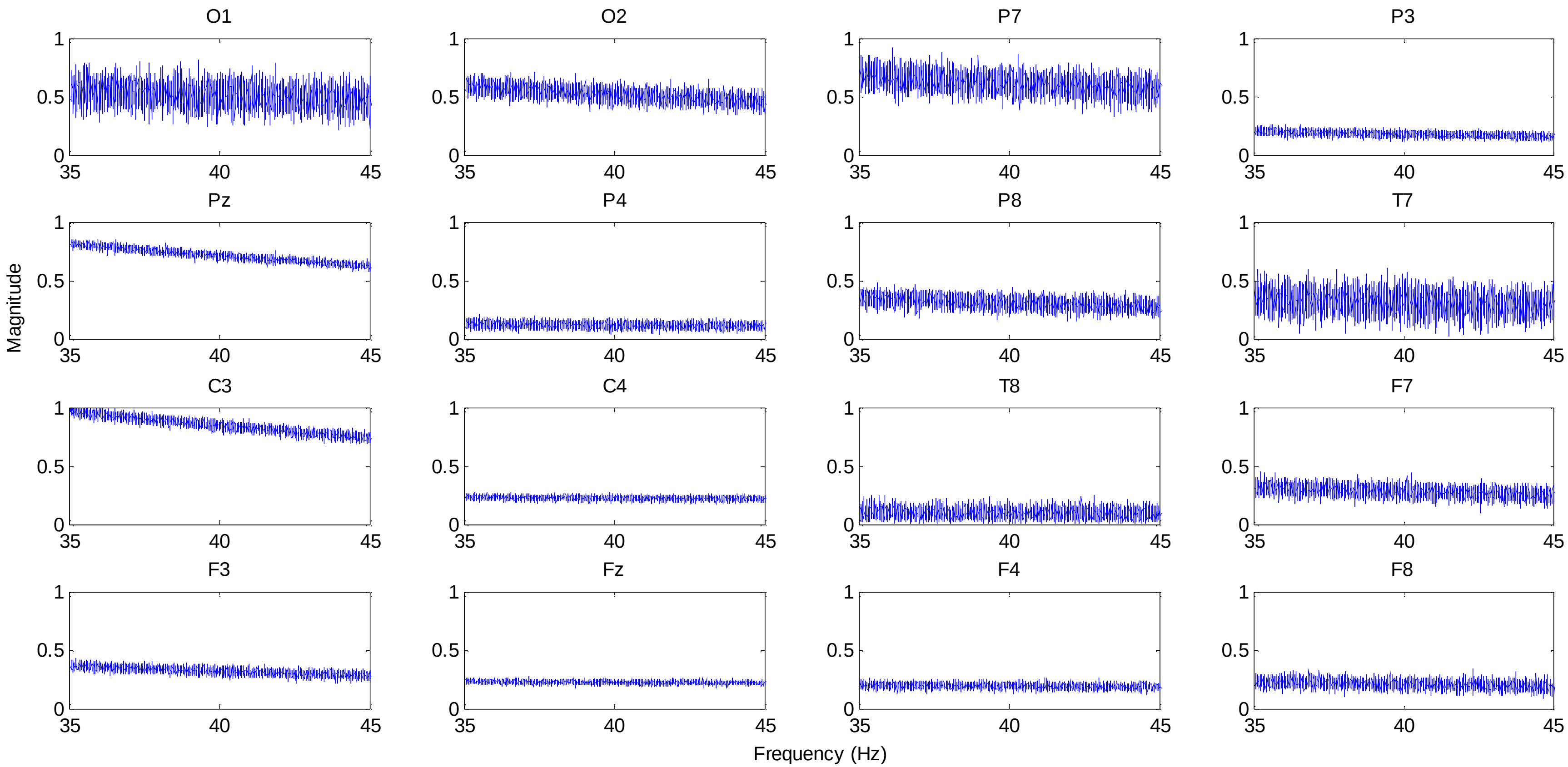

Figure 24: Audio Steady State Response to 42Hz Stimuli

Tactile

Assessment of Sensory Pathway integrity and nerve conduction for Somatosensory Evoked Potential was performed by Neurophysiology Laboratory at Flinders Medical Centre (FMC), Bedford Park, South Australia. Following is the scan of the report provided by the Neurophysiology Laboratory. Results indicated no response in upper and lower limbs.

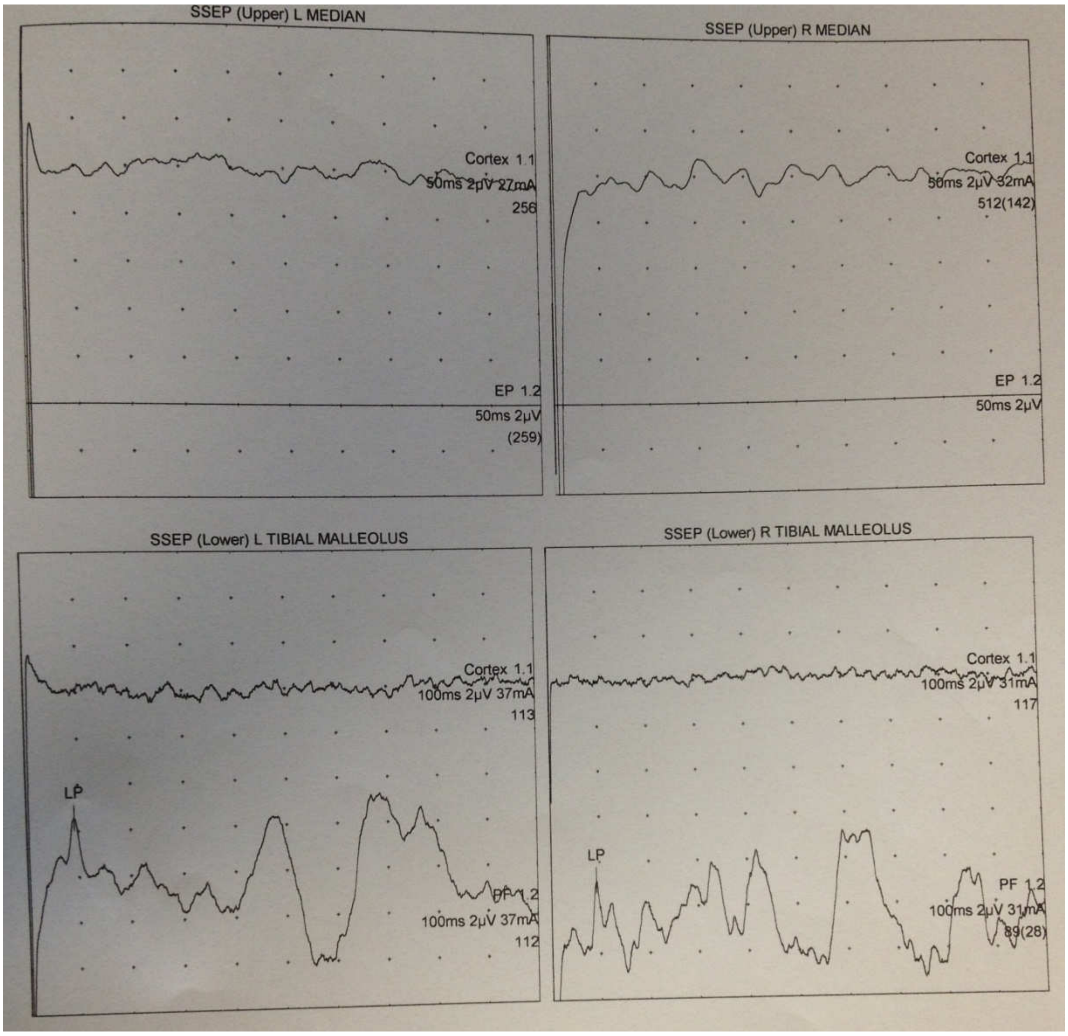

Figure 25: Tactile Steady State Evoked Potential Results Performed by Neurophysiology Laboratory at FMC

According to the report, recordings over upper limbs and the lower limbs were degraded by movement artefact. The cortical recordings however, were of reasonable quality. The upper and lower limb Steady State Evoked Potentials were absent bilaterally in the cortical recordings.

- **Evoked potential Response**

Visual

Visual Evoked Response in the patient was studied by presenting 1 Hz visual stimuli to the patient using strobe. The response was studied in the time domain. A block of 200ms was collected from the time stimulus was presented each time. 240 blocks of collected data were then averaged in order to increase signal to noise ratio and were analysed for each channel. Figure 27 illustrates response of patient's brain to the visual stimuli of 1 Hz presented. The averaged responses to all 16 channels are displayed.

A typical Visual Evoked Response for a normal subject t is expected to show a graph in time domain as shown in Figure 26 A. Negative peaks occur at 75ms and 140 ms with a positive peak in between around 100ms. These responses can be delayed in patients with neurological disorders as illustrated in Figure 26 B. (Thurtell et al. 2009)

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Figure 26: Visual Evoked Potential, P100 Latencies in response to checkerboard stimuli with 100% and 10% contrast (Thurtell et al. 2009)

N75, P100 and N140 were present in electrodes locations over occipital area of brain, i.e. O1 and O2. Occipital lobe associates with visual cortex. Responses over occipital area are expected due to the stimuli being visual and expected to activate visual cortex.

Abnormalities in the visual pathways or cortex can affect VEP. For example the amplitude of the wave peaks is reduced when optic pathways are compressed due to hydrocephalus or tumour for instance. Moreover, speed of VEP wave peaks is slowed due to myelin plaques common in multiple sclerosis. (Creel n.d)

Latency for electrodes over Occipital area i.e. O1 and O2 at which responses to visual stimuli in visual evoked potential test were observed, are displayed in the following table:

Electrode Location	O1	O2
P100 Latency	96	98

Table 3: P100 Latency in Electrodes O1 and O2

The latencies of the Visual Evoked Potential P100 response are within the expected latency. The amplitudes of the responses as illustrated in the following graph are reduced as compared to a VEP response from a healthy subject. This would be an indication of lesion in the patient’s visual pathway.

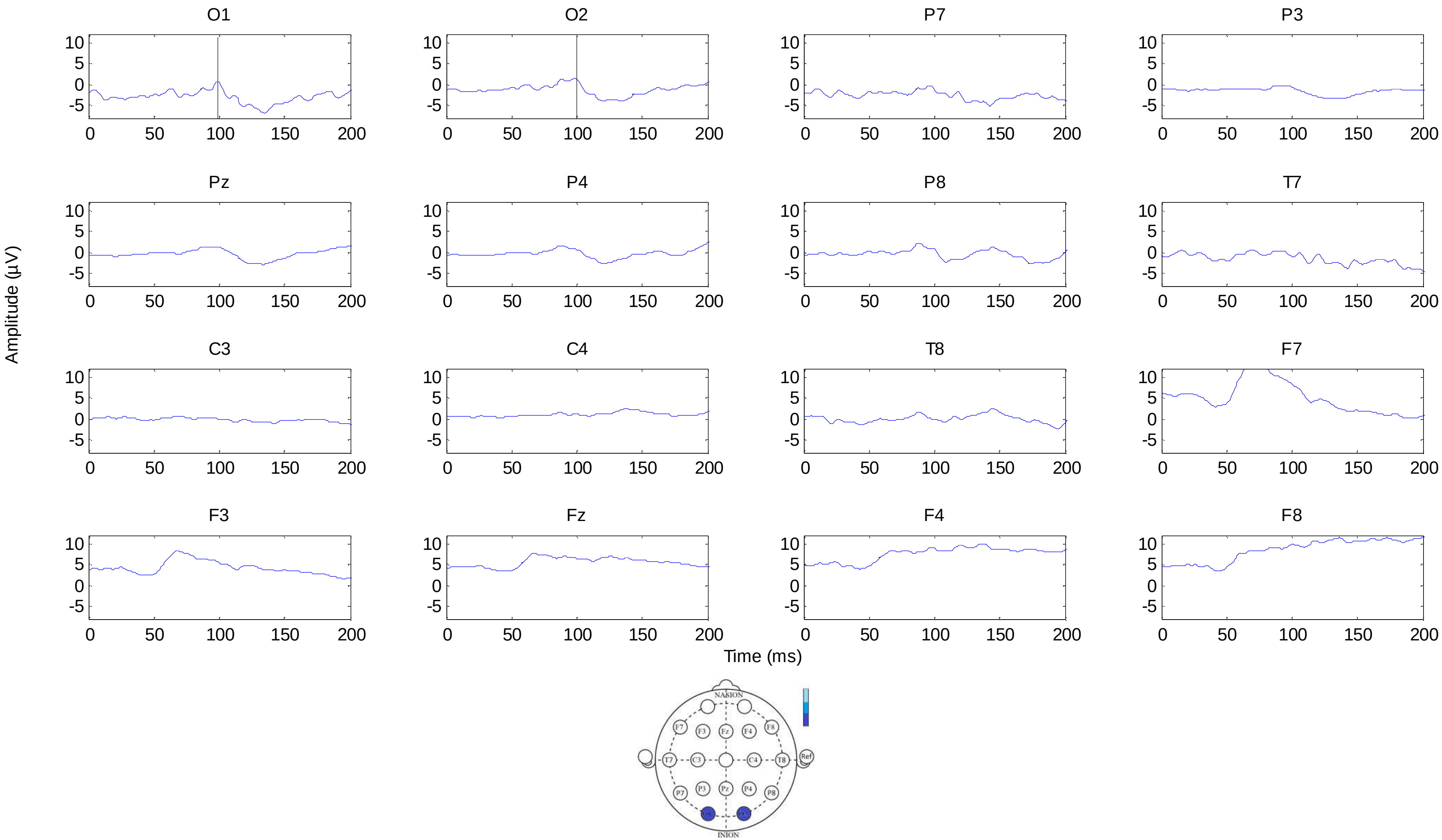

Figure 27: Visual Evoked Potential

Audio

Auditory Evoked Response was studied by presenting audible stimuli through earplugs. The stimuli consisted of 1Hz sinusoidal on a carrier of 1000Hz. Responses from all 16 channels located on the scalp were recorded. The data from 240 trials were averaged for each single channel. The graphs are presented in the following figure. The graph is illustrated in amplitude verses time.

In this study Middle Latency section of Auditory Evoked Response was analysed. This section has the most promising objective test for examining alterations in central auditory nerve systems. The Middle Latency section consists of waves that occur in between 10 to 50 ms after initial auditory stimulus. These potentials reflect activities in thalamal-cortical region and auditory cortex when involving in listening, including primary listening skills (such as recognition, discrimination, and figure-ground) and non-primary skills (i.e. selective attention, auditory sequence and audio-visual integration). Na, Pa, Pb and Nb are positive (P) and negative (N) peak waves during MAEP. Pa is the wave most frequently used in diagnosis, due to its amplitude being visualized easily as compared to brainstem evoked response component, V. In MAEP, the first wave is Na with latency of 12 to 15ms and then Pa with latency of 25ms followed by Nb and Pb. Na pathway is constant therefore, deflection analysis of Na is very important. (Romero et al. 2012) Therefore, features Pa, Nb and Pb (P1) were the components that were studied and investigated in the results obtained from the patient.

Middle Latency Auditory Evoked Potentials are not dependant on subject’s response therefore; it has the clinically acceptable accuracy and objectivity to be used to study auditory processing disorder. The latency and amplitude in the response is analysed to study auditory pathway dysfunctions. Decrease in intensity of stimuli provokes an increase in latency and decrease in amplitude of the response. (Romero et al. 2012)

The expected latencies in a normal subject are included in the following table and any variations from the set values in the range are an indication of auditory system damage or malfunction.

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Table 4: Expected Latencies of the Middle Latency Responses (MLR) in Auditory Evoked Response (Lamoré 2009)

As illustrated in the following graphs, electrode locations P7 and T7 have shown features of Auditory Evoked Potential which are Pa, Nb and P1. Those electrode locations are in or close to temporal and auditory cortex. Therefore, they are expected to elicit a response to auditory stimuli. However, only the left hand side temporal and auditory cortex had the response and this response was not detected in contra-lateral site. The latencies for each of the electrode locations i.e. P7 and T7 are displayed in the following table.

Peak	Pa	Nb	Pb(P1)
Latency - Electrode T7 (ms)	37	44	51
Latency - Electrode P7 (ms)	31	44	55

Table 5: Latencies of Middle Latency Responses in Auditory Evoked Response from Electrodes T7 and P7

Latencies from electrode P7 are within normal expected latencies in Middle Latency Reponses of Auditory Evoked Potential. For electrode P7, the Pb or P100 response has a shorter latency as compared to the normal latency.

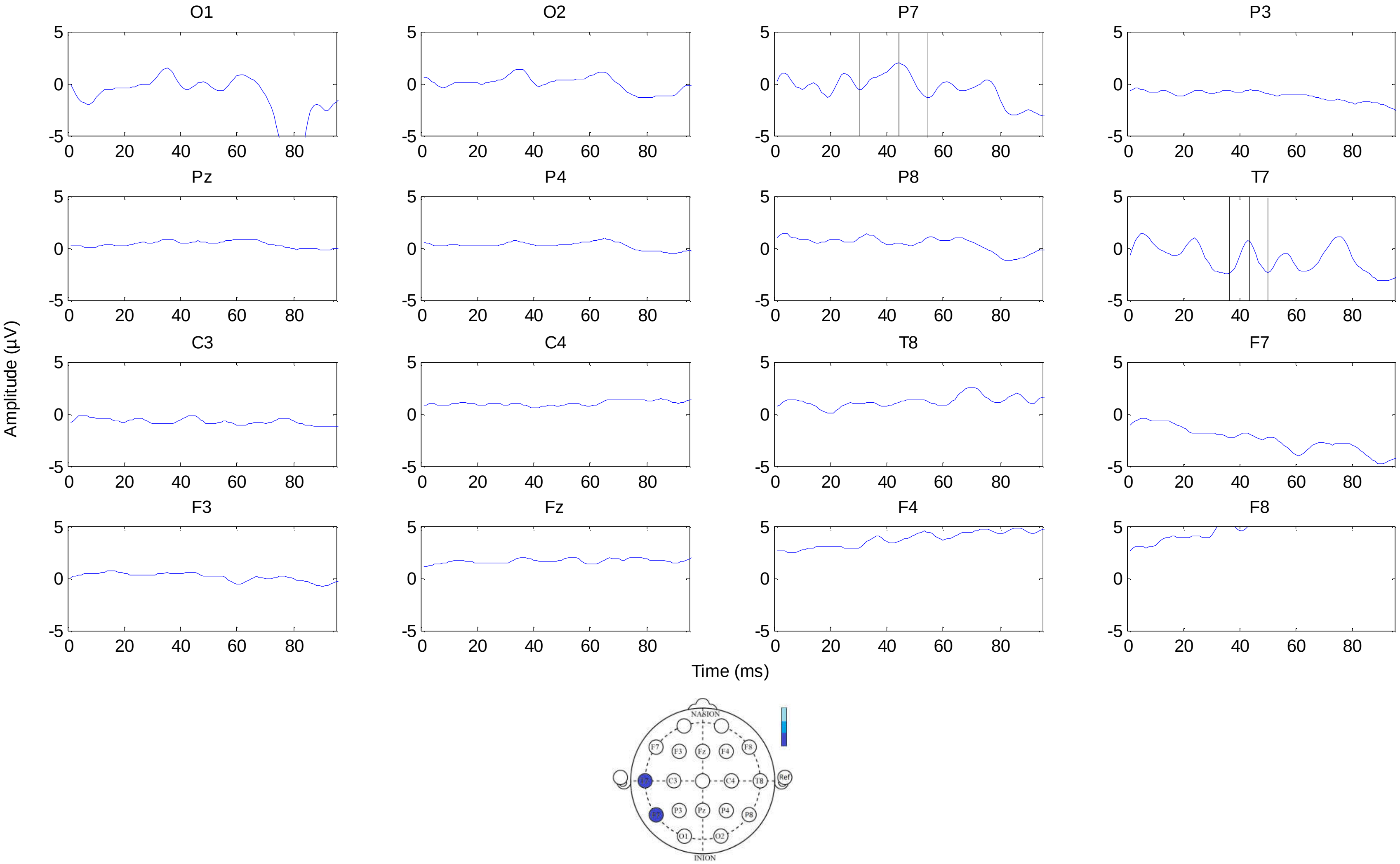

Figure 28: Audio Evoked Potential

- **Odd ball Response**

Oddball test was performed by presenting a target stimulus randomly during other non-target stimuli presented. This test was performed in two modalities of visual and audio. Since combination of the modalities (cross modal) has shown performance improvements in literature (Campanella et al. 2010), in a set of test audio and visual stimuli were presented together in order to take advantage of both visual and audio sensory pathways for an enhanced response.

The graphs plotted brain's responses for each electrode averaged over all the events (i.e. 48 blocks). The blue line in the graphs below illustrate 500 ms of brain response after each target stimulus and the green line indicate the 500ms of brain activity after non-target stimulus was presented.

The largest amplitudes for P300 responses are expected at frontal and centroparietal (Fz, Pz) recordings. The amplitude difference between target and rare/frequent non-target is expected to be significant at centroparietal cortex (Pz). (Klostermann et al. 2006) Classification of P300 signal was found to be significantly improved by augmenting the set of four midline electrodes i.e. Fz, Cz, Pz, Oz and parietal electrodes i.e. P7, P3, P4, and P8. (Hoffmann et al. 2008)

The averaged response of a patient with severe impairment is plotted when there was a target stimulus together with when non-target stimulus was presented. There is suggestion of P300 with small amplitude and greater latency due to neurological disorder. (Güçlütürk et al. 2010)

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Figure 29: Average signals recorded from Cz electrode with and without p300 ERP (Güçlütürk et al. 2010)

Visual

In the visual oddball study, non-target stimulus was a circle with parallel black lines over the circle at 45 degrees. The target stimulus was 45 degrees rotation of the non-target stimulus with 20% probability of occurring. The non-target stimuli presentation was repeated at a variable rate of 3 to 10 times before a target stimulus was presented for five seconds. This procedure was repeated 10 times for each trial. There were four trials for visual oddball test.

The results were presented in time domain and a positive peak after 300 ms of target presentation was expected to be visualized. All 16 channels responses to the stimuli were investigated. In visual oddball study no significant P300 response was detected in any of the channels when compared to the brain response to non-target stimulus.

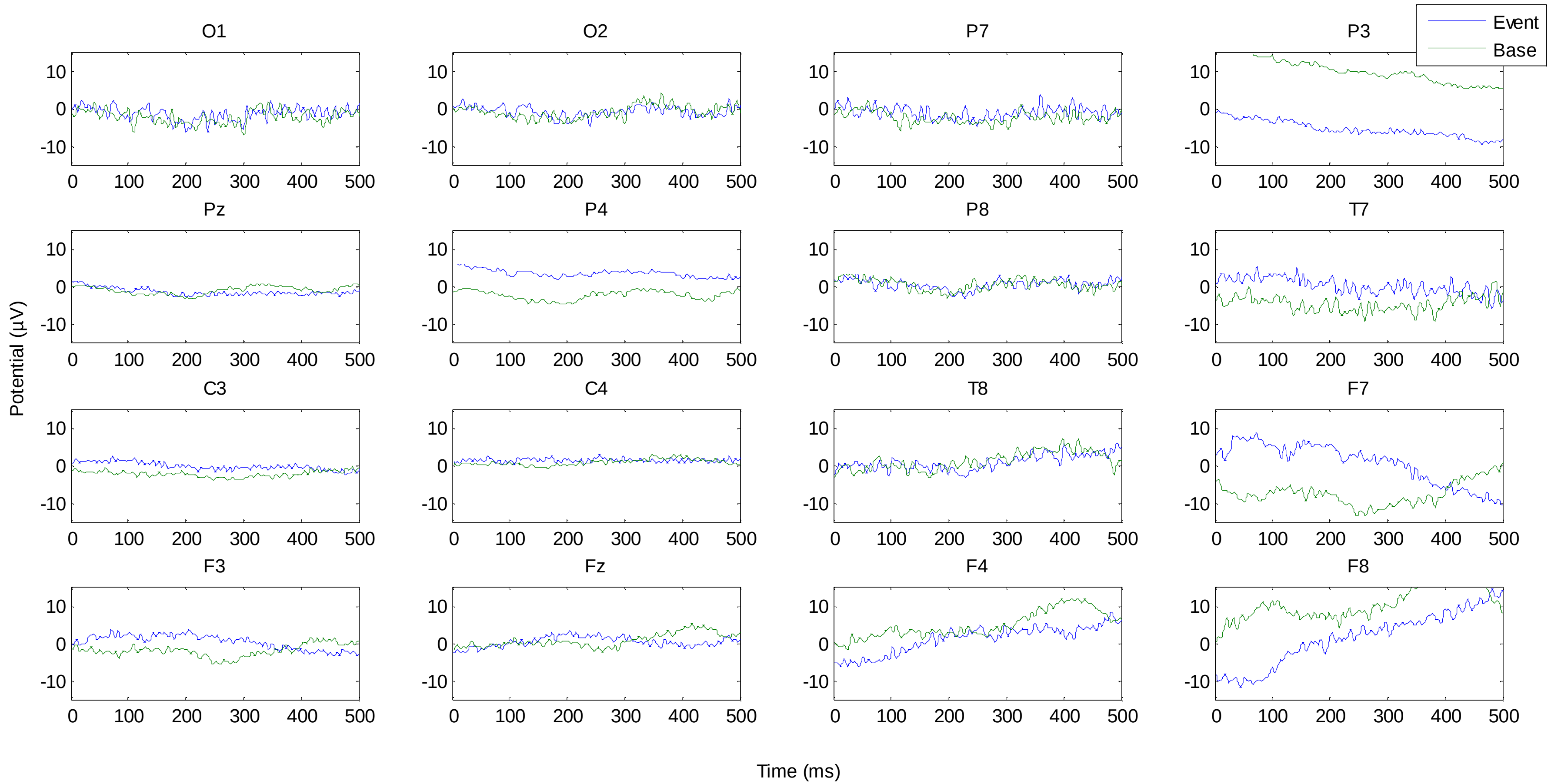

Figure 30: Visual Oddball

Audio

Auditory oddball test was performed by presenting target stimulus after familiarizing the subject with the non-target audio stimulus. The non-target stimulus consisted of a tone at 1000 Hz and the target stimulus was a tone at 2000 Hz. Tones were presented at 70 dB above hearing threshold and at a stimulation length of 70 ms with rise and fall time of 10 ms included. The non-target stimuli presented for 10 times and then target stimulus was presented and then repeated with variable number of 3 to 12 more non-target stimuli. The overall procedure was repeated for 10 trials.

Results from all the trials were averaged for each of 16 channels presented. There is no suggestion of P300 response apparent in the response to auditory oddball target stimuli as compared to brain activity after non-target stimuli.

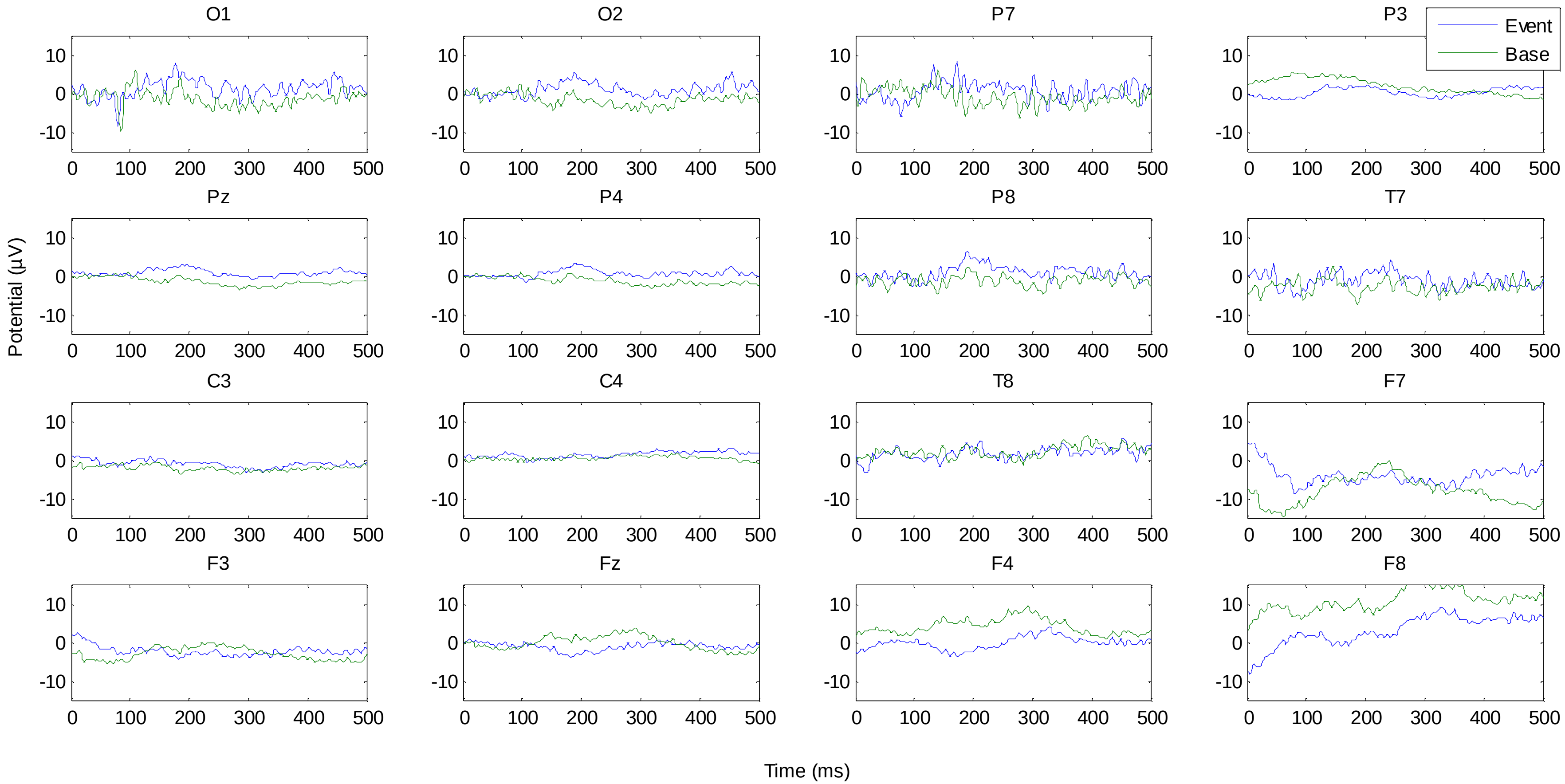

Figure 31: Auditory Oddball

Cross-Modal (Audio-Visual) Oddball

Based on Campanella et al. (2010) cross-modal (e.g. audio-visual) stimuli can increase the clinical sensitivity of P3b modulations. Therefore, this test was designed to take advantage of both visual and auditory abilities in the patient to possibly obtain a reliable and practical signal for the purpose of BCI adaptation.

In the Audio-visual oddball task, an audio stimulus was combined to visual stimulus. 1000Hz tone was presented with the non-target visual stimuli illustrated in Visual Oddball section above and 2000Hz tone was presented when target visual stimuli was presented. Each stimulus was presented for 700 ms with randomized 500 to 1000 ms delay till the next stimulus. A non-target stimulus was presented 10 times before target stimulus was presented in order to form a baseline for the subject to detect the target stimulus easier. The target stimulus was presented and then followed by non-target stimulus for a variable number of 3 to 9 times. This was repeated for 10 trials.

Results from the visual & audio (cross modal) oddball test illustrated that channels O2, T7, P8 and P3 had suggestion of P300 response. However, these responses were not significant as compared to the brain signals prior to the onset of target stimuli. The rises in the signals after the target oddball were in the same format as compared to the brain signal after non-target stimuli presentation.

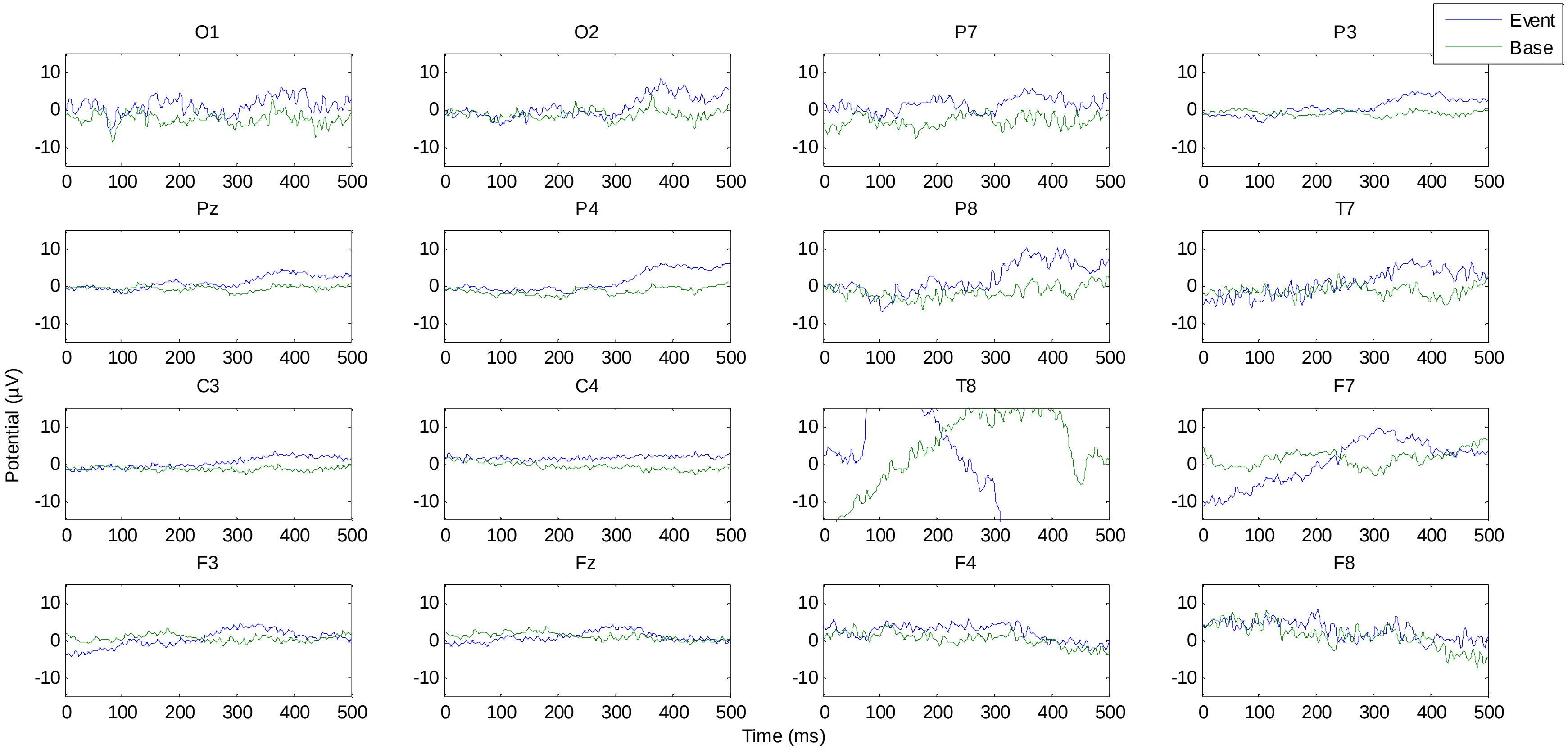

Figure 32: Visual & Auditory Oddball

4.3 Conclusion

Steady state responses in two modalities of visual and audio had been examined on a normal subject. According to the results, the brain response to the correspondent stimuli were observed in the brain areas expected i.e. occipital area activation due to visual stimuli and temporal area activation due to auditory stimuli.

Steady state responses, sensory evoked potentials and oddball test were designed and implemented for the patient in order to study patient's brain activity and abilities in adapting to BCI technology.

Evoked potentials responses both for visual and audio stimuli were present in the signals captured. The brain area associated with each of the sensory modalities, i.e. auditory and visual, were activated correspondent to the type of presented stimuli modality.

Tactile steady state evoke response was also investigated. However, since the pain threshold could not be studied due to lack of any reliable way of communication with the patient, this test was performed by Neurophysiology Laboratory at FMC, Bedford Park, South Australia. Report indicated that the upper and lower limb Steady State Evoked Potentials were absent bilaterally in the cortical recordings.

Steady state visual and audio responses were also studied for the patient. Visual steady state stimuli were present in the results obtained. However, there was no suggestion of auditory response in the obtained results. This disagrees with the information obtained in the clinical study about the auditory system being intact.

Oddball event related responses in modalities of visual and auditory were studied with no suggestion of any response present in the results obtained. Cross modality tests for combination of visual and auditory stimuli were performed for oddball event related response in order to enhance patient's response. The response suggested few P300 responses in few electrodes however; the responses were not significant as compared to the responses where non-target stimulus was presented.

5. Conclusions and Recommendations

This study analyses the possibility of implementing a BCI technique as an assistive device focusing on a patient with brain damage that happened more than twenty years ago. The patient condition was studied in detail. The clinicians, carers and families who have been in contact with the patient reported their examinations and concerns. The abilities of the patient were considered to maximise the explanation of all techniques that might be of use. A preliminary study of patient's brain functions were designed and performed.

The patient in this study presented many challenges. Many of medical practitioners, specialist and technicians were unable to perform the standard tests successfully, leading to misleading results, with some of them expressing doubts as to "whether there was anybody at home". Thus the focus of this project was to establish for a severely "locked in" patient:

1. Awareness of their environment
2. Intent to communicate
3. Possible pathways for BCI

A protocol was introduced to be used as a procedure for analysing a patient with severely impaired cognitive ability and BCI technology adaptability. The procedures included designing and implementing BCI feasibility assessment tests considering patient's abilities and strength. An overall understanding of a person's cognitive status and sensory pathways are achieved through a few of these tests.

During this study, there were special considerations made to make the environment and experiment accessible and convenient for the patient. These considerations also made in order to find the most accurate and reliable understanding of the patient brain functions and adaptability to BCI technology. Modifications made to the laboratory to make the environment accessible for assistive mobility using a wheelchair.

The experiments were designed to consider patient's abilities. For example, the strobe that used for presenting visual stimuli for evoked response and steady state response was placed as close as possible to the patient's eyes in order to maximise the field of view for the patient in case the visual impairments prevent the patient from having enough visual exposure to the stimuli.

Overall, the tests performed suggested presence of visual steady state response, visual and auditory evoked potentials and cross modal combination of visual and audio oddball response to the stimuli presented.

There was a suggestion of 16Hz response in the visual steady state response; however, this compared to the result obtained from a normal subject indicated that the visual cortex did not responses as strong in the patient as compared to the normal subject. In the normal subject result, as suggested by literature, the magnitude of response was highest over occipital area; however, this response had best magnitude over temporal area of cortex for the patient. In the auditory steady state test, no response was present despite reports about patient's auditory system abilities.

Visual oddball and audio oddball results obtained did not suggest the presence of any P300 response when compared to the brain activity for trials non-target stimulus was presented. There was a possible suggestion of P300 response for cross modality oddball; however, the response was not significantly different to the responses of brain when a non-target stimulus was present. Training has shown to improve some patients' performance in BCI adapted technologies. Another study can be designed and implemented for investigating patient's reaction improvement over time and with trainings for the oddball response or attention related tasks.

The analyses of this patient's results illustrated the presence of some brain responses that can be further studied in order to finalize feasibility of implementing BCI technology as an assistive device. Visual steady state response can be studied further in order to find if the patient can reliably select a desired icon or item displayed on a screen. Different set of frequencies can be presented at the corners of a monitor while each corner displays an option to be selected. This would assess if the patient can willingly and reliably select a desired icon.

Sensory steady state responses tested in this study were not dependent on attention, whereas the oddball or P300 response is an attention-related task and would require the subject to focus on the target stimuli. The results obtained from oddball tasks suggested no reliable and promising attention or focusing ability in the patient at the time where the test was performed. This can also be further studied if any test such as the one explained in the previous paragraph is conducted i.e. relating visual steady state response to a task where requires attention for completion.

The results obtained in the study provided an overview of the areas of strength in the patient. Considering the outcome of this study, the patient can be further examined on the areas where there might be a suggestion of a response however weak. As a result of an injury there are areas of brain that have been inactive for years and there are other areas that work more strongly and might have learnt to become a pathways for the paths which have/had vanished due to the brain damage. These areas can be further considered in the next set of tests to study the variation of responses due to different stimuli presentation.

In conclusion, obtained results tend to the positive in all three respects (although there seem to be good times and bad times, and in particular issues with attention and alertness). However, none of the tests were unambiguous and in particular the evidence for existence of usable BCI pathways was marginal. Therefore, this study's conclusion is that there is no substantial likelihood of success to proceed with the subject given current technology and techniques, and that it was unfair to offer false hope in doing so. The patient and carers were advised that they'll be contacted for further study only if there were any promising results leading to BCI technology implementation.

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