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A NOVEL P300 SPELLER WITH MOTOR IMAGERY EMBEDDED IN A
TRADITIONAL ODDBALL PARADIGM

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science
at Virginia Commonwealth University.

By

VAISHNAVI KARNAD

Bachelor of Engineering (Electronics),

Vishwakarma Institute of Technology under University of Pune, India, 2007

Director: DR. OU BAI, PH.D.

Assistant Professor, Department of Biomedical Engineering

Virginia Commonwealth University

Richmond, Virginia

August, 2011

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List of abbreviations

BCI	Brain Computer Interface
EEG	Electroencephalography
ECoG	Electrocorticogram
MEG	Magneto encephalography
PET	Positron Emission Tomography
fMRI	functional magnetic resonance imaging
NIRS	Near Infrared Spectroscopy
ERP	Event Related Potential
EOG	Electrooculography
EMG	Electromyography
fPMP	Frontal Motor Peak Potential
ALS	Amyotrophic Lateral Sclerosis
GA	Generic Algorithm
MLD	Mahalanobis Linear Distance
SWLDA	Stepwise Linear Discriminant Analysis

Abstract

A NOVEL P300 SPELLER WITH MOTOR IMAGERY EMBEDDED IN A
TRADITIONAL ODDBALL PARADIGM

By Vaishnavi Vijay Karnad, M.S.

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science
at Virginia Commonwealth University.

Virginia Commonwealth University, 2011

Major Director: Dr. Ou Bai, PH.D.

Assistant Professor, Department of Biomedical Engineering

A Brain Computer Interface (BCI) provides a means, to control external devices, through the electrical activity of the brain, bypassing motor movement. Recent years have seen an increase in the application of P300 cognitive potential as a control and/or communication signal for the motor restoration in paralyzed patients, such as those in the later stages of ALS (Amyotrophic lateral sclerosis). Although many of these patients are in locked-in state i.e. where motor control is not possible, their cognition is known to remain intact. The P300 speller paradigm explored in this study relying on this cognition represented by the P300 peak potential in EEG (Electroencephalography) signals to restore communication. The conventional visual oddball

paradigms used to elicit P300 potential may not be the optimum choice due to their need for precise eye-gazing, which may be challenge for many patients. This study introduces a novel paradigm with motor imagery as a secondary after-stimulus task in a traditional visual oddball paradigm for P300 Speller application. We observed increased P300 peak amplitude as well as the event-related desynchronization (ERD) associated with motor imagery in six healthy novice subjects. Acceptable detection accuracy was obtained in the five-trial averaged signals from 250 ms to 750 ms after the visual stimulation, whereby the early visual evoked potentials were excluded from classification. As an enhancement, efforts are being made to assess implementation by motor imagery embedded in an auditory oddball paradigm which would minimize the need for eye-gazing further. We can conclude from the results of this study that the proposed paradigm with motor imagery embedded in a traditional visual oddball paradigm might be a feasible option for communication restoration in paralyzed patients.

Chapter 1: Introduction:

1.1. Brain Computer Interfacing:

Hans Berger in 1929 was the first to mention the possibility of ‘reading thoughts’ i.e. using computers to analyze EEG and in that he laid the foundation of a BCI [1]. Grey Walter built the first automatic frequency analyzer and the computer of ‘averaging transients’ with the intention to discriminate covert thoughts and languages in human EEG [2]. He was thus the pioneer in human EEG analysis. The first paper on invasive operant conditioning of cortical spikes in monkeys was published by Fetz [3]. Although the analysis of Brain signals dates way back in history, only the recent developments have made it possible to see the progress envisioned by the pioneers in what is called Brain Computer Interface or Interfacing (BCI) [4]. After initial encouraging efforts in the past 20 years, research continued and over the past 12 years the recognizable field of Brain Computer Interface (BCI) research has begun[5]. Brain Computer Interface (BCI) is thus defined to be any system that translates electrical activity of the brain into signals controlling an external device [6].

The intention of the person to perform an action is inferred from the analysis of brain activity which forms the control element for the external devices thus providing a means of communication and control to the individuals. Invasive BCI are those in which the electrical activity of the brain is recorded from electrodes located inside the brain; on or into the cortical region. Non-invasive are those in which electrode site of recording is outside the brain; scalp electrodes or brain imaging. Various data recording techniques such as scalp EEG (electroencephalography), Electrocorticogram (ECoG), Magnetoencephalography (MEG), positron emission tomography (PET), functional magnetic resonance imaging (fMRI), near infrared spectroscopy (NIRS) and optical imaging have been explored so far

[4, 5]. The different signals used as control signals so far include EEG oscillations (sensorimotor rhythms- SMR and its harmonics), signals obtained from ECoG, event-related potentials (ERP) and slow cortical potentials [4] among many others.

Over the years, BCI has successfully been used to restore communication and control in patients with severe motor disorders such as amyotrophic lateral sclerosis (ALS), brain stem stroke, spinal cord injury, muscular dystrophies and cerebral palsy [5].

1.2. P300 and the speller:

P300 speller is one such BCI application which is targeted towards a communication and is based on P300 event-related potential (ERP). It is a positive peak in scalp EEG recordings seen around 300ms after a less-frequent stimulus is perceived. It is an innate response representing cognitive processing of the stimulus and its context [7]. Farewell and Donchin introduced its use as a control signal for BCI applications in the P300 speller paradigm [8]. This traditional paradigm used a visual oddball stimulus with a character matrix, randomly presented an infrequent target cue and frequent non-target cues. Each cue is a flash of a row or column of the matrix and the subject is asked to count the number of target cues. The larger P300 peaks in response to the attended target cues than unattended non-target cues enable detection of target character without need for motor movement. Several studies have proved P300 to be a robust control signal for P300 speller applications [5, 9, 10] and also in patients with neuromotor issues such as amyotrophic lateral sclerosis (ALS) patients [11-15].

The optimized visual P300 paradigms in recent studies have used varied inter-stimulus intervals, most of which are of 150-350 ms duration. Allison and Pineda used stimulus onset asynchrony (SOA) of 125, 200 and 500 ms and preferred the faster one of those [16]. Serby

preferred 125 ms while Krusienski preferred 100 ms for better performing P300 spellers [9, 17]. All of these were shorter than the P300 peak occurrence instant. A positive peak P100 around 100 ms and negative peak N200 around 200 ms were the other characteristics seen in this duration [18]. The inclusion of these peaks in the working of the speller may require precise eye-gazing. The dependence of P300 on eye-gazing has been proved by Brunner in recent studies [19]. The motor limitations of patients such as those in progressed stage of ALS are to the extent of not being able to gaze at a particular point on the screen effectively [15]. As such, eye-gazing requirement is a major concern for these patients, falling short of its use in this focus group. Nevertheless, cognition is seen to be intact to some extent [15, 20]. A speller less dependent on eye-gazing would thus be more useful. Auditory oddball stimulus as a possible alternative has been reported, however, the performance with auditory modality was much lower than the visual modality [15, 21].

The need to restore communication in patients such as paralyzed or especially locked-in conditions with loss of motor skills has driven the efforts for improvement in the P300 speller paradigm. The proposed paradigm provides an approach introducing motor imagery as the post-stimulus task in a visual oddball paradigm implementation. Characteristics associated with motor imagery in other paradigms have been successfully used in other BCI applications [22-24]. During human voluntary movement, a positive peak in motor potentials or the frontal peak motor potentials (fpMP) was observed just after movement onset [25]. When subjects are asked to perform a brisk motor imagery task following the target cue immediately, the fpMP and P300 response will be overlapped and the resultant positive peak amplitude might be higher than the conventional P300 peak amplitude without motor imagery. Furthermore, motor imagery also provides a strong enhancement in event-

related desynchronization (ERD) as an additional independent feature for P300 response detection. Based on the above two assumption of higher P300 amplitude and independent ERD feature, we hypothesized that the detection accuracy of the P300 response in the proposed P300 paradigm, with motor imagery embedded in it, was higher than the detection with P300 paradigm alone. In this study, the above hypothesis was tested in healthy novice volunteers who performed the P300 copy-spelling tasks under both conventional P300 paradigm and the proposed paradigm with motor imagery embedded, in which the peak P300 amplitude, ERD, and P300 detection accuracy were assess. A longer inter-stimulus interval between successive responses was selected in order to separate and exclude early visual components that may require precise eye-gazing. As a further step towards reducing the dependence on visual stimulus, the next set of pilot data was collected by embedding motor imagery in an auditory oddball stimulus paradigm.

Chapter 2: Paradigm with visual cues:

2.1. Methods:

2.1.1. Setup:

The system set-up consisted of a monitor placed 1 meter away from the subject on which the matrix of alpha-numerals was displayed. The amplifier used was gUSBamp by gTech. Electrode potentials were amplified and recorded onto the desktop connected. Sampling rate was 256 Hz.

A pair of bipolar electrodes recorded EMG from the right forearm with the intention to monitor the hand movement. EOG channels were placed one below the right eye and other above the left eye and used for artifact correction. Eleven ear-referenced channels were placed according to the international 10-20 system as shown in the figure 1 with most of them in the central-parietal areas.

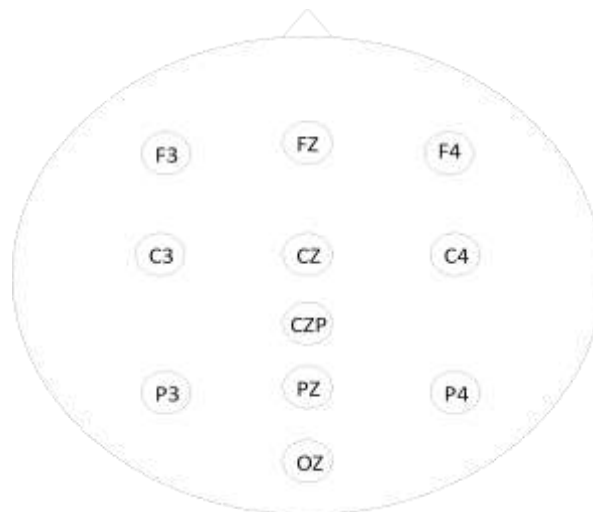


Figure 1: Electrode placement on the scalp. Eleven of the electrodes were placed on the scalp with more channels in the central and parietal areas. The figure shows top view of the head with nose facing the top of this page.

Data was collected from eight (four female and four male) healthy subjects in the age range of 19 - 23 years. None of these subjects had used P300 speller or other kinds of Brain Computer Interface applications prior to this study. All of these were either purely or mixed right-handed according to use of the Edinburgh handedness test [26] completed by them.

2.1.2. Paradigm design and implementation:

The traditional paradigm introduced by Farewell and Donchin as the P300 visual oddball paradigm was modified to incorporate motor imagery to design the novel paradigm for this study. The subject was given the character to be selected making it a copy-spelling mode implementation. A 4x4 matrix of alpha-numerals was displayed on the screen as in a traditional paradigm, shown in figure 2. The subject could see the character to select in the top left corner of the screen. Either a row or a column at a time was randomly intensified for 100 ms with 850 ms inter-stimulus interval as the visual stimulus. Target stimuli were the row and column flashes with the required character in it while the others were non-target. There were 10 flashes per row and column for each character selection. One session consisted of 16 runs selecting 16 characters for a total of 320 target and 960 non-target characters. A relaxation time of 2 minutes was added every 8 runs.

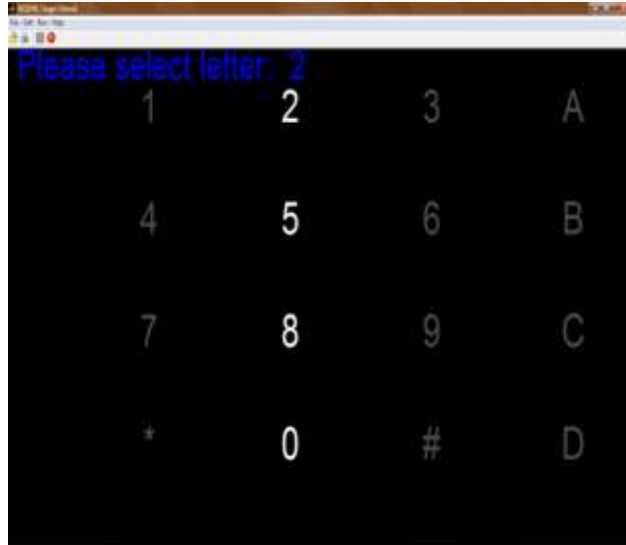


Figure 2: Snapshot of the paradigm with visual stimulus.

A 4x4 matrix of alpha-numerals was displayed on the screen and randomly either a row or a column was flashed as the visual stimulus. In this figure the column 2 was stimulated. Since the required character is a part of the flashed column, it was considered to be a target stimulus.

In the first session, as in a conventional paradigm, the subject was asked to count the number of target stimuli. During the second session, the motor imagery was incorporated by asking the subject to urge or imagine performing one occurrence of a brisk flick of the right wrist immediately on perceiving the stimulus. Both sessions were performed on the same day with a 10 minute break between them. In two of the first four subjects (randomly selected), the order of the task sessions was reversed to observe learning adaptation if any.

Albeit not directly related to the hypothesis, a third session with physical movement executed as a single occurrence of brisk right wrist flick in response to target stimulus was also performed. There was a 10 min break between the second and third sessions performed consecutively on the same day.

2.2. Data Analysis:

All the data was processed off-line using self-developed toolbox BCI2VR (brain computer interface to virtual reality) [27] in MATLAB.

Two (one male and one female) of the eight subjects had unexpected high P300 peak potential even in the non-target stimuli responses in all sessions along with the expected P300 peak in the target stimuli responses. This may have been caused by instructions not being followed accurately, as a result of which, the data from these subjects was excluded from further analysis.

2.2.1. Feature extraction:

Data was separated into epochs of samples in the time window 100 ms before to 850ms from the stimulus onset. Digital link referencing and eye-movement correction using least-mean square method with EOG recording as the reference was carried out. Also baseline correction was performed with baseline defined by data in time range 100 ms before to 100 ms after stimulus onset.

Data from all three sessions- counting, motor imagery and physical movement for each subject was individually analyzed via the techniques mentioned below. Also the grand-average of six-subjects was calculated per task session as mentioned below.

2.2.1.1. Average P300 peak potential: P300 waveform was observed after ensemble averaging of target and non-target epoched trials independently per subject.

2.2.1.2. Time-frequency representation: Continuous wavelet transform with morlet window was performed on the epoched trials. The time window was 50 ms before the stimulus onset to 800 ms after for frequencies in the alpha and beta range. Continuous Wavelet

transform (Morlet window) of the preprocessed data was performed on epochs for time window 50 ms before to 800 ms after the stimulus onset.

2.2.2. Feature classification:

Calculation of classification accuracy was restricted to the channels C3, CZ, C4, CZP, P3, PZ and P4 for data from both sessions counting as well as motor imagery. Time duration was restricted to 250 ms to 750 ms after the stimulus onset. Preprocessed data epochs were averaged such that average of five-trials was taken as one trial.

Feature selection by Generic Algorithm [23] followed by classification of the features by Mahalanobis linear distance classifier was used to find the accuracy for correct classification of the target row and column. All five-trial averaged data points in corresponding channels formed the features. The configuration of the Generic Algorithm was to select the five best features. 10-fold cross-validation of the Mahalanobis linear distance classifier was used to evaluate the feature classification accuracy [28]. The other parameters for the classification were a population size of 42, number of generations of 210, cross-over probability of 0.8, mutation probability of 0.01 and the stall generation of 50.

The classification accuracy of correctly selecting the particular target character was also determined in this study using Stepwise Linear Discriminant Analysis (SWLDA) method implemented similar to earlier reported [17]. Preprocessed data was decimated to 20 Hz. Feature weights were obtained from feature vectors of the training data. These were then used as a model for classification to find the letter selection accuracy of the testing data. In order to implement 10 fold cross-validation, $1/10^{\text{th}}$ of the data set was defined as

training data and remaining 9/10th was the testing data set. The model was formed and testing set was tested 10 times in this manner.

2.3. Results:

2.3.1. Feature extraction:

2.3.1.1. Average P300 peak potential: The figure 3a shows grand-average of all target trials of six-subjects at channels CZ, CZP and PZ in counting and motor imagery task sessions.

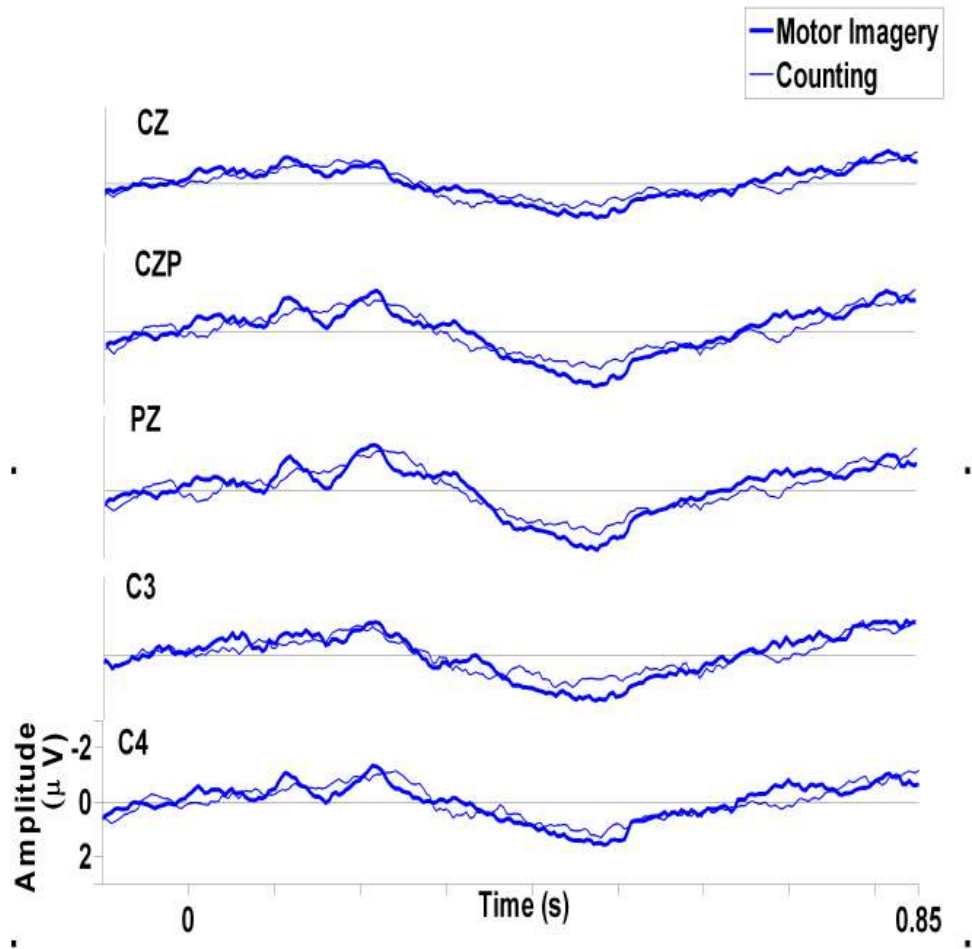


Figure 3a: Grand average P300 peak potentials for counting and motor imagery for visual stimulus.

The grand-average of P300 potentials in six subjects for the counting and motor imagery task conditions with the target stimulation. The positive peak amplitude was higher with the motor imagery task than with the counting task.

As seen in the figure, inclusion of motor imagery as the post-stimulus task proved to have higher P300 peak amplitude compared to conventional counting. The increase was consistent over all channels for the duration between 250 ms to 500 ms from stimulus onset. The maximum increase was seen along midline channels CZ, CZP and PZ, shown in figure 3a. Responses to non-target stimuli had low amplitude P300 peaks for both sessions.

The latency of the peak varied per subject per task but was still within the expected range of 250 – 500 ms from stimulus onset as previously reported[29]. Each subject exhibited longer latency in the motor imagery task session epochs as compared to their respective counting task session.

From the statistical point of view, the averaged P300 peak potentials were also compared using student's paired T-test using MATLAB statistical toolbox. The mean of subject-wise average of target P300 peak amplitude in six subjects for both task sessions were compared at channel CZP. The results reported that the P300 peak amplitude with motor imagery as the post-stimulus task was significantly higher than that with the conventional counting task (probability = 0.013, t-value= 3.14, and df=5, significance level $\alpha = 0.05$).

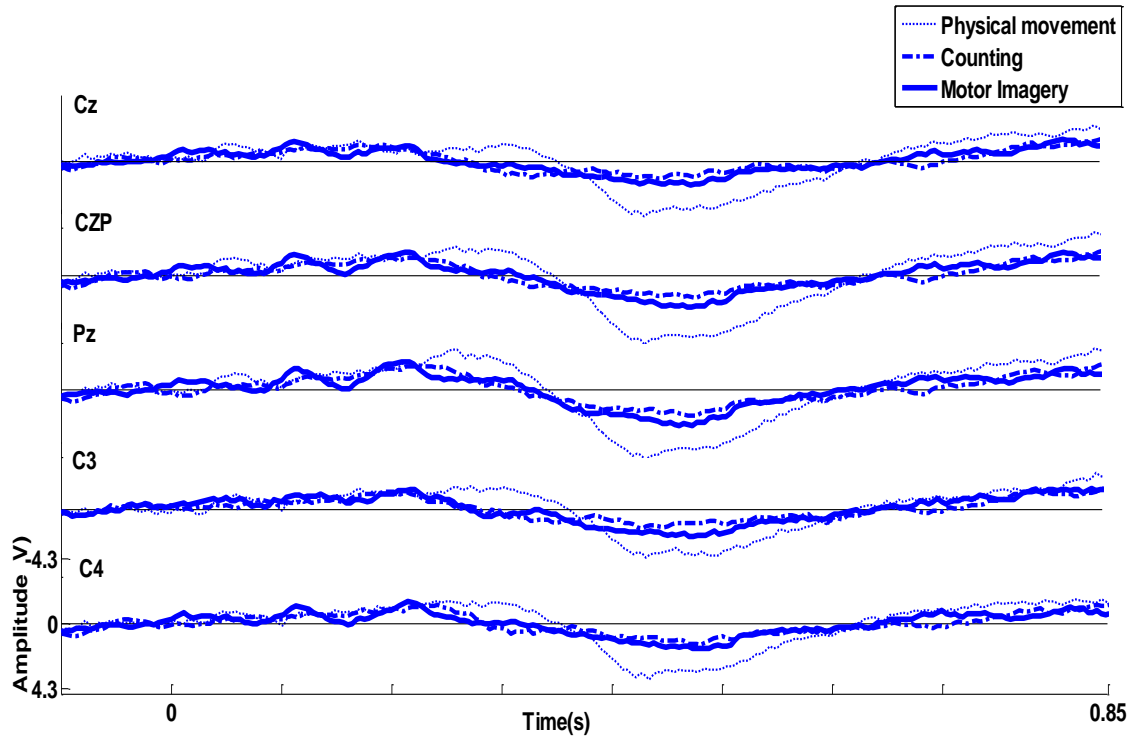


Figure 3b: Grand average P300 peak potentials for all task sessions for visual stimulus. The grand-average of P300 potentials in six subjects for the counting, motor imagery and physical movement task conditions with the target stimulation. The positive peak amplitude was the maximum with physical movement, high with the motor imagery task and the least with the counting task.

The figure 3b shows grand-average of target trials of six-subjects at channels CZ, CZP and PZ in counting, motor imagery and physical movement task sessions. Physical movement task sessions demonstrated an even higher P300 peak potential in comparison to the counting and motor imagery task sessions. The maximum increase in peak potential was seen at the channels CZ, CZP and PZ as observed in the other two task sessions. Non-target stimuli showed considerably lower P300 peak potential. The latency per individual was also found to be much longer than counting and slightly longer than motor imagery task sessions.

The figure 4 shows the distribution of peak amplitude over the scalp with higher in the central and parietal regions, increasing with motor imagery embedded paradigm as compared to the conventional counting task session. The top figure shows the distribution for the counting task session, followed by the motor imagery and lastly the physical movement related task session.

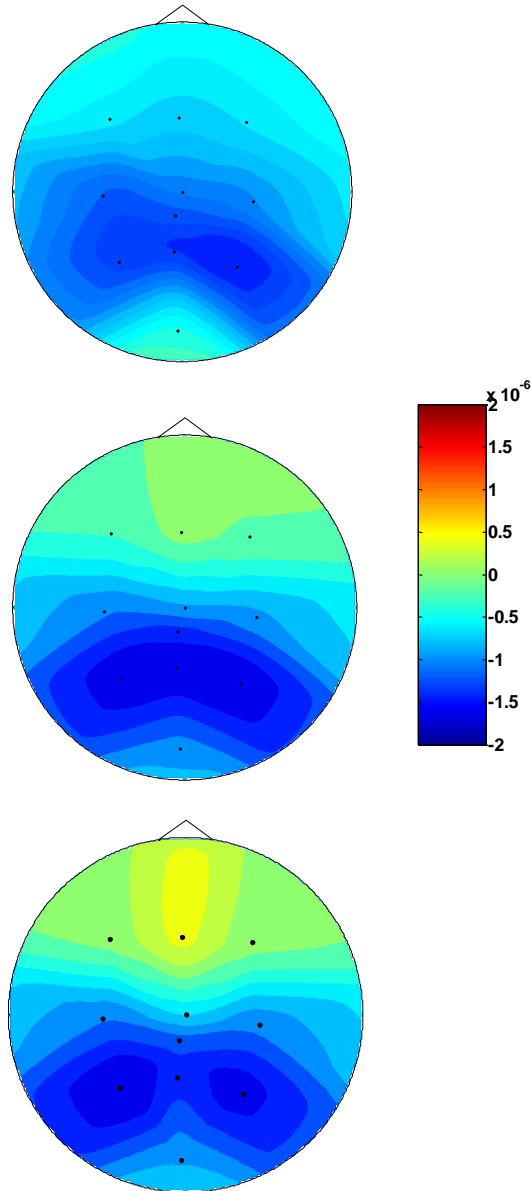


Figure 4: Head topography of grand average P300 peak potentials for all task sessions for visual stimulus.

The distribution of peak potentials over the scalp electrode locations is shown for all three task session, counting at the top with motor imagery in the center and physical movement in the last of the three figures. The blue region of increasing positive peak amplitude grows larger and darker indicating increase in potentials for motor imagery embedded and physical movement involved task sessions.

The primary observation was that the enhancement in the peak potential was the maximum along the midline channels. As a secondary observation, we compared the enhancement seen at the lateral channels C3 with C4 and P3 with P4 which showed a dependence on handedness. Higher enhancement in P300 peak potential was seen at C3 than at C4 in moving from counting to motor imagery task sessions for the one purely right-handed subject. The five mixed-right handed subjects showed even enhancement at both lateral channels. The data in the figures 3a and 3b correspond to the average of all six subjects and hence seems to show even enhancement on C3 and C4. The same observations were seen in case of P3 and P4. Nevertheless, the maximum amplitude enhancement was always seen along the midline channels CZ, CZP and PZ.

The results were independent of the gender of the subject.

Similar results were found even after reversing the order of sessions between the first four subjects. Irrespective of the order, an increase in peak amplitude was observed moving from counting task session to the motor imagery task session. Hence the order was kept constant at counting followed by motor imagery for the following 4 subjects.

2.3.1.2. Time-frequency representation: The figures 5a, 5b and 5c show the wavelet transformation results for target stimuli responses grand-averaged over six subjects for both counting, motor imagery task and physical movement sessions respectively.

The event-related desynchronization (ERD) increased i.e. rhythmic amplitude decreased with motor imagery as the post-stimulus task in comparison to conventional counting case as seen in the figures 5a and 5b.

The ERD increase was even higher for the task session with physical movement involved. The effect of handedness as mentioned in terms of the P300 peak amplitudes can be clearly seen in the figures above in the ERD case also. When observing the enhancement in ERD between the counting and motor imagery task sessions, the maximum remains along CZ, CZP and PZ. However, if the lateral channel C3 is compared with C4, one pure right-handed subject showed higher enhancement in ERD on C3 while five mixed-right handed subjects showed even enhancement on C3 and C4. The same observation holds true for P3 and P4. Handedness influence as mentioned above is also seen for the enhancement between motor imagery and physical movement task sessions.

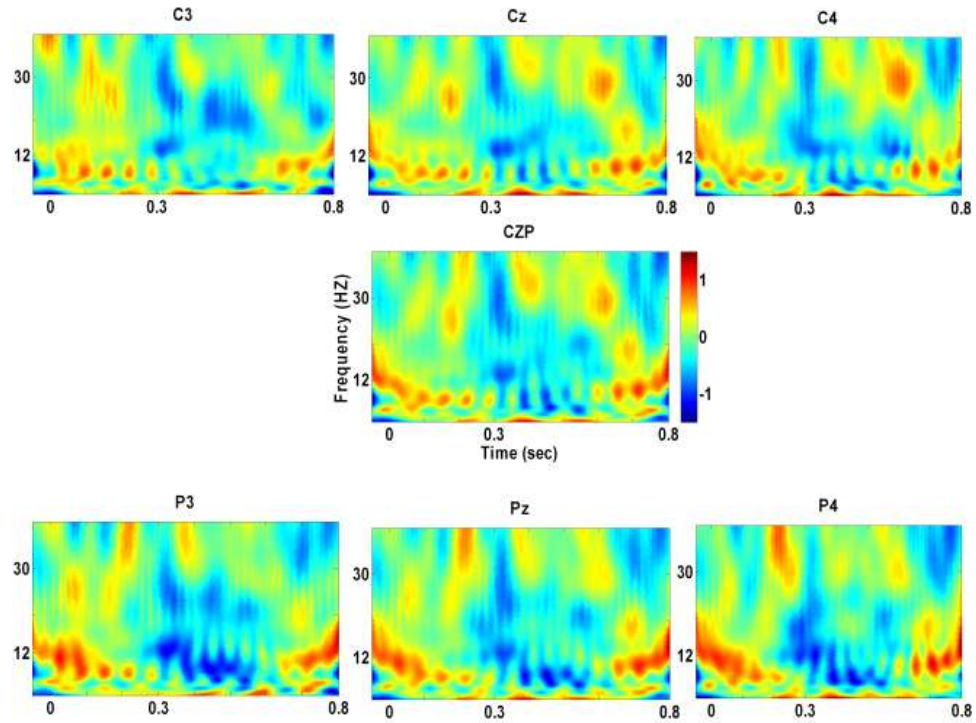


Figure 5a: Time-frequency analysis plot for counting task session for visual stimulus. Time-frequency analysis of the target stimulation responses associated with the traditional odd-ball P300 paradigm with counting.

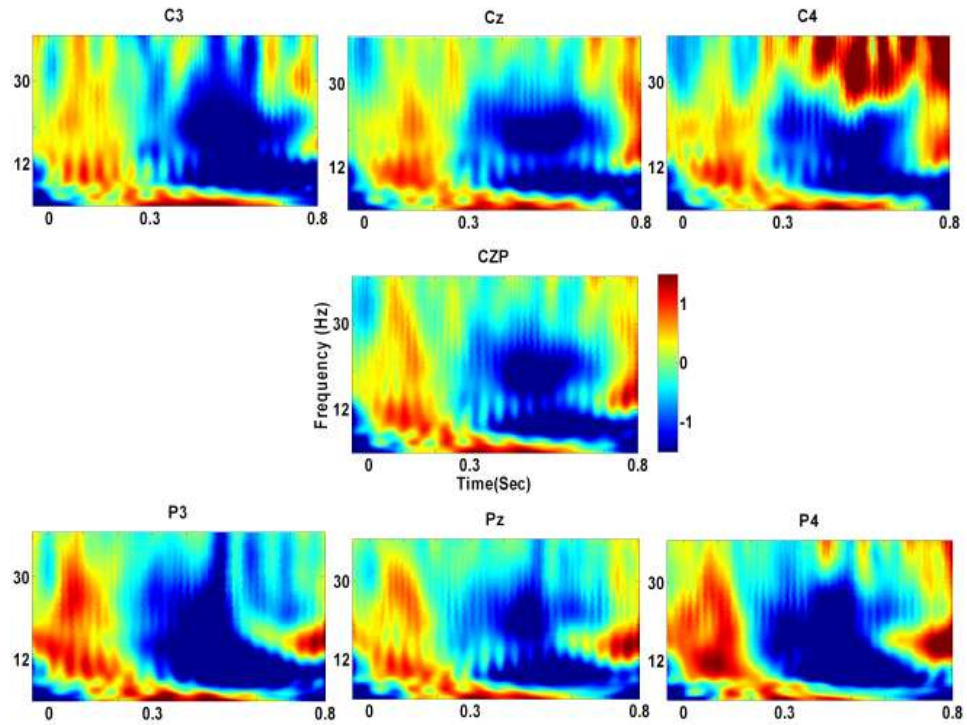


Figure 5b: Time-frequency analysis plot for motor imagery task session for visual stimulus.

Time-frequency analysis of the target stimulation responses associated with the traditional odd-ball P300 paradigm with motor imagery as the after stimulus task. An increase in ERD i.e. a decrease in rhythmic amplitude around frequency range of about 8-30 Hz was observed.

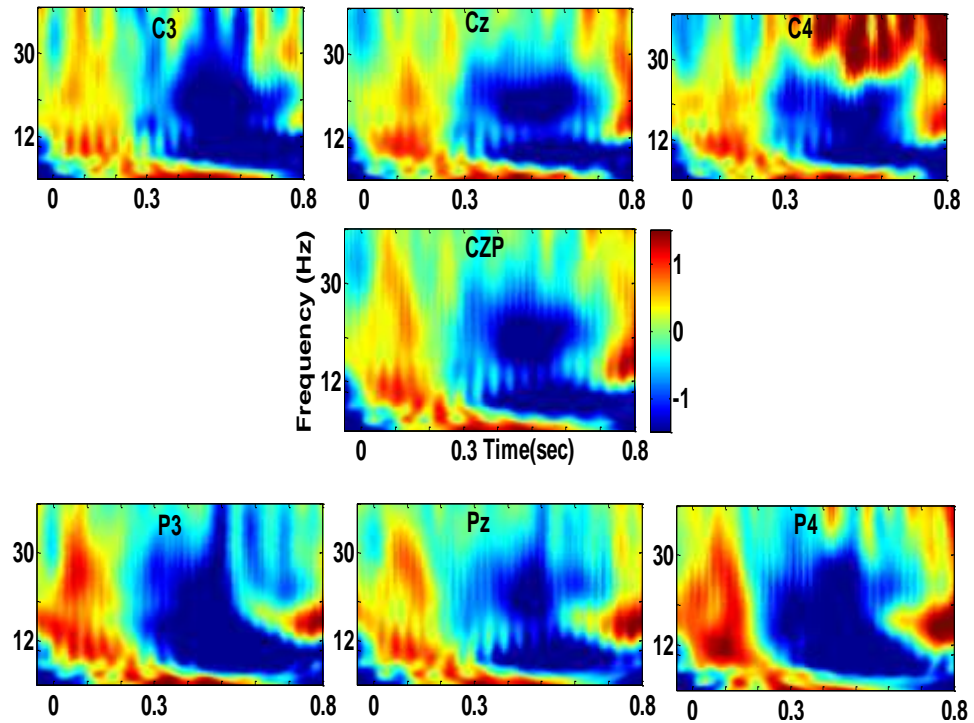


Figure 5c: Time-frequency analysis plot for physical movement task session for visual stimulus.

Time-frequency analysis of the target stimulation responses associated with the traditional odd-ball P300 paradigm with physical movement as the after-stimulus task. A further increase in ERD i.e. a decrease in rhythmic amplitude around frequency range of about 8-30 Hz was observed.

2.3.2. Accuracy of classification:

Five-trial averaged accuracy was computed individually for all six subjects for data from all task sessions. The results for row/column accuracy using the combination of Generic Algorithm followed by Mahalanobis linear distance classifier (GA + MLD) are as given in table 1. The Table 1 also has results for five-trial averaged letter-selection accuracy using Stepwise Linear Discriminant Analysis (SWLDA).

An Inter-stimulus duration of 850 ms and the given accuracy lead to a speed of 2 characters/min.

**Table 1: Classification Accuracy for P300 paradigm with visual stimulus.
P300 detection accuracy from five-trial averaged signal with counting and motor
imagery task sessions.**

Subject	Generic algorithm and Mahalanobis Linear discriminator for row/column accuracy (GA + MLD)		Stepwise Linear Discriminant Analysis for letter selection accuracy (SWLDA)	
	Counting (%)	Motor Imagery (%)	Counting (%)	Motor Imagery (%)
1	66.83	70.03	71.66	94.00
2	65.37	65.42	51.67	64.01
3	58.13	64.06	<50	58.90
4	66.20	67.96	60.00	66.66
5	57.59	60.95	<50	60.00
6	65.37	65.42	<50	78.24

Chapter 3: Paradigm with auditory cues:

3.1. Methods:

3.1.1. Setup:

The system setup used for the paradigm with visual cues was kept constant, with only a few changes as mentioned below. Eleven ear-referenced electrodes placed as given in figure 2 above recorded the data from the subjects. As of today, data from three subjects (two males and 1 female) has been collected. The subjects were new to BCI of any kind and had not previously used P300 speller or the novel paradigm described in chapter 2 above.

3.1.2. Paradigm design and implementation:

As in the paradigm with visual cues, the paradigm introduced by Farewell and Donchin as the P300 visual oddball paradigm was modified to include motor imagery with auditory cues. Few changes were the same as for the novel visual paradigm given above. A larger 6x6 matrix of alpha-numerals was displayed on the screen. The visual stimulus was replaced by six audio sounds – Ting, Buzz, Thock, Gong, Bloing and Blob, 200 ms duration each. Each row and column was assigned one of the sounds in the listed order with row 1 and column 1 assigned ‘Ting’ to row 6 and column 6 assigned ‘Blob’. These formed the auditory stimuli. The character to be selected was displayed at the top left corner of the screen making it a copy-spelling mode implementation. In addition, the name of the sounds corresponding to the row and column the character was placed in was also displayed to aid the user as shown in figure 6 below. The names were user customized if preferred.

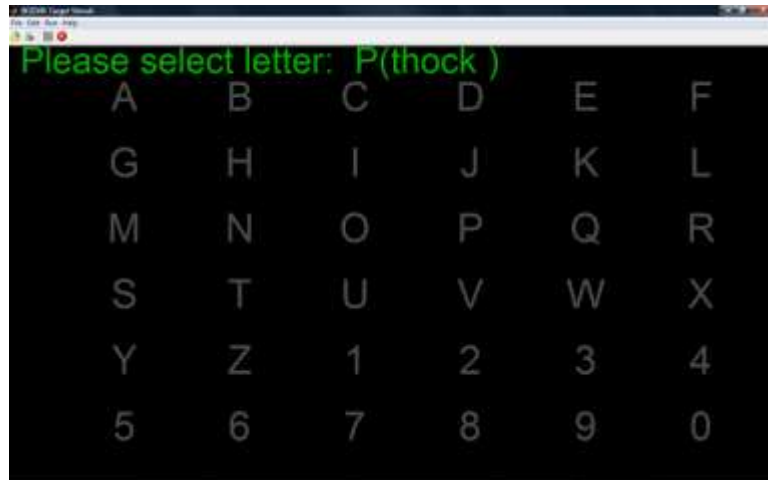


Figure 6: Snapshot of the paradigm with visual stimulus.

A 6x6 matrix of alpha-numerals was displayed on the screen and in numeric order all rows 5 times followed by all column 5 times were stimulated by playing the corresponding sounds as the audio stimulus. In this figure the target character was ‘P’ and during the stimulation of the rows, the sound corresponding to the third row- thock was displayed at top left corner for the subject’s convenience. Similarly ‘Gong’ was displayed during column stimulation.

The sound stimuli lasted 200 ms played once every 600 ms successively. The row and column with the required character was considered as target stimulus while the others are non-target stimulus. In every run, stimulation followed numerical order of rows and columns as row 1 to row 6 and again row 1 till all the rows were stimulated 5 times each. Likewise, all columns were stimulated 5 times each in numerical order. Thus each run comprised of 60 stimuli leading to selection of one character. One session consisted of 16 runs selecting 16 characters from a total of 160 target and 800 non-target stimuli. A relaxation time of 1 min was set every 4 runs.

The first and second sessions were performed as given in the novel visual paradigm in chapter 2. The first session followed the conventional P300 paradigm wherein the subject counted the number of target stimuli. In the second session, the subject was asked to urge or imagine one brisk right wrist movement immediately on perceiving the stimulus, thus

incorporating motor imagery in this novel paradigm with auditory cues. A 10 minute break was provided between the two session performed consecutively on the same day.

Intuitive audio sounds found in day-to-day activities were chosen for the cues. However, to familiarize themselves with the array of sounds, the subjects were supplied with an interactive GUI to use for approximately 15 minutes. The subjects had the option to play the sounds according to their choice of order and repetitions. They also performed 2 practice sessions around 4 days prior to the data recording with 8 runs of the counting task session followed by 8 runs of the motor imagery task session in response to the auditory stimuli. The practice sessions had a visual stimulus with the row/column corresponding to the audio stimulus illuminated for 100 ms simultaneously with the auditory stimulus. Visual stimulus was only an aid during the practice and was absent from the actual data recording sessions.

Over-the-ear type of head-sets allowed the subject to receive clear audio sounds from the system and also helped isolate the subject from any background sounds likely to cause distraction.

3.2. Data Analysis:

All of the data was processed off-line using self-developed MATLAB toolbox BCI2VR (brain computer interface to virtual reality) [27].

3.2.1. Feature extraction:

Data from both sessions was individually analyzed per subject as given below.

Data epochs of duration 100 ms before to 600 ms after stimulus were processed for digital link referencing. This was followed by eye-movement artifact correction by least-mean

square method with EOG recording as the reference. Baseline correction was performed with data in time range 100 ms before to 100 ms after stimulus onset as the baseline.

3.2.1.1. Average P300 peak amplitude: P300 waveform was observed after ensemble averaging of target and no-target epochs separately for each subject.

3.2.1.2. Time-frequency representation: The data was processed using continuous wavelet transform with morlet window. The other parameters were – time duration of 50 ms before to 600 after stimulus onset for frequencies in alpha and beta range.

3.3. Results:

3.3.1. Feature extraction:

Average P300 peak potential: The figures 7a, 7b and 7c below show data corresponding to auditory stimulus paradigm recordings for subject 1, 2 and 3 correspondingly. The data in the figures is the average of target trials for both counting as well as motor imagery task session separately at channels CZ, CZP and PZ in each subject.

As for subject 1, as in figure 7a, higher P300 peak potential is seen with the motor imagery task session as compared to the counting task session even in this novel paradigm with auditory cues. At channel CZP, the value of P300 peak amplitude increased from 0.795 μV in counting task session, to 1.484 μV , which is a 42.46% increase. The enhancement in P300 peak resonated in other channels also although not presented in the figure above. The P300 peak in non-target case for both sessions was negligible.

Latency varied subject-wise and increased with inclusion of motor imagery as was seen in the paradigm with visual cues. However, it remained in the expected duration of 250 ms – 500 ms post-stimulus onset [29].

The results were independent of the gender of the subject.

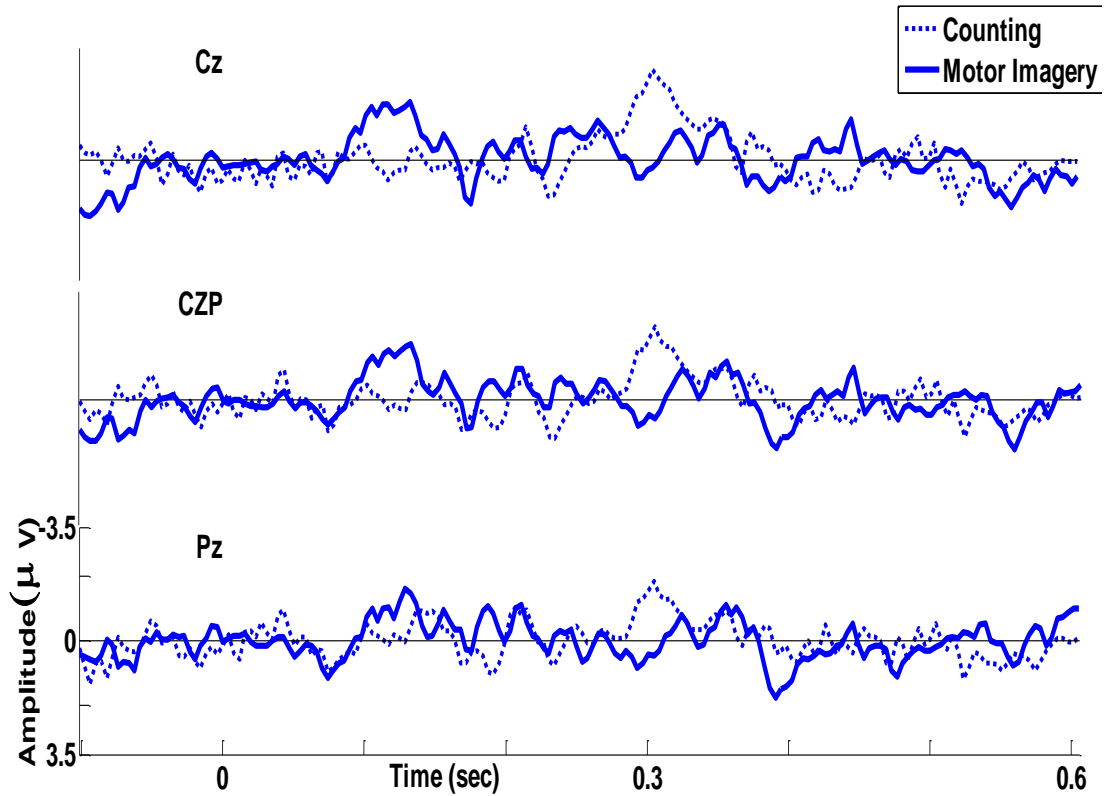


Figure 7a: Average P300 peak potentials for counting and motor imagery task sessions for subject 1 auditory stimulus.

The average of P300 potentials for subject 1 for the counting and motor imagery task conditions with the target stimulation in auditory cued paradigm. The positive peak amplitude was higher with the motor imagery task than with the counting task, around 350 ms.

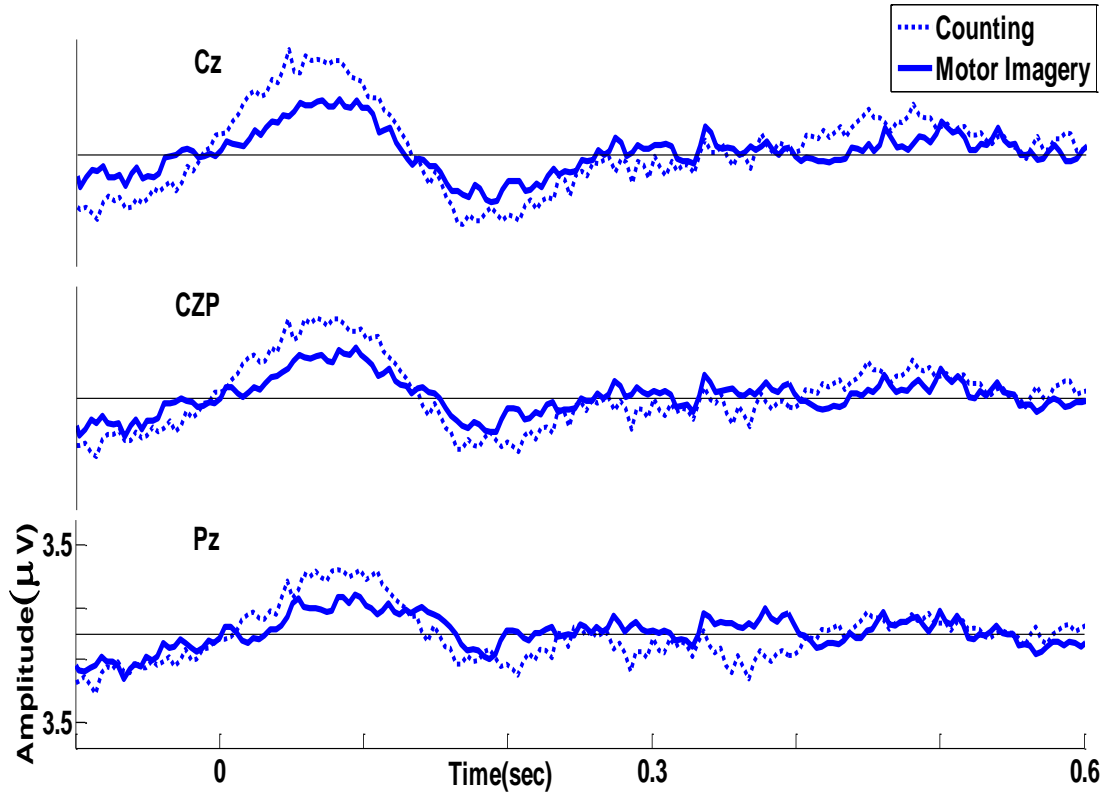


Figure 7b: Average P300 peak potentials for counting and motor imagery task sessions for subject 2 for auditory stimulus.

The average of P300 potentials for subject 2 for the counting and motor imagery task conditions with the target stimulation in auditory cued paradigm. The positive peak amplitude minimally increased with motor imagery embedded in place of conventional counting, at around 330 ms.

The high P300 peak was not prominent in the counting task session data of the subject 2 as seen in figure 7b. However, a higher P300 peak is seen at all channels (including those not in the figure) for the motor imagery task session, as compared to the counting task session. Similar observation was made at other channel recordings also. Even so, P300 peak in non-target case was negligible for both sessions.

Latency varied subject-wise and increased with inclusion of motor imagery as was seen in the paradigm with visual cues. However, it remained in the expected duration of 250 ms – 500 ms post-stimulus onset [29].

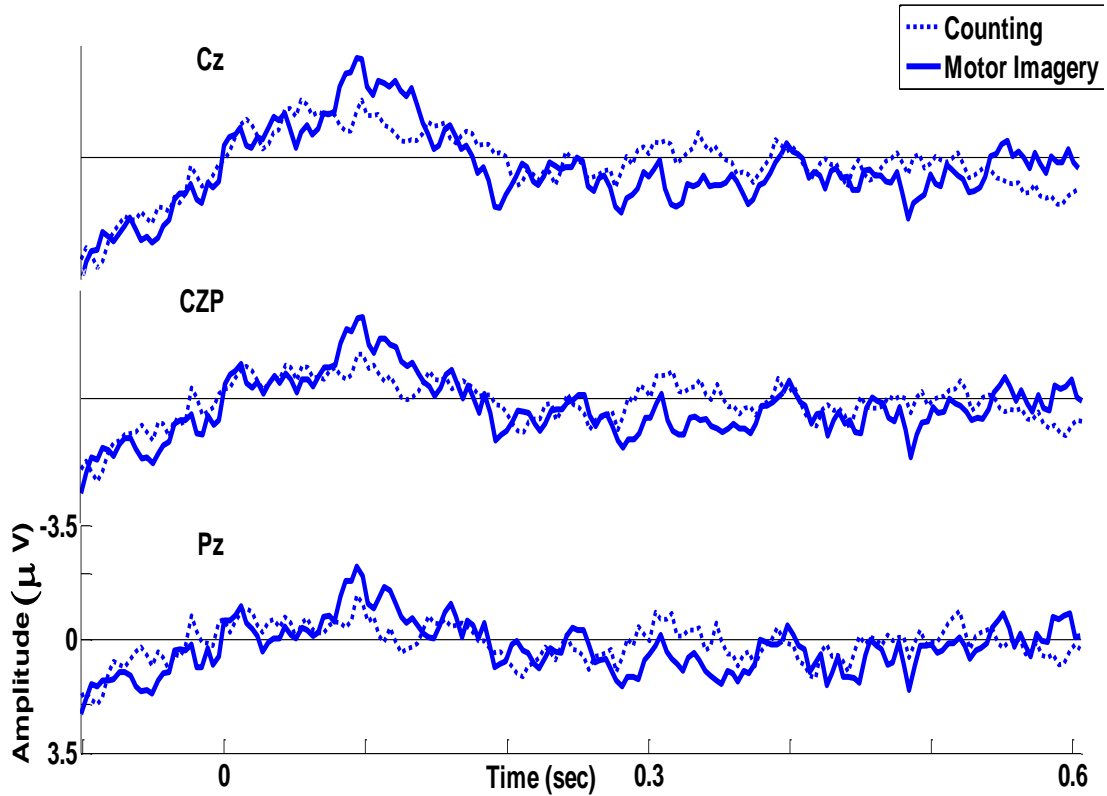


Figure 7c: Average P300 peak potentials for counting and motor imagery task sessions for subject 3 for auditory stimulus.

The average of P300 potentials for subject 2 for the counting and motor imagery task conditions with the target stimulation in auditory cued paradigm. The positive peak amplitude minimally increased with motor imagery embedded in place of conventional counting, at around 330 ms.

3.3.1.1. Time-frequency representation: The figures 8a, 8b, 8c show the wavelet transform results for subjects 1, 2 and 3 of the data corresponding to the auditory paradigm. The results are for averaged target stimulus trials for counting and motor imagery task sessions separately in each subject.

In subjects 1 and 3, the ERD increases with motor imagery embedded in the paradigm compared to counting as seen in the visual cued paradigm, as in figure 8a and 8c. In subject 2, the ERD increase is not prominent with motor imagery embedded in the paradigm compared to counting.

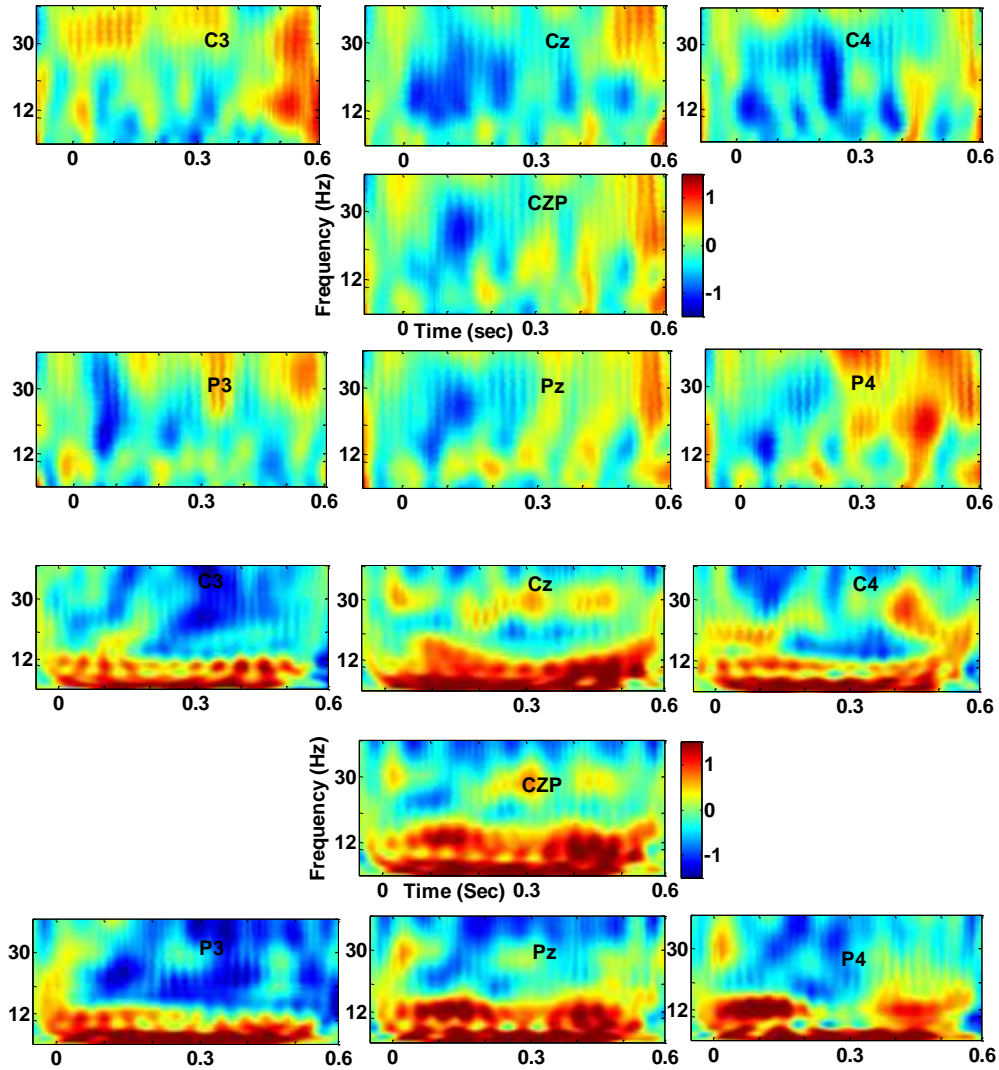


Figure 8a: Time-frequency analysis plot for counting and motor imagery task session for auditory stimulus for subject 1.

Time-frequency analysis of the target stimulation responses associated with the traditional odd-ball P300 paradigm with motor imagery as the after stimulus task. The top part of the figure has data corresponding to the counting task session while the next is the motor imagery task session. An increase in ERD i.e. a decrease in rhythmic amplitude around frequency range of about 12-30 Hz was observed. The increase is higher with motor imagery inclusion compared to the conventional counting task session.

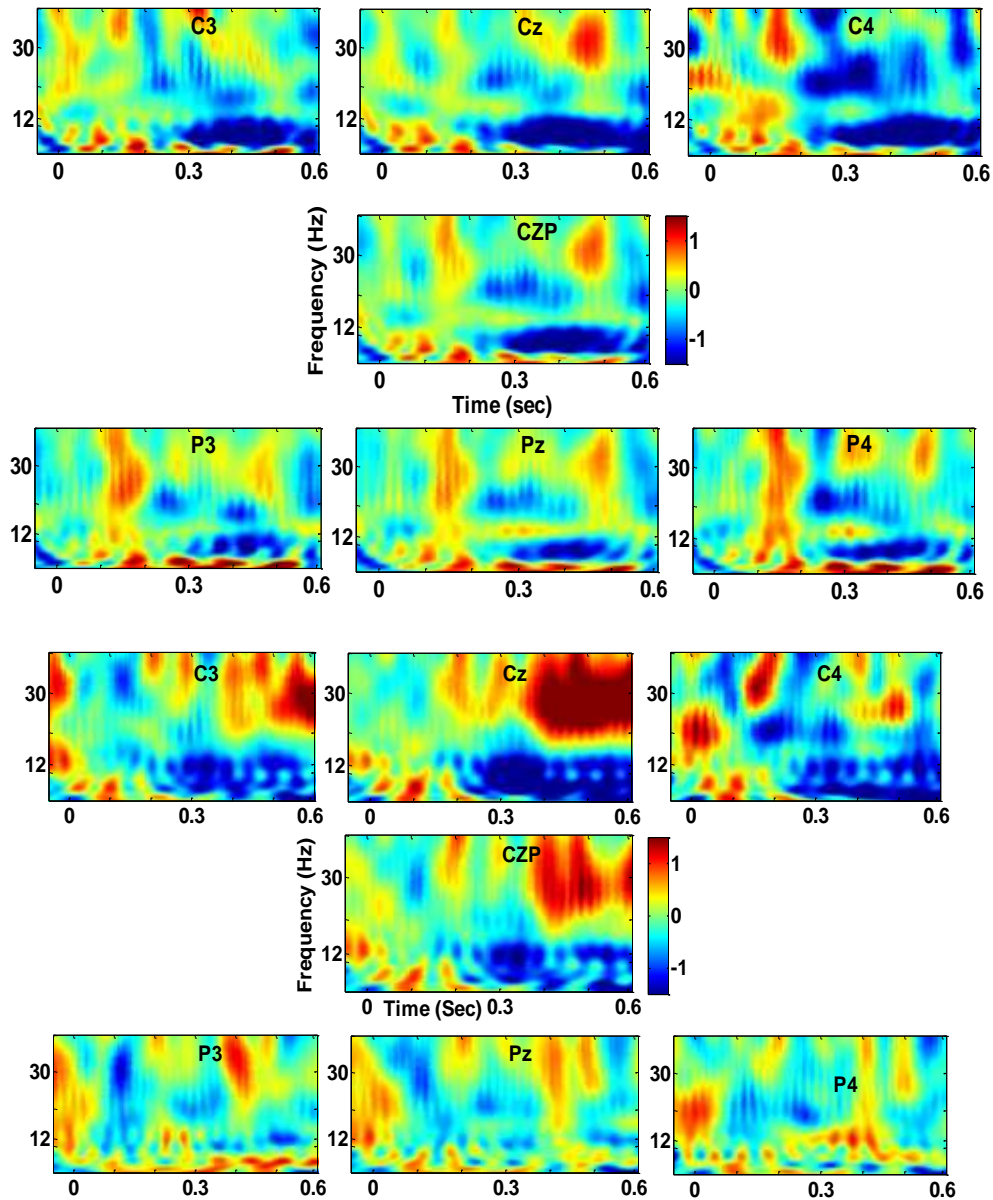


Figure 8b: Time-frequency analysis plot for counting and motor imagery task session for auditory stimulus for subject 2.

Time-frequency analysis of the target stimulation responses associated with the traditional odd-ball P300 paradigm with motor imagery as the after stimulus task. The top part of the figure has data corresponding to the counting task session while the next is the motor imagery task session. An increase in ERD i.e. a decrease in rhythmic amplitude around frequency range of about 8-30 Hz was observed. The increase is higher with motor imagery inclusion compared to the conventional counting task session.

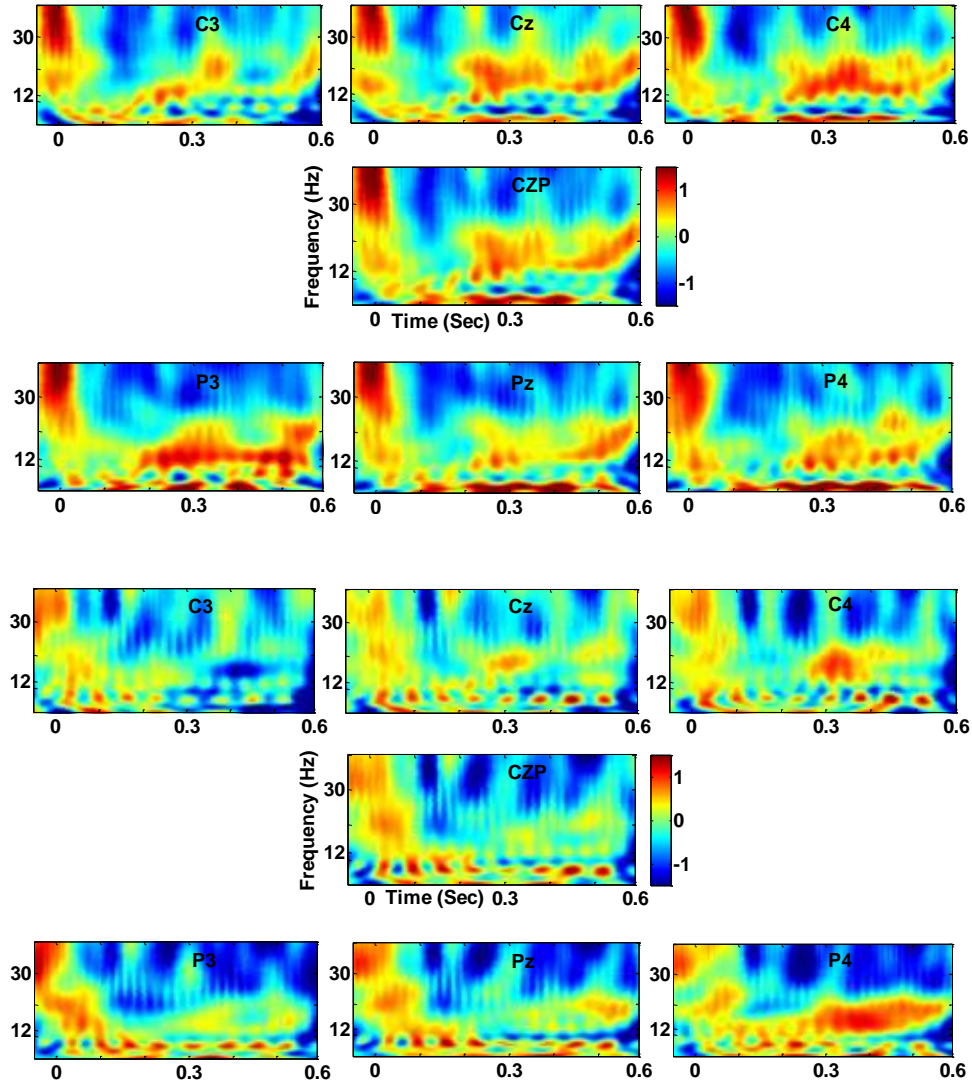


Figure 8c: Time-frequency analysis plot for counting and motor imagery task session for auditory stimulus for subject 3.

Time-frequency analysis of the target stimulation responses associated with the traditional odd-ball P300 paradigm with motor imagery as the after stimulus task. The top part of the figure has data corresponding to the counting task session while the next is the motor imagery task session. An increase in ERD i.e. a decrease in rhythmic amplitude around frequency range of about 8-30 Hz was observed. The increase is higher with motor imagery inclusion compared to the conventional counting task session.

Chapter 4: Discussion:

In the paradigm with visual cues, the inclusion of motor imagery provided higher peak P300 amplitude than the conventional counting as the post-stimulus task. According to our hypothesis, the increased amplitude might come from the overlapping of the P300 with Frontal Motor Peak Potential (fPMP). The fPMP is a positive peak potential occurring 100 ms after EMG onset i.e. after a movement is initiated. However, in case of a brisk movement or a short EMG burst. In this externally cued paradigm, subjects perceived the target cue and then made an active motor imagery limb movement. Therefore, the fPMP was overlapped with P300 response at around 300 to 500 ms after the stimulus. The same may be the reason behind the increased P300 peak potential for motor imagery embedded in the auditory cued paradigm, although marginal. The sounds chosen as auditory cues though common were dissimilar as was needed in the paradigm. This also led to it being difficult to isolate the target from the non-target sound since all cues were unique. More practice of the sounds than provided in this study of the sounds might make it easier to isolate them. That might help a better implementation of the paradigm.

Informal feedback from the subjects who performed the paradigm with auditory cues revealed that reduction in visual stimulus reduced the strain on the eyes. They were exposed to the visual cues as aids in the practice session. The paradigm with less or no flashes was a more comfortable paradigm according to the feedback. The over-the-ear head-sets helped isolate the subject from external distractive sounds.

Sustained movement is seen as a negative depolarization which if overlaps with P300 positive peak potential could reduce the peak value. This may be one of the reasons why the findings of recent work [30] on similar lines differ from those of the study in this paper. The goal of better

classification through embedding motor imagery is achieved although by different paths in this study and the recent work cited.

Motor imagery inclusion provided an additional feature of ERD. A prominent ERD coincided with the time duration of the P300 peak potentials in the alpha and beta frequency ranges. An enhancement in ERD is seen with motor imagery compared to the conventional counting in the visual cued paradigm. This additional feature could improve the P300 response detection leading to a better performing speller.

The effect of handedness seen in the peak potentials and ERD prove that motor imagery could be the reason for the better results seen in the corresponding data. Although, not directly related to the hypothesis, an even further enhancement in ERD seen with the actual physical movement that validates the enhancement of ERD due to motor imagery in the corresponding task session data. The P300 speller is intended for use by paralyzed patients with limited motor skills. As such, the use of actual physical movement in the paradigm beyond validation reasons would not be a useful comparison to infer from. Hence the session with actual physical movement was not performed in the paradigm with auditory stimuli.

An acceptable increase in accuracy was seen in five-trial classification with motor imagery as compared to the conventional counting, for paradigm with visual cues. Similar observation was made in both row/column and letter selection accuracy. The single trial accuracy was also evaluated for the letter selection by SWLDA method but could not show significant results. Future efforts can be directed towards exploring better computational methods in order to improve the accuracy even further.

In the paradigm with visual cues, the order of the task sessions was varied in the first four subjects in order to study any learning adaptation, excluding outliers. Two subjects were asked to perform the motor imagery embedded session before the conventional counting session. In the other two subjects, conventional counting session was performed before the motor imagery session. The increase in peak potentials was similar in all four subjects, irrespective of the order of the task sessions. No learning curve was seen within the order of the two task sessions. The order was kept constant as conventional counting followed by motor imagery for the other four subjects in the visual cued paradigm and three subjects in the auditory cued paradigm. Practice could, though, improve the understanding and execution of the brisk motor imagery leading to further enhancement in the peak potentials.

Less ambiguous and more consistent results were achieved since overlapping for successive responses were reduced by using a longer inter-stimulus interval. A longer inter-stimulus interval also allowed us to ignore the early visual components in the paradigm with visual cues. The classification decision was thus made on the data in duration 250 ms to 750 ms with negligible requirement of precise eye-gazing. Although speed of selection was lower, about 2 characters/min i.e. 2 bits/min, it may not be the first priority for the target group of patients with less eye-gazing abilities. Even so, future efforts need to be made to boost the speed.

Given that the peak potentials in the paradigm with visual cues were in the expected range of 250 to 500 ms, the inter-stimulus interval for the paradigm with auditory paradigm was reduced to 600 ms without loss of useful data.

The dependence on eye-gazing was reduced by embedding the motor imagery in the paradigm with visual cues. Although the statistical power of the data for paradigm with visual stimulus is

low, the results obtained so far could provide for a better performing speller. Nevertheless, future efforts to increase the power should be made. Embedding motor imagery in the paradigm with auditory cues is a future improvement partially implemented, since the data collected for it so far may not be sufficient for a pilot data set. Further efforts in this regard can provide more insight into whether the eye-gazing requirement is truly minimized while keeping the performance acceptable.

As part of future study, single trial accuracy by implementing different computation methods can be explored to enhance the performance in terms of accuracy as well as speed. In order to increase the statistical power to validate the results found in this pilot study, more subject trials can be conducted for paradigms with both visual and auditory paradigm. A better understanding of the execution of the motor imagery task would improve the quality of the data providing more consistent and comparable results in both the paradigms. As for the auditory paradigm, more the subjects get used to the sounds, clearer the data could be.

Chapter 5: Conclusion:

A pilot study was conducted for the proposed paradigm that embedded motor imagery as post-stimulus task in a traditional visual oddball P300 speller paradigm. The results demonstrated enhanced P300 peak potential, ERD and row/column classification accuracy while reducing the need for precise eye-gazing. The same was implemented with motor imagery embedded in a traditional odd-ball P300 speller paradigm with auditory stimuli in place of the visual. A larger future study based on these pilot results could provide more insights into other aspects ultimately leading to a more feasible P300 speller paradigm to restore communication for users with limited motor skills unable to eye-gaze for a long period of time.

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Vita

Vaishnavi Vijay Karnad was born on October 4th, 1985 in Bangalore, India and is a citizen of India. She received her Bachelor of Engineering degree in electronics engineering, from Vishwakarma Institute of Technology, under University of Pune in May 2007. In August 2009, she joined graduate studies as a student of Master of Science in the Department of Biomedical Engineering at the School of Engineering, Virginia Commonwealth University. She was a grader (Spring 2010) and Lab Research Technician (Fall 2010) for two separate courses with the Department of Electrical and Computer Engineering. She also received the School of Engineering Thesis/Dissertation assistantship for Spring/Summer 2011. At the EEG & BCI lab, she worked on the project titled 'A Novel P300 Speller with Motor Imagery embedded in a Traditional Oddball Paradigm' as her thesis project under Dr. Ou Bai during the course of her degree. A poster on her work was presented at the Fourth International Brain Computer Interface Meeting, Monterey, California in May-June 2010. Currently she is pursuing her Master of Science degree of which the above thesis is a partial requirement.