Methologies on BCI Research - A Comparative Study

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Abstract. Since the decade of 90's the research on Brain Computer Interfaces (BCI) systems changes the way we use our brain abilities, showing that the brain is an available mean of communication. Nowadays many works related with brain activity start to get commercial and the interest on this kind of systems increased. Despite of these promising advances many work still to be done, many questions still to be answered. This work has as principal objective compare the methodologies of research that the main research centers in BCI followed to achieve their results. To perform the study the most relevant papers on this topic were selected and the methodologies were compared taking account the following subjects: research procedures, experimental setup and procedures, results validation and success achievement.

1 Introdution

A Brain Computer Interface (BCI) is a communication system that enables the user to control special applications using only the thoughts [1]. The research in the area of BCIs began in the 1960s but the truly most relevant results only has been made in the 1990s motivated by the development of the computer industry. Some of the most important groups in BCI research has already build their own BCI devices with encouraging results showing that the concept could be used as a truly computer interface. However this area of research still has many problems to solve, the main issues are related to the low information transfer rate and the high latency concerned with the time necessary to process the electroencephalography (EEG) signal. Tree words resume the main issues in BCI research: accuracy, speed and usability [2].

> *"A research methodology defines what the activity of research is, how to proceed, how to measure progress, and what constitutes success"* [3]

Taking the definition used in the MIT about what is a research methodology, and being conscious of the importance that the methodology have in a research project, this work aims to perform a comparative analysis of the most relevant studies made in this research area.

The topics analyzed are concerned with methodology procedures, more specifically, how the authors perform their research in order to achieve the results.

To accomplish these issues four topics were analyzed: research procedures, experimental setup and procedures, result validation and success achievement, in all studies. The first is related with the mathematical and signal processing methods that were used, the second aims to give a more precise view about the methodology followed to perform the tests, giving also special attention to the methodologies used to test the proposed system. The last two regards the results validation, trying to identify how the results were reported and finally how they had defined success.

In the following sections will be analyzed the methodologies performed by the most relevant works on BCI area. In the end a table will be presented to resume the most relevant characteristics of each study. In the section "Discussion" the methodologies used will be analyzed and the most relevant conclusions will be discussed. Finally we summarize the report, give our main conclusions and suggest directions for future improvements of the methodologies used in BCI research.

2 Methodology Analisys

In this section the most relevant works in BCI area will be analyzed and compared. To help the presentation of the studies the analysis will be detailed for each work. In the end of the section a comparative table will resume the most relevant characteristics of each study.

2.1 Methodology Overview

Alberta University

Overview

The work in this University was conducted by Alexander Kostov and Mark Polak and the research had started in 1995. Their BCI project intended to control a cursor to a specified target [4], using pattern recognition methods. The user was instructed to move the cursor to a target located at top or bottom (1-D setup) or on 4 directions, top, bottom, left and right (2-D setup). The principal goal of this project was to develop a BCI capable of accurate two-dimensional cursor control. In addition, the intention was to develop a range of applications for BCI [5].

Methodologies

- *Research Procedures*
  This work used the pattern recognition approach. The filtering and amplification was done by an external device called Brain Imager. Features extraction was also applied using the 4^{th} order autoregressive (AR) method. To perform the pattern recognition was used a Neural Network method called Adaptive Logic Network (ALN).

- *Experimental Setup and Procedures*
  The EEG signals were sampled and digitized at a rate of 200 Hz. Was used the International 10-20 electrode system to place the electrodes and only the C3, C4, P3 and P4 electrodes were used. The position of the cursor was updated every 50 ms and the number of steps required to hit the target was controlled by the operator. Every subject have to achieve a target on a screen, to do that the subject could choose the mental tasks that uses to control the cursor. The first half of the experience was used to train the ALN, when the subject achieved the control of the cursor the system was halted to the second half of the session where the evaluation of the system was performed.
- *Results Validation*
  To evaluate the system the authors give the results in the form of hit rate, both for 1-D and 2-D setups. Only two subjects were used in 2-D experimental setup.
- *Success Achievement*
  The authors report a hit rate close to 100% for the 1-D setup with 32 cursor steps, and the hit rates of 70% and 85% for the two subjects of the 2-D setup, however the number of steps required to hit the target were not reported.

Oxford University

Overview

The BCI research at the Oxford University, England, started in 1996 and was performed by William Penny and Stephen Roberts research team. The work related in 1999 [6] shows the improvements in differentiate between imagine movement tasks and imagine abstract tasks like a math operation to control movement. This work uses other kind of imaginaries in order to get better performance from the classifiers. In 2000 was published the results of the online experiments using seven volunteer subjects [7].

Methodologies

- *Research Procedures*
  To filter the signals were used a band-pass filter with a cutoff frequency in 0.1 Hz and 100 Hz and the data was analyzed using a 8^{th} order autoregressive (AR) model. To classify and perform the pattern recognition was used Bayes logistic classifiers. Additionally the author had study two methods to improve the classification performance, these methods was latent-space smoothing and a reject option. The first means that the low certainty decisions may be rejected taking in account the recent past higher certainty decisions. The other method consists in the insertion of a new class, the reject class that holds the decisions with a low certainty.
- *Experimental Setup and Procedures*
  The signal was sampled and digitized at a rate of 384 Hz and only the C3 and C4 electrodes, based on the 10-20 international system, were used. In

this study the author had used other imaginaries than only motor imaginaries to increase the performance of the classifier, the upward movement was associated to a math task and the downward movement to the motor imaginary. The classification system was re-trained after each experiment, using the previous experimental data as a training data. To process the data were used time blocks with 128 samples each, which slid 32 samples from one processing time step to the next.

- *Results Validation*
  The result was reported for three scenarios: hard rejection, soft rejection and baseline. These three scenarios correspond to the use of latent-space smoothing method with different thresholds. For each one of the scenarios the results were reported in accuracy of the classification.
- *Success Achievement*
  The authors reports the hit rates of 86%, 76% and 53% to each one of the scenarios. The rejection of data blocks was also reported, in the two first scenarios were, respectively, 79% and 39%. In the last scenario no data blocks were rejected.

Wadsworth Center

Overview

The research at the Wadsworth Center began in 1986 with Jonathan Wolpaw as main researcher. The research performed in this center is based on self-regulation of the μ and β rithms. The objective of this BCI was to allow individuals, with severe motor deficits, to communicate by moving a cursor up or down on a monitor screen with changes in μ rhythm amplitude or power. The most relevant study reported for this team was made in 1998 [8]. In this work the subjects have to change the brain activity in order to move a cursor on a screen.

Methodologies

- *Research Procedures*
  Two filters were applied to separate the two studied bands of the signals, the μ band 8-12 Hz and beta band 18-24 Hz using pass-band filters. Additionally the common average reference derivation or a large Laplacian derivation was used to reference all the signals. The power of the signals in these bands was computed and this result was used in a linear equation to perform the cursor movement.
- *Experimental Setup and Procedures*
  In this work was used 64 electrodes placed accordingly with the 10-20 international system. 62 of the 64 electrodes were sampled and digitized at a rate of 128 Hz, these were recorded for further processing. The C3 and C4 were sampled and digitized at a rate of 196 Hz. The time was divided in periods of 100 ms, during this time the next cursor movement is calculated

using the last 200 ms of data. At each 100 ms the cursor position was updated and has to be performed 94 steps to hit the target. The training was performed in sessions of 30 minutes divided in 8 runs of 3 minutes each and separated by 1 minute period. After the training the target were replaced by two words "Yes" or "No" and simple questions were made to the subjects. The objective was to move the cursor to the right answer. The answers were confirmed with a response verification (RV) procedure, in which the "Yes" and "No" targets were switched and the question was answered again. The data was gathered from each subject from 5 sessions containing around 370 questions representing an answer rate of 4.0 to 4.6 questions per minute.

- *Results Validation*
  To validate the results were used the accuracy rate of correct answers.
- *Success Achievement*
  The results achieved in this work shows that 93% to 99% of the answers were correct (these percentages correspond the hit rates with 94 cursor steps).

Thought Translation Device

Overview

During 1990s Birbaumer and his colleagues developed a BCI called the "Thought Translation Device" (TTD) at the University of Tűbingen in Germany. Over the years the TTD has been used by 12 ALS or other patients with severe or total paralysis. This kind of BCI is based on slow cortical potentials (SCP). The subjects train their SCP's to achieve the control of the system. The study presented in [9] the TTD was applied to 5 patients. The methodologies used are analyzed in the next paragraphs.

Methodologies

- *Research Procedures*
  The signal was filtered and cleaned from eye movement artifacts, then the SCP's are identified from the signal attending to the amplitude.
- *Experimental Setup and Procedures*
  Only one electrode was used in this experience, the Cz, from the international 10-20 system. The signal were sampled and digitized at a rate of 256 Hz. In a initial training part the user were trained to produce either negative or positive SCP's. To perform this train a cursor based method was used, to move the cursor to upward the user have to produce positive SCP's: to move the cursor to downwards, negative SCP's were used. During the train the EEG was averaged over a sliding window of 500ms moving in steps of 63 ms. After achieving the performance of 75% correct trials, the user starts the language support program. In this program the user has a virtual keyboard and has to learn to write a word using SCP's. This program was divided in three parts, in the last one the user could select a letter that wishes.

- *Results Validation*
  The most significant results are concerned with how much the patient was able to improve the SCP's amplitude, and what was the training time needed to achieve that results. The results of the training phase were presented in accuracy rate.
- *Success Achievement*
  Only two subjects, from the five beginning, were able to achieve the last phase of the project, taking 140 and 210 training sessions. The mean accuracy from all subjects was around 70%.

Graz University

Overview

The research in Graz university began in 1991 with the project "Graz Brain-Computer Interface". Pfurtscheller and his group based their research on the detection of the ERD and the ERS patterns during the motor imagery. The most relevant work published by this group was made in 2001. This study [10] report a BCI based on the classification of the EEG patterns during five different mental tasks . One aim of the research was to study how the number of mental tasks affected the channel capacity.

Methodologies

- *Research Procedures*
  The logarithm of the band power for five bands (7-10 Hz, 10-13 Hz, 16-20 Hz, 20-24 Hz, 24-30 Hz) was calculated for every channel using a fifth-order Butterworth filter on a precise time window. This formed a feature vector describing all EEG signals from all electrodes. To perform the classification an hidden Markov model (HMM) was used. Classification accuracy was evaluated using 5-fold cross-validation test.
- *Experimental Setup and Procedures*
  The EEG was recorded with 29 gold electrodes and the signals were sampled and digitized at a rate of 256 Hz. The experimental procedure consists on presenting a fixation cross in the center of a monitor at a start of each trial and 2 seconds later the subject heard a beep. After the warning sound one symbol, representing one of the five mental tasks, was shown between 3 s and 4.25 s. The studied mental tasks were left-hand movement (L), right-hand movement (R), foot movement (F), repeated subtraction of a constant number from a randomly chosen number (A), and tongue movement (T). After the presentation of the symbol, the subjects performed the mental tasks according to the symbol until the end of the trial (8 s). The time between trials were randomly picked from 0.5 to 2.5 s and 200 trials were performed divided in 4 sessions. The study compared the classification accuracy for 2, 3, 4 and 5 classes, and only three subjects performed the test.

- *Results Validation*
  The results were reported in the form of confusion matrices. The maximum channel capacity was also used to report the results.
- *Success Achievement*
  The results shows that the classification accuracy decreased with an increasing of the number of classes. The maximum channel capacity reported was 0.81 bits/s for subject two with 4 classes.

Adaptive Brain Interface

Overview

The Adaptive Brain Interface (ABI) project [2, 11] started in 1998 and ended in 2001. The ABI is based on the pattern recognition approach. In this approach the user concentrates on different mental tasks, for example, moving the left hand or visually rotating a cube. The main purpose of this work is to identify the mental task that the user is performing.

Methodologies

- *Research Procedures*
  To the acquired signals were applied a band-pass filter with a 2nd order Butterworth filter on 4-45 Hz frequencies. A surface Laplacian is estimated locally over the six used electrodes. To perform the features extraction was used a power spectrum density analysis and to perform the classification was used a neural network based classifier named local neural classifier. The classifier tries to identify the mental task that the user is performing.
- *Experimental Setup and Procedures*
  To acquire the signals were used 8 scalp electrodes placed accordingly with the 10-20 international system in the F3, F4, C3, Cz, C4, P3, Pz and P4 places. The signals were sampled and digitized at a rate of 128 Hz. The mental tasks that the system tried to identify were Relax, Right hand movementand Left hand movement. During the training the subject is induced to perform an action. The data from the training sessions was gathered to offline processing. After the training session the system was halted to allow measure the performance of the system controlling some applications being: virtual keyboard, pacman game and control a robot.
- *Results Validation*
  All the results were presented in the form of a confusion matrices and the training time required to achieve this level of performance.
- *Success Achievement*
  The training time required to achieve this performance was a few days of moderate training (1 hour per day). The ABI was able to classify three mental tasks from online spontaneous EEG signals with round 70 % accuracy. The false classifications were kept below 5%, because uncertain classifications were rejected.

Machine Brain Interface

Overview

Millan and him colleagues presented the BMI (Brain Machine Interface) system. The contribution of the BMI system is its element of control, in this system the main objective is to control a robot. In most BCI systems the element of control is a software application. In addition to this control device the system also implements a virtual keyboard that allows the user to select a letter. In the study reported in [12] was used the following methodology.

Methodologies

- *Research Procedures*
  To control the robot a high-level language was used. The robot was able to make decisions based both on user thoughts and sensor information. The signal was filtered in the 8-30 Hz band and at each 62.5 ms the power spectrum were computed over the last 1 s of data using Welch's periodogram algorithm. After this process a feature vector is created and a statistical classifier was used to classify the data.
- *Experimental Setup and Procedures*
  Were used three mental tasks named #1, #2 and #3. The #1 mental task always means to go forward, however #2 and #3 means: to turn left or follow left wall (for #2), and turn right or follow right wall (#3). The robot choose between, for instance, turn left or follow left wall basing on sensor information. Four classes were used: #1, #2, #3 and unknown To collect the signals were used 8 electrodes: F3, F4, C3, Cz, C4, P3, Pz, and P4, placed accordingly with the 10-20 international system. The signal was sampled and digitized at a rate of 128 Hz. The subjects were training during 5 and 3 days, respectively, the two subjects learned to control three mental tasks of their choice. The train session, at each day, was performed four sessions of 5 min each separated by 5 10 min. After each training session the classifier was offline optimized.
- *Results Validation*
  The results were reported in the form of rejection and error rate. Also results showing bit rate were used.
- *Success Achievement*
  The bit rate for the two subjects were 1.02 and 0.91 bits/s. And the better result during the second training session was 30% of rejection rate and 16% of erroneous classifications, for 4 prototypes.

2.2 Resumed Table

The resumed table is shown on table 1.

Res. Center	Res. Proc.	Exp. Setup and Proc.	Results Val.	Suc. Achiv.
Alberta Univ.	Filter and amplification, 4^{th} order autoregressive method and Neural Network classifier	4 electrodes placed accordingly with 10-20 system and sampled at 200 Hz, Cursor application, system and subject train and test	Hit rate	Hit rate values
Oxford Univ.	Band-pass filter, 8^{th} order autoregressive method, Bayes logigtic classifier + space smoothing and reject option	2 electrodes placed accordingly with 10-20 system and sampled at 384 Hz, Cursor application, system and subject train and test	Hit rate	Hit rate values
Wadsworth Center	2 Band-pass filters, common average derivation or the large Laplacian derivation method and signal spectrum analysis	2 electrodes placed accordingly with 10-20 system and sampled at 196 Hz, cursor application, subject train and test	Accuracy rate	Accuracy values
TTD	Filtering, Artifacts removal,signal spectrum analysis	1 electrode placed accordingly with 10-20 system and sampled at 256 Hz, cursor application and Virtual Keyboard, subject train and test	Accuracy and Training time	Accuracy values, Training time (in number of sessions) and how many subjects were able to finish the booth parts of the test program.
Graz Univ.	Band-pass filter, Hiden Markov Model with 5-fold validation	29 electrodes placed accordingly with 10-20 system and sampled at 256 Hz, perform a suggested mental task, system and subject train and test	Confusion matrices and maximum channel capacity	Confusion matrices values and maximum channel capacity value.
ABI	Band-pass filter,Surface Laplacian method, power spectrum density analysis and Neural Networks classifier	8 electrodes placed accordingly with 10-20 system and sampled at 128 Hz, identification of a mental task, system and subject train and test	Confusion matrices and Training time	Confusion matrices values, false classification rates and training time values
MBI	Band-pass filter, power spectrum density analysis, statistical classifier	8 electrodes placed accordingly with 10-20 system and sampled at 128 Hz, robotic application, system and subject train and test	Rejection and error rate, bit rate	Rejection and error rate values, bit rate values.

Table 1. Methodologies Resumed Table

3 Discussion

Regarding the methodology used in the most relevant studies in BCI area we were able to make some assumptions about BCI research.

Analyzing the field “Research Procedures” we were able to identify the main procedures concerned with the followed methodology. In all studies we can find

the typical block of EEG signal processing: filtering and features extraction. In some works were also used spatial filters, was the case of Wadswoth center and the ABI studies. These methods make part of a common processing block called Preprocessing Block.

Depending on what approach the study was based, can be found differences in the following processing blocks. In the case of the study bases on pattern recognition approach the block will be a classifier. In the case of the study be based on self regulation, Wadsworth and TTD, the block is a deterministic method, because in this case is only the user that have to perform the learning. The comparative analysis of this methods is not the aim of this work, each work have specificities accordingly with the experience of each research center have in signal processing. Talking about methodologies we can easily identify that to build a BCI system is mandatory build a Preprocessing block that filter and perform features extraction from the EEG signal; and an output block that identify the mental task that is been performed.

The field "Experimental Setup and Procedures" is consensual the use of the 10-20 international system to perform the placement of the electrodes. Additionally the most used applications are the cursor control and the virtual keyboard. Referring now to the subjects, the typical number is around 3 that trains the brain activity and, in pattern recognition approach, also the classifier. This number could be consider insufficient, however is hard to find subjects that are able to lose their time, which in some cases could be days, to perform the training and testing sessions.

The "Results Validation" field analysis shows some interesting results. The most common way to report results are in the form of accuracy based values and training time. Only a few numbers of results were shown in the form of confusion matrices, and also a few anos were shown in the form of channel capacity values.

Finally in the field "Success Achievement" the definition of success is the performance of their system. This is shown through the result values.

Resuming all the information that were analyzed we can clearly insert the research in BCI area in the area of engineering. The main reasons for this classification are the pattern that can be identified in all studies: deployment of a prototype and verification of the performance of the system. In all studies these systems has the same structural blocks, also the way how the systems were tested is the same, using human subjects. The applications were also based in the same two approaches, bi-dimensional control and menu based control. However the results need more discussion about the better way to report the performance of the system.

4 Conclusion

In this paper the most relevant studies in BCI area were analyzed. Each of the studies were analyzed taking in account the following subjects: research procedures, experimental setup and procedures, results validation and success achievement. To resume the main characteristics of each study a table was pre-

sented and the comparative analyses were discussed. The main conclusions of the global analysis of the referred studies was the classification of the BCI research in the area of engineering due to the fact that the research groups present a new system and evaluates its performance. Also were concluded that some issues in result validation have to be considered because there are no consensus in how can be evaluated a certain system.

This paper presents an analysis to the methodologies that were used in the most relevant research groups in the BCI area, trying to contribute to a deeper discussion about the methods and validation procedures that a research in BCI area should implement.

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