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Department of
Health Science and Technology

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Steady-State Visual Evoked Potentials to Drive a Brain Computer Interface

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Steady-State Visual Evoked Potentials to Drive a Brain Computer Interface

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Summary

The development of a Brain Computer Interface (BCI) system based on Steady-State Visual Evoked Potentials (SS-VEP) is described in three steps; the design of a visual stimulation paradigm, the design of a classifier, and the on-line implementation of the system. For the visual stimulation paradigm single and bi-frequency stimulation were tested. The single-frequency stimulation showed to elicit higher SS-VEP on the stimulating frequency than bi-frequency stimulation. Based on single-frequency stimulation a simple classifier was developed based on FFT power spectrum amplitude criteria. The on-line system was tested on 7 healthy subjects, giving an overall classification rate of 79.4 %. Finally, the applications in development for this system are described together with future research that will guide us to the implementation of a BCI system capable of providing communication and transportation means for disables persons.

Index Terms— Brain Computer Interface (BCI), Steady-State Visual Evoked potential (SS-VEP), electroencephalographic (EEG) analysis, FFT power Spectrum, Augmentative communication.

A. INTRODUCTION

An electroencephalogram (EEG) based Brain-Computer Interface (BCI) uses electrical signals from the cortex to control external devices like a computer or other systems and is aimed to facilitate communication for subjects with severe motor impairments. As also reported by numerous authors (see [3]), we use the principle of Steady-State Visual Evoked Potentials.

SS-VEP’s are elicited by a visual stimulus modulated at a certain frequency, which are enhanced in the EEG activity [2]. We generate a set of 9 symbols, using a standard computer monitor (CRT), which serves as visual stimulation to elicit the SS-VEP. These symbols are displayed on the computer screen using pre-developed software that permits to set any pixel of the screen at any refresh cycle to a specific color.

This document describes the steps that conducted to the implementation of a real time BCI system based on SS-VEP and the applications in development for such a system. Two pilot experiments where conducted in order to design the visual stimulation paradigm and the classifier of the BCI system. The final experiment tested both, visual stimulation (matrix of 3x3 squares, labelled with numbers from 1 to 9) and classification procedure in a real time session where subjects were asked to “dial” their own phone number and select the numbers associated with their birthday.

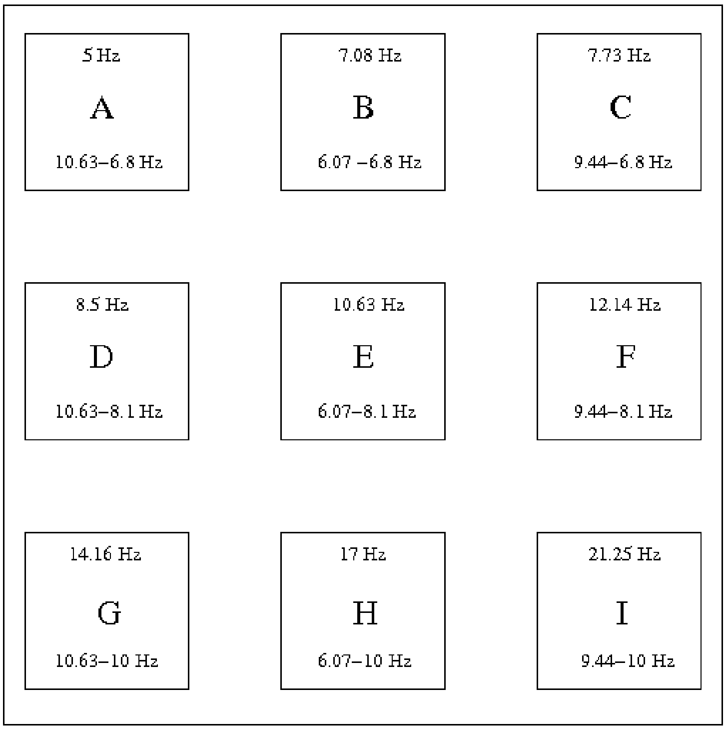

Figure 1: Distribution of the blocks on the screen. On top of each square are the frequencies used for single frequency stimulation. On the bottom of each square are the frequencies used for bi-frequency stimulations. Each square is 4x4 cm and they are separated from each other by 4 cm.

B. EEG SPECTRA USING SINGLE AND BI-FREQUENCY STIMULATION

This experiment is aimed to find out either if single or bi-frequency stimulation give letter spectra. Nine 2x2 cm blocks are settled on the screen.

1. Subjects

Three healthy subjects participate in this experiment, two males and 1 female, between 25 and 31 years old, with normal vision using glasses (subjects 1 and 3) and normal vision (subject 2).

2. Equipment

The EEG data acquisition was performed using the Quick-Cap EEG positioning system, the Nu-Amp digital amplifier and the Scan 4.3 Data Acquisition Software (Neuroscan). Data were sampled at 1000 Hz using a band pass filter set to 0.5-70 Hz, a notch filter at 50 Hz and a standard resolution of 32 bit. The skin impedance was checked four times within the experiment and maintained below 5 kΩ.

3. *Visual Stimulation*

The visual stimulation consists of a matrix of 3 by 3 yellow squares, labelled with letters from A to I, flickering on a black background, positioned as shown in Fig. 1. The squares are 4 cm^2 and they are separated from each other by 4 cm. The visual stimulation is presented to the subject through a 21 inches CRT (Cathode-Ray Tube) computer screen (Nokia Multigraph 445Xpro) with a refreshment rate of 85 Hz.
Two different visual stimulation paradigms were presented to the subjects, namely bi-frequency stimulation consisting of nine blocks flickering at nine different bi-frequencies and single-frequency stimulation consisting of nine blocks flickering at different single frequency. In the single frequency stimulation paradigm each block flickers at a particular frequency, while in the bi-frequency stimulation paradigm each block flickers at two different frequencies. Figure 1 depicts the screen configurations for the nine blocks and its respective single-frequency and bi-frequency stimulation, on top and bottom of each block respectively. To validate the frequencies delivered by the computer screen were the ones intended the light waves emitted by each square on the screen were recorded using a photo detector connected to an oscilloscope as described in [15]. For each square, 10-s of signal were recorded and the frequency content analyzed. All of the nine squares showed to deliver the right frequencies. For a detailed explanation of how to generate bi-frequency stimulation see appendix 4.

4. *Performance of the Task*

The subjects sat on a chair with the forehead 50 cm from the centre of the computer screen in a room with no other luminance than the computer screen. For each stimulation paradigm, the subjects were instructed to look at each block for five seconds, each time having an inter stimulus interval equal to five seconds. During the inter-stimulus interval a synthesized voice instructed the subject on which letter to look next. Two seconds after, a 20 ms beep gave the cue to actually look at the number and after 5 s the same cue instructed the subject to stop looking at the block. Each visual stimulation paradigm (single and bi-frequency stimulation) was randomly presented three times to each subject with a rest time of three minutes. Each time the subjects looked three times at each block (the order was randomly selected), what gives a total number of nine 5 s-trials for each single-frequency and bi-fre4quency block.

5. *Electrode Placement*

EEG signals were recorded from Oz electrode, referenced to the electrode A1 placed on the left ear lobe.

6. *Results*

The frequencies elicited by the visual stimulation are shown in Tables A1 and A2 (Appendix 1). The amplitudes presented in these tables were obtained by averaging the nine FFT spectrum (4096 points) obtained for each block. When a frequency or by-frequency stimulation shows no amplitude means that the amplitude on that

specific frequency was equal or smaller than double the average of all the samples in the spectrum. The results shown in Table A1 (Appendix 1) demonstrates that the bi-frequency stimulation elicits most of the time only one of the two stimulating frequencies, what leads to bad detection since each of the six different stimulating frequencies are used in three different blocks. For example 6.8 Hz is used in blocks A, B and C. Let's take subject 3 for blocks A, B and C, a peak in 6.8 Hz was elicited but for block A a peak in 10.6 Hz was also elicited, thus, B and C have the same feature vector as seen in Figure 2 Left-Top and Right-Top. On the other hand, single-frequency stimulation elicits the fundamental for all the blocks with exception of A, which elicits more harmonics, as seen in Table A2 (Appendix 1) and in Figure 3 Left-Middle and Right-Middle.
The spectra produced by bi-frequency stimulation have much more noise than the ones produced by single-frequency stimulation. Some of the peaks elicited by bi-frequency stimulation correspond to stimulation frequencies related to another blocks, as shown in Figure 2 Left-Bottom and Right-Bottom.

7. Discussion and Conclusions

Bi-frequency stimulation seems to have more noise than single-frequency stimulation and not always both frequencies are elicited. On the other hand single-frequency stimulation produces, in most of the cases, the fundamental frequency in the spectrum, what makes each feature vector unique, and some times some of its harmonics, what could help to develop a personalized classifier, relying on the specific characteristic of the spectra of each subject.

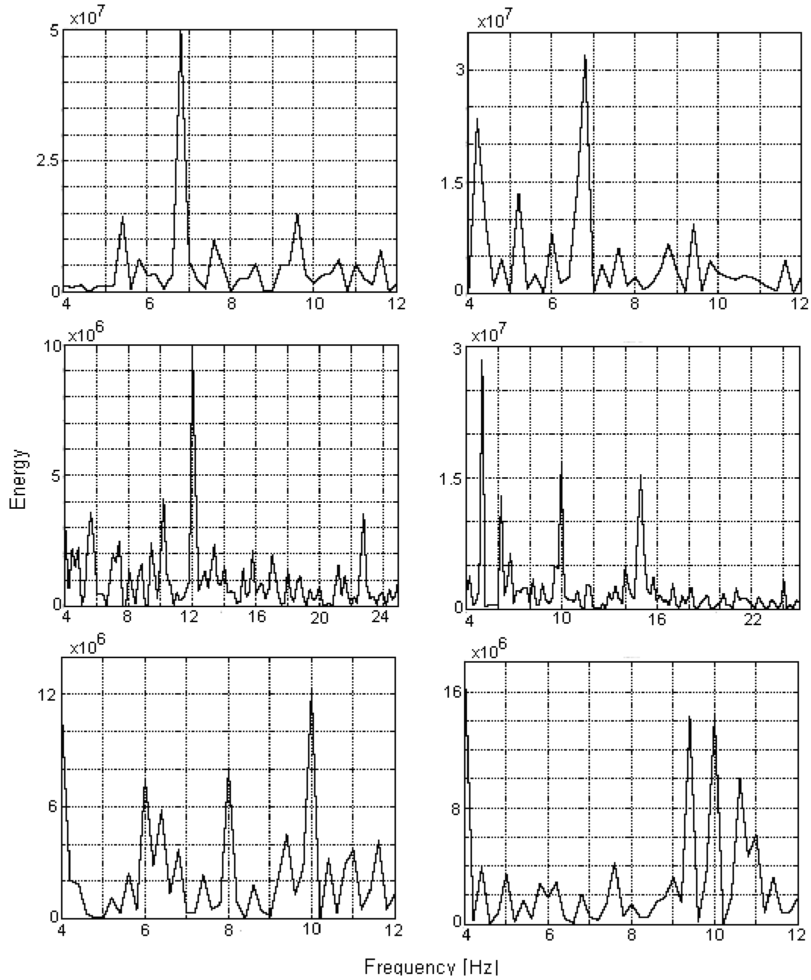

Figure 2: Left-Top Spectra of the block B with bi-frequency stimulation (6.8 and 10.63 Hz). Only 6.8 Hz was elicited. **Right-Top** Spectra of the block C with bi-frequency stimulation (6.8 and 9.44 Hz). Only 6.8 Hz was elicited. **Left-Middle** Spectra of the block F whit single-frequency stimulation. A strong component in 12.02 Hz is elicited, which correspond to the stimulating frequency. **Right-Middle** Spectra of the block A whit single-frequency stimulation. Three peaks are elicited corresponding to fundamental (5 Hz), and its first and second harmonics. **Left-Bottom** Spectra of the block E. The stimulating frequencies of the block E (6.08 and 8.1 Hz) are elicited correctly but 10 Hz, frequency that do not correspond to this block, is also elicited.
Right-Bottom Spectra of the block I. The stimulating frequencies of the block I (9.44 and 10.06 Hz) are elicited correctly but 10.6 Hz, frequency that do not correspond to this block, is also elicited.

C. DEVELOPMENT OF THE CLASSIFIER

Based on the results obtained in Section B, an off-line brain computer interface (BCI) was implemented based on power spectral analysis of single trials of steady-state visual evoked potentials (SS-VEP) elicited by single frequency visual stimulation. The visual stimulation is delivered by a standard computer screen, which presents the user with a matrix of 3 by 3 squares, each flickering at a different frequency and labelled with a number from 1 to 9. The classification made was based on simple amplitude criteria. The result for 7 healthy subjects indicates that the BCI system achieves an accuracy of 92.8 % using 5 seconds of EEG signal and 90.4 % using 3 seconds. The findings described in this section have been partially published in [12]

1. Subjects

Seven healthy subjects (5 male and two female) between 21 and 32 years old (mean 25.4, SD 3.5) participated in the experiment all with normal or corrected vision.

2. Equipment

The EEG data acquisition was performed using the Quick-Cap EEG positioning system, the Nu-Amp digital amplifier and the Scan 4.3 Data Acquisition Software (Neuroscan). Data were sampled at 500 Hz using a band pass filter set to 0.5-70 Hz, a notch filter at 50 Hz and a standard resolution of 32 bit. The skin impedance was checked four times within the experiment and maintained below 5 kΩ.

3. Visual Stimulation

The visual stimulation consists of a matrix of 3 by 3 yellow squares, labelled with numbers from 1 to 9, flickering on a black background at 5, 7.08, 7.73, 8.5, 10.63, 12.14, 14.16, 17, and 21.25 Hz. The position and frequencies of the blocks are the same as in the single-frequency paradigm stimulation described in the experiment in Section B. The squares are 4 cm^2 and they are separated from each other by 4 cm. The visual stimulation is presented to the subject through a 21 inches CRT (Cathode-Ray Tube) computer screen (Nokia Multigraph 445Xpro) with a refreshment rate of 85 Hz.

4. Performance of the Task

The subjects sat on a chair with the forehead 50 cm from the centre of the computer screen in a room with no other luminance than the computer screen. They were instructed to focus their attention on the number in the centre of the square, and to not blur their sight while looking at it. The EEG signals were recorded in segments of 5 seconds. Each trial corresponds to the evoked potential elicited by one of the

TABLE I
Stimulating frequencies with the approximated frequencies used in the recognition software, due to the frequency resolution of the FFT (0.2 Hz).

number	No. trials	Stim.Freq.-Aprox. Freq.	Aprox. 2nd harmonic	Aprox. 3rd harmonic
1	44	5 Hz-5 Hz	10 Hz	
2	49	7.08 Hz -7 Hz	14.2 Hz	21.2 Hz
3	44	7.73 Hz -7.8 Hz	15.4 Hz	23.4 Hz
4	44	8.5 Hz -8.6 Hz		
5	54	10.63 Hz -10.6 Hz	21.2 Hz	
6	44	12.14 Hz -12.2 Hz	24.4 Hz	
7	49	14.16 Hz -14.2 Hz		
8	44	17 Hz -17 Hz		
9	44	21.25 Hz -21.2 Hz		

flickering squares. 63 trials were performed by subjects number one and two and 58 trials were performed by the other 5 subjects.

5. *Signal processing*

The signal processing is based on the fact that the spectrum of the EEG signal elicited on the Oz electrode when the user focuses his attention on a specific number shows its biggest peak on the stimulation frequency or one of its harmonics [3]. FFT power spectrum was applied to 3 and 5 seconds of EEG signal. The number of the FFT in both cases was settled to 2500 (the 3 sec. signals was zero-padded).

6. *Classifier*

The classification procedure was based on simple amplitude criteria applied to the relevant frequencies. These frequencies were written into a vector: *freqvect*=[5, 10, 7, 7.8, 8.6, 10.6, 12.2, 14.2, 15.4, 17, 21.2, 23.4, 24.4]. From these frequencies the two highest peaks along with its respective amplitudes are kept for the classification phase. These frequencies correspond to the simulating frequencies and some of its harmonics, as shown in Table I (Note that the decimal values of the frequencies were approximated to the closest even number, due to the frequency resolution of the FFT). The maximum value in a ratio equal to 0.2 Hz was obtained for each of these frequencies. This procedure is applied since pilot experiments showed that the highest amplitude elicited it may correspond either to the stimulating frequency or to its second or third harmonic, with a deviation of ± 0.2 Hz. As a result of this process another vector of the same dimensions of *freqvect* is obtained. From this vector the two highest amplitudes are taken, along with its corresponding frequency. Based on these two amplitudes and its corresponding frequencies the classification process was carried as explained in following lines:

- Number 1 is recognized if: maximum amplitude corresponds to 5 Hz or 10 Hz
- Number 2 is recognized if: maximum amplitude corresponds to 7 Hz or if the maximum amplitude corresponds to a=14.2 Hz (second harmonic) and the second maximum amplitude corresponds to b=7 Hz, with b>a/3, or if the maximum amplitude corresponds to a=14.2 Hz (second harmonic) and the second maximum amplitude corresponds to b=21.2 Hz (third harmonic), with b>a/3}, or if the maximum amplitude corresponds to a=21.2 Hz (third harmonic) and the second maximum amplitude corresponds to b=7 Hz , with b>a/3, or if the maximumamplitude corresponds to a=21.2 Hz (third harmonic) and the second maximum amplitude corresponds to b=14.2 Hz , with b>a/3
- Number 3 is recognized if: maximum amplitude to 7.8 Hz, 15.4 Hz (second harmonic) or 21.2 Hz (third harmonic)
- Number 4 is recognized if: maximum amplitude corresponds to 8.6 Hz
- Number 5 is recognized if: maximum amplitude corresponds to 10.6 Hz or if the maximum amplitude corresponds to a=21.2 Hz (second harmonic) and the second maximum amplitude corresponds to b=10.6 Hz, with b>a/3
- Number 6 is recognized if: maximum amplitude corresponds to 12.2 Hz or 24.4 Hz
- Number 7 is recognized if: maximum amplitude corresponds to 14.2 Hz
- Number 8 is recognized if: maximum amplitude corresponds to 17 Hz
- Number 9 is recognized if: maximum amplitude corresponds to 21.2 Hz

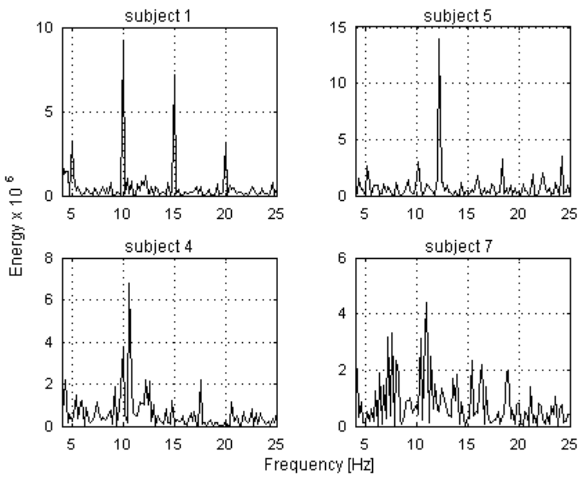

Figure 3: Top Left: Right recognition of Nr. 1. Top Right: Right recognition of Nr. 5. Bottom Left: Looked at Nr. 9 and Nr. 5 is recognized. Bottom Right: Looked at Nr. 9 and Nr. 3 is recognized. (5 sec. EEG signal)

TABLE II
Average accuracy of the BCI system for each of the 7 subjects (over the 9 characters) using 3 seconds and 5 seconds of EEG signal.

Subject	Average Accuracy (5 s)	Average Accuracy (3 s)
Sub.1	98.4 %	98.4 %
Sub.2	95.2 %	93.7 %
Sub.3	93.1 %	86.2 %
Sub.4	93.1 %	89.7 %
Sub.5	98.2 %	93.1 %
Sub.6	98.2 %	96.6 %
Sub.7	75.9 %	72.4 %
grand average	**92.8 %**	**90.4 %**

7. Results

The analysis with 5 seconds over seven subjects showed an average accuracy of the BCI system of 92.8 %. For 3 seconds of EEG signal the average accuracy over seven subjects is 90.4 %. The results for each of the seven subjects are shown in Table II. Spectra leading to right recognition are shown in Figure 3, Top Left: Nr.1 (harmonics of 5 Hz) and Top Right: Nr. 6 (12.14 Hz). Individual recognition rates for each stimulation frequency together with the recognition rates for each stimulation frequency over all 7 subjects are shown in Appendix 2.

8. Discussions

We have studied the performance of an SS-VEP based BCI system, which use the power spectrum of the EEG signals and apply an amplitude detection criterion to classify 9 different commands, voluntarily elicited by the subjects.
The better performance of the system using 5 s is a result of the FFT-based periodogram analysis due to a combination of the inverse proportionality between observation length and resolution, and the improvement of signal/noise ratio obtained with longer observation time.
Subject 7 showed to have a lower recognition rate than the other 6 subjects, specially regarding characters 7, 8 and 9. The wrong detections were mainly caused by blur spectra, with very different frequency content from a normal SS-VEP spectrum. This subject reported to be sleepy and dizzy at the moment of the experiment. Fig 3 (bottom right) shows how subject 7 elicits a number of peaks in frequencies that have nothing to do with the stimulation frequency (21.2 Hz). In this case number 3 was recognized, which stimulating frequency (7.8 Hz) is neither a multiple nor a fraction of 21.2 Hz, the frequency related to number 9. Errors for the other subjects are related to the elicitation of frequencies related with other characters, i.e. number 9 often elicit 10.6 Hz (sub-harmonic) as shown in Fig.2 (bottom left), which is the stimulating frequency for character number 5. Thus number 5 is detected. Same situation occurs with the next two pairs: 9-1 and 2-7, where the former elicits peaks in frequencies related to the later.

9. *Conclusions*

The results of this study show a high recognition rate for the SS-VEP based BCI, giving nine different commands to control, with no muscle activity but eye movement, any external device, i.e., a word processor for paralysed subjects. The time dependency of the FFT analysis makes it difficult to reduce the time required for an optimal detection, what suggest either a different approach for the spectral analysis, i.e., ARMA modelling or/and a more optimal detection algorithm. In order to avoid wrong classification due to overlapping between stimulating frequencies and sub-harmonics a change in the stimulating frequencies related with numbers 9 and 2 (21.25 and 7.06 Hz) is also necessary.

D. ON-LINE SYSTEM

Based on the results from experiments described in Section B and C an on-line BCI system was developed using single frequency stimulation paradigm and a simple classifier based on amplitudes of FFT spectrum. The findings described in this section have been partially published in [11]

1. *Subjects*

Seven healthy subjects, six males (two of them with myopia and wearing glasses) and one female participate on the experiment.

2. *Equipment*

The EEG data acquisition was performed using the Quick-Cap EEG positioning system, the Nu-Amp digital amplifier and the Scan 4.3 Data Acquisition Software (Neuroscan). Data were sampled at 500 Hz using a band pass filter set to 0.5-70 Hz, a notch filter at 50 Hz and a standard resolution of 32 bit. The skin impedance was checked four times within the experiment and maintained below 5 kΩ.

3. *Visual Stimulation*

The visual stimulation consists of a matrix of 3 by 3 yellow squares, labelled with numbers from 1 to 9, flickering on a black background at 5, 7.08, 7.73, 8.5, 10.63, 12.14, 14.16, 17, and 9.44 Hz. The position of the blocks is the same as in the single-frequency paradigm stimulation described in the experiments in Section B and Section C and depicted in Fig. 1. The squares are 4 cm^2 and they are separated from each other by 4 cm. The visual stimulation is presented to the subject through a 21 inches CRT (Cathode-Ray Tube) computer screen (Nokia Multigraph 445Xpro) with a refreshment rate of 85 Hz.

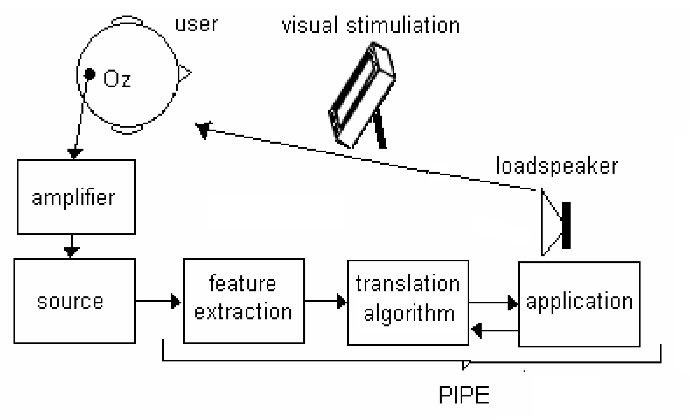

Figure 4: Parts of the implemented BCI system. The pipe consists of three different modules: feature extraction, translation algorithm and application. The amplifier acquires and digitizes the EEG potentials evoked by the visual stimulation, which are pushed into the pipe by the source module. The feature extraction module produces features that are fed into the translation algorithm, which delivers a device command to the application, the latter gives audible feedback to subject.

4. Performance of the Task

The subjects sat on a chair with the forehead 50 cm from the centre of the computer screen. The subject was instructed to "dial" his/her phone number, birth date, and the numbers from one to nine, by gazing at the different numbered squares on the computer screen. Regarding the visual stimulation the subjects were asked to focus their attention on the number in the centre of the square. Subjects were instructed to pass to the next number after they heard a spoken number, whether or not it matched with the desired. Each phone number and birth date was dialed three times and numbers from one to nine were dialed four times, giving a total of 81-85 numbers depending on the phone number and if the month of birth had one or two digits.

5. Feature Extraction and Classification

Feature extraction and detection was controlled by a modular C^{++} software system, developed at Aalborg University, running on a Windows XP platform (see appendix 3). FFT power spectrum was performed, with an FFT number equal to 2048 (~4 s segments). Fourteen frequency bins, [5, 10.63, 7.08, 7.73, 8.5, 10.63, 12.14, 14.16, 15.4, 17, 21.2, 23.4, 24.4, 9.44], were picked from the power spectrum of each trial. From these frequencies the two highest peaks along with its respective frequencies form the feature vector. The classification procedure was performed according to the classifier described in Section C, with one sole difference: the stimulating frequency corresponding to block number 9 was changed from 21.25 Hz to 9.44 Hz, thus, the system would recognize the number 9 when the highest peak correspond to 9.44 Hz.

TABLE III.
SSVEP detection results from 7 healthy subjects using an online SS-VEP based BCI system. Subject 4 was only female subject, and subject 6 and 7 had myopia corrected with glasses. Detections are percentage correct classifications of all recorded segments. Signaling speed is in symbols/minute. Information Transfer Rate (ITR) is in bits/min.

Subject	Detections	Sig. speed [min^{-1}]	ITR [b/min]
Sub.1	94.15 %	8.3	22.19
Sub.2	94.34 %	9	24.18
Sub.3	92.37 %	7.2	18.37
Sub.4	100 %	10.5	33.28
Sub.5	89.54 %	11.5	27.29
Sub.6	71.6 %	9	13.11
Sub.7	57.65 %	9.5	8.71
average	**79.74 %**	**9.29**	**21.0**

6. The On-line Software

The on-line system developed here was designed as a modularised system, and is described in Fig. 4. The source is the module in charge of retrieving the continuous EEG signal from the amplifier and pushing blocks of N samples into the pipe, which consists of three modules: feature extraction, translation algorithm (which includes the classification process and the translation of the classification result into a command which is meaningful to the application, known as device command) and application. The EEG blocks are processed by each module and passed to the next one, until it gets to the application module, which gives feedback to the user. Online extraction of SSVEP features and classification is accomplished by power spectral analysis using FFT-based non-averaged periodograms on 2048 samples. Symbol selection is based on the amplitudes in the first, second and third harmonics as described in Section C. If the amplitudes are below an empirically set threshold no symbol is selected and the next segment is analyzed with an overlap of 1024 samples. The subjects were given feedback as an auditory playback of the detected number using a sampled voice.

7. Results

Experimental results from 7 subjects showed that 79.7% [57.7-100%] of the trials were correctly detected and classified with an average signaling rate of 9.3 [7.2-11.5] characters per minute. The Information Transfer Rate (ITR), a measure of communication transfer speed and accuracy, was also calculated according to [3] and [5]. These results can be seen in Table III.

8. Discussions

The required training time is negligible when using SS-VEP as compared to methods using event-related desynchronization/synchronization (ERD/ERS), for instance, [3] and [7]. Additionally, relatively high ITR’s are possible. Our system reaches an average ITR over 7 subejcts of 21 b/min, the Berlin BCI, which is based in motor imagery, reaches an average ITR over 9 subjects of 12.8 b/min [13], the system developed at the Tsinghua University in Bijing, based on SS-VEP, shows an average ITR of 27.15 b/min over 13 subjects [6].

The detection algorithm was implemented using a strategy favoring true positive detections at the expense of speed, i.e. shorter EEG segments would give faster but poorer detection results with more false positives and amplitudes below the empirical threshold selected for each subject will not produce any output, avoiding again false positives but making slower decisions (the next segment is analyzed with an overlap of 1024 samples).

Possible approaches to make the system faster are: to use more than one channel for detection as done in [5], [6] and [14], use Independent Component Analysis to capture early activation (below 1-s) of visual evoked responses, as suggested by Samir et al. [14].

Using SS-VEP based BCI some control of eye movements is needed, although we have experienced that attention without direct gazing can be used, as also reported by Kelly et al. and Allison et al [8], [9]. SS-VEP is a fast and “ready to use” communication tool for patients impaired by e.g. stroke or lesions on the spinal level.

9. Conclusion

The studies presented herein confirm that a simple yet relatively fast BCI can be obtained using the synchronized method of SS-VEP utilizing EEG as a command signal and using standard programmable equipment. One of the major challenges in systems using EEG based command signals is the rather low information transfer rates from 12.8 b/min using a motor imagery based BCI-system [13] and up to 68 b/min for SS-VEP based systems (one subject who was familiar with the system) [5]. Achievement of greater speed and accuracy depends on improvements in signal processing, translation algorithms, and in certain cases user training. These improvements depend on increased interdisciplinary cooperation between neuroscientists, engineers, psychologists, and rehabilitation specialists

The EEG has already shown to be a useful command signal for disabled without motor functions and thus no alternative signaling capabilities. Future work will very likely improve the signaling speed and the controlling paradigms and develop new assisting devices**.**

E. APPLICATIONS NOW AND IN THE FUTURE

The current efforts on the SS-VEP BCI are directed towards the implementation of an electric wheelchair with a portable computer mounted, whose screen will present to the patient with the BCI's Graphic User Interface (GUI). Two applications are being implemented for this SS-VEP controlled wheelchair, to provide communication and transportation means to persons with disabilities. For the communication purposes a "multi-tap" alphabet (like those used for text messaging in mobile phones) in connection with a Predictive Text Writer (PTW) has been designed in order to speed up the information transfer rate and promote an efficient communication tool for patients. On the other hand, for transportation purposes, an autonomous wheelchair is being designed, which will be able localize it self within a know environment and mobilize the patient to any desired location within the facilities, we have named this application wheelchair Navigation (WN). These two applications are being developed in an interdisciplinary effort by the Center for Sensory-Motor Interaction (SMI), the Intelligent Multimedia (IMM) Department and the Control Department of the Aalborg University. An overview of the complete BCI system, that has been called Device for Communication and Transportation Purposes (DCTP), and the state of both applications are described in the following subsections.

1. Device for Communication and Transportation Purposes (DCTP)

The hardware of the DCTP consists of four main components: the EEG acquisition system, an electric wheel, a portable computer and different kind of sensors, as shown in Fig. 5. All of them interact with each other in different ways depending on the application being used. The software of the DCTP is constituted of the BCI, PTW and WN programs. The former has been described in detail is previous section and the two latter will be described in the present one. The portable computer hosts the software that controls the BCI system and the applications, which are controlled by the EEG activity acquired by the EEG acquisition system. Trough the applications the electric wheelchair and the PTW are controlled providing the patient with communication and mobilization means. The sensors have the function of delivering feedback to system concerning the positioning of the wheelchair and its trajectory.

The main menu of the DCTP consists of three blocks flickering at different frequencies, as shown in Fig. 6. The size of the block is 2x2 cm. and the separation among them will depend on the number of blocks used, in this case only three blocks are used, but up to nine blocks can be used, what would provide 8 different applications in one Menu or several more if sub-menus are added.

The two blocks on top are shortcuts for the PTW and the WN and the block on the bottom switches on/off the entire system. When the system is initialized the on/off switch looks likes in Fig. 6a, with the 'off' text underneath the block stress in red letters and the 'on' text above the block written in dark letters. At this point the EEG signals are being monitored, features are extracted (FFT power spectrum) and classified but no action is taken unless the stimulation frequency of the switch block if found to be the main component in three consecutive one second FFT spectra; the system is in standby.

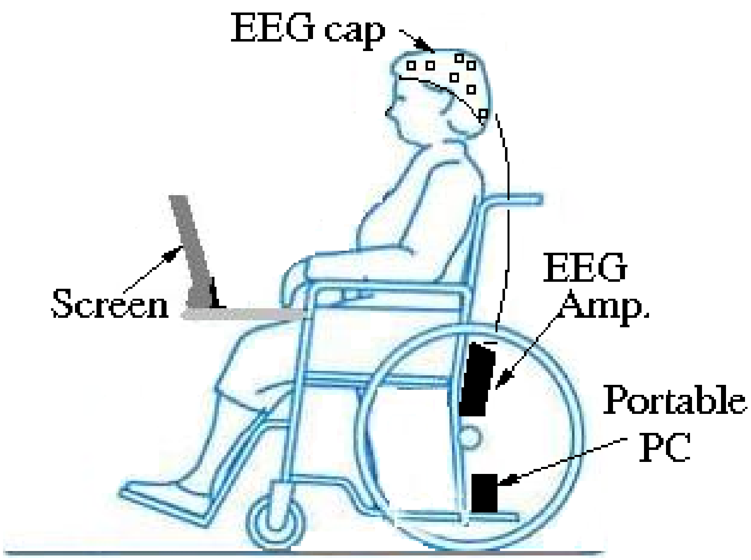

Figure 5: The DCTP system. The subject is sited on the electric wheelchair which serves as support for the PC and EEG acquisition system. The EEG cap is connected to the EEG amplifier which is connected to the PC via USB. The screen displays the GUI of the BCI and its applications. The location and type of the sensors has still not been settled since the WN application is in development.

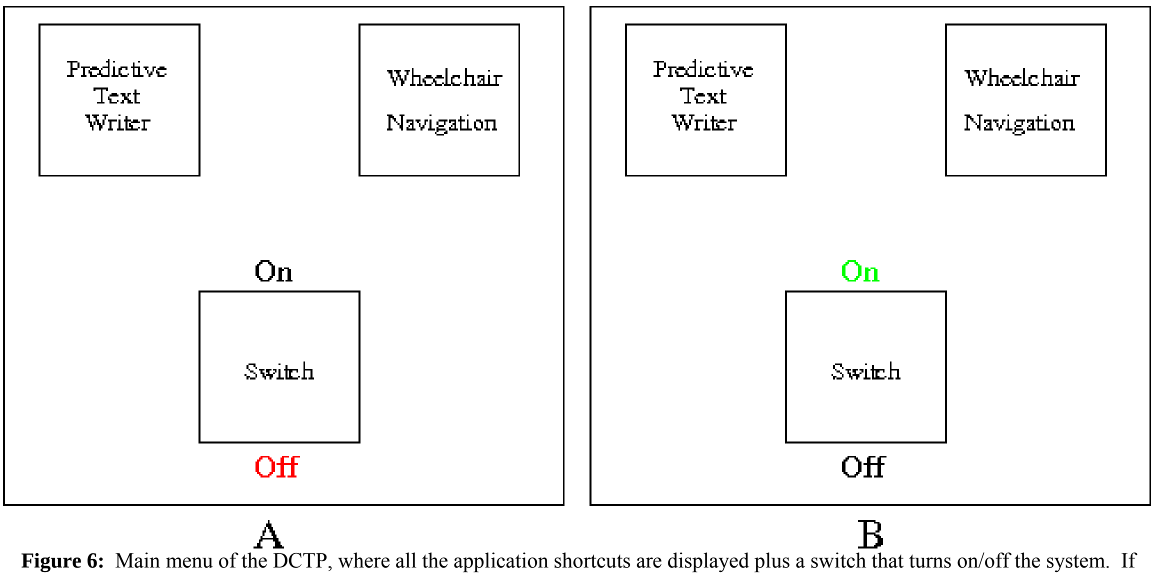

Figure 6: Main menu of the DCTP, where all the application shortcuts are displayed plus a switch that turns on/off the system. If more applications are developed, the number of blocks will grow accordingly. A) Main menu where the system is off or in standby, as the text underneath the switch block shows in red letters. B) Main menu where the system is on, as the text above the switch block shows in green.

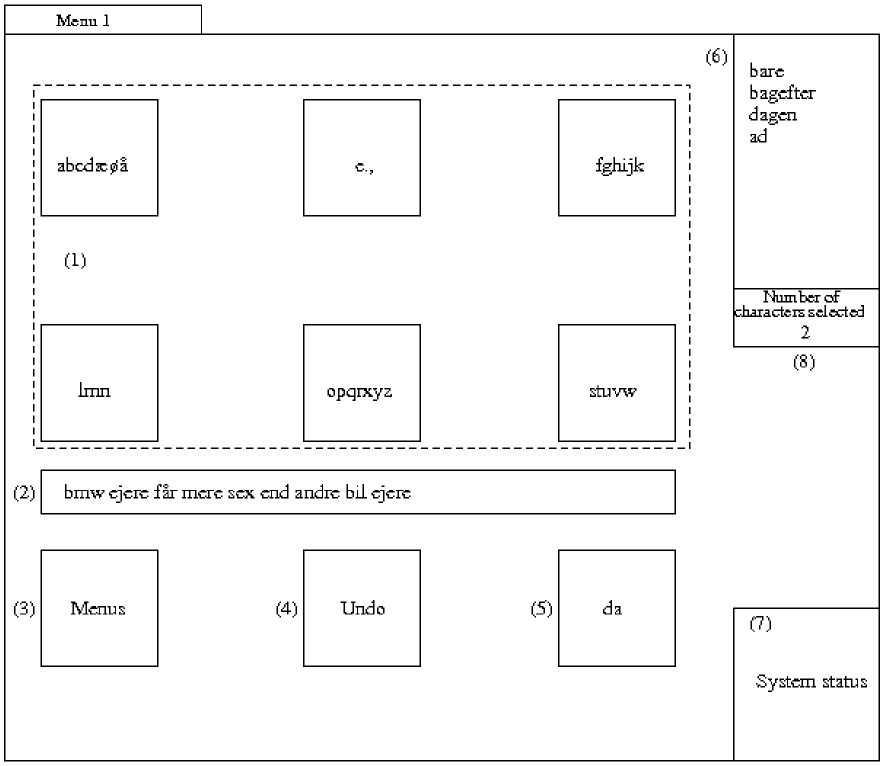

Figure 7: Menu 1. Is the initial menu presented, from where the subject can begin to write a text (Adapted from [10]).

If the system detects the switch block's stimulation frequency in three consecutive spectra the BCI is turn on, and actions will be taken if either of the three block's stimulation frequencies are found. At this time the switch block change its appearance, displaying the 'on' text above the block stress in green letters and the 'off' text underneath the block written in dark letters, as shown in Fig. 6b. From now on we will understand by 'detection' of a frequency the detection of a frequency component as the highest peak in three consecutive FFT spectra.

If the stimulation frequency of the PTW block is detected a new window pops up, displaying the PTW's GUI. If the stimulation frequency of the WN block is detected a new window pops up, displaying the WN's GUI. Finally if the stimulation frequency of the switch block is detected the system goes back to standby.

2. Predictive Text Writer (PTW)

The PTW[1] described in this section has been designed to enable a user to write text using a BCI system and a speech synthesizer to convert text to speech [10]. The language model has been trained using the 'Korpus 2000', which is a Danish corpus from the *Danish Language and Literature Society.* The PTW's GUI is divided into five menus; each of them displays nine flickering blocks:

---

[1] The PTW has been developed by Laust bach Larsen and Mads Torp Jacobsen whom have been supervised by Paul Dalsgaars and Zhang Hau Tan during an IMM 8th semester project proposed by Alvaro Fuentes Cabrera and Kim Dremstrup [10]

Menu 1: Word Prediction
Menu 2: Word Selection
Menu 3: Character prediction
Menu 4: Character selection
Menu 5: Show all text

As an example **Menu 1**, which is the main menu, is depicted in Fig. 7. Nine interactive blocks and three feedback text blocks are the components of this menu. Eight interactive blocks provide different functionalities to the user and the last block is used to shift between menus. The three feedback text blocks display information related with the state of the system, the text written so far and a prediction list.

Fig.7is divided into 7 parts, each of them denoted with round parenthesis (), which are described as follow:

(1) Six character blocks which cover the whole Danish alphabet
(2) Output text field which shows the last part of the written text
(3) Shift to the menus window, where the user can choose to go to any of the above described menus or go back to the main DCTP menu depicted in Fig.6.
(4) Undo block
(5) Prediction block showing the word with the highest probability of being next in the sentence
(6) Prediction list showing the next four words with highest probability of being the next in the sentence
(7) Text field used by the PTW to give feedback to the user in case of system errors
(8) Text field showing the number of character in the word selected by the user

Every time the user selects a character block a new prediction is performed and the prediction block and prediction lists are updated.
The PTW is in development and at present time a complete analysis and design of the PTW and the GUI has been carried out. So far only the PTW has been implemented. For a complete description of all menus and the PTW see [10].

3. *Wheelchair Navigation (WN)*

The WN[2] application is intended to control a wheel chair in a known environment, i.e. the house, apartment or working place of an individual with motor disabilities. The main WN GUI, shown in Fig.8, contains a floor plan of the place, a 'GO/STOP' block, which gives the command to start moving after selecting the desired location or stops the wheelchair if is already in movement, and a 'MAIN MENU' block which shifts to the main DCTP menu depicted in Fig.6. Each of the rooms in the floorplan contains a block with the name of the room which flickers at a certain frequency. The subject will gaze at the room he/she wants to go, and the translation device of the BCI system will detect the stimulating frequency of the room the subject is gazing at, a device command then is sent to the WN application and the wheel chair will take the subject to the desired location.

The wheel chair should be able to:

a) Location Algorithm: locate it self within the chosen environment, i.e. whether it is in the kitchen, the toilet or one of the rooms, and in which part of the specific room, i.e. close to the door or behind the table..
b) Path Planning: after receiving a command from the translation device, the wheel chair should be able to find the route from the current position to the desired location (path planning).
c) Obstacle Avoiding: avoid any obstacles that might be on the way, either objects that are not usually in the trajectory, i.e. toys, boxes, etc. or objects that are usually placed in a determined position, i.e. a coffee table, a desk, etc.

At present time the location algorithm, path planning and obstacle avoiding have being designed and implemented in Simulink using a LegoBot as a model of the wheelchair. The next step is the implementation of the control for the actual electric wheelchair.

4. *Future Applications*

In the future applications like sending text messages using mobile phones and web browser are contemplated to wider the range of communication alternatives for person with disabilities. These applications will be developed in an interdisciplinary framework which consists of professionals from the Intelligent Multimedia specialization, IT department and Center for Sensory-Motor Interaction of the Aalborg University.

[2] The WN is being developed by Jeppe Møller Holm and Søren Lynge Pedersen under the supervision of Anders La Cour-Harbo during a 9th -10th semester project proposed by Alvaro Fuentes Cabrera, Omar Feix Do Nascimento and Kim Dremstrup.

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The authors would like to thanks Antanas Veiverys for his valuable help with the real time programming of the BCI system, Judex Datasystemer for the DLL and to the student and supervisors that worked and are working on the applications of the BCI system:

WN: Jeppe Møller Holm and Søren Lynge Pedersen under the supervision of Anders La Cour-Harbo

PTW: Laust bach Larsen and Mads Torp Jacobsen whom had been supervised by Paul Dalsgaard and Zhang Hau Tan

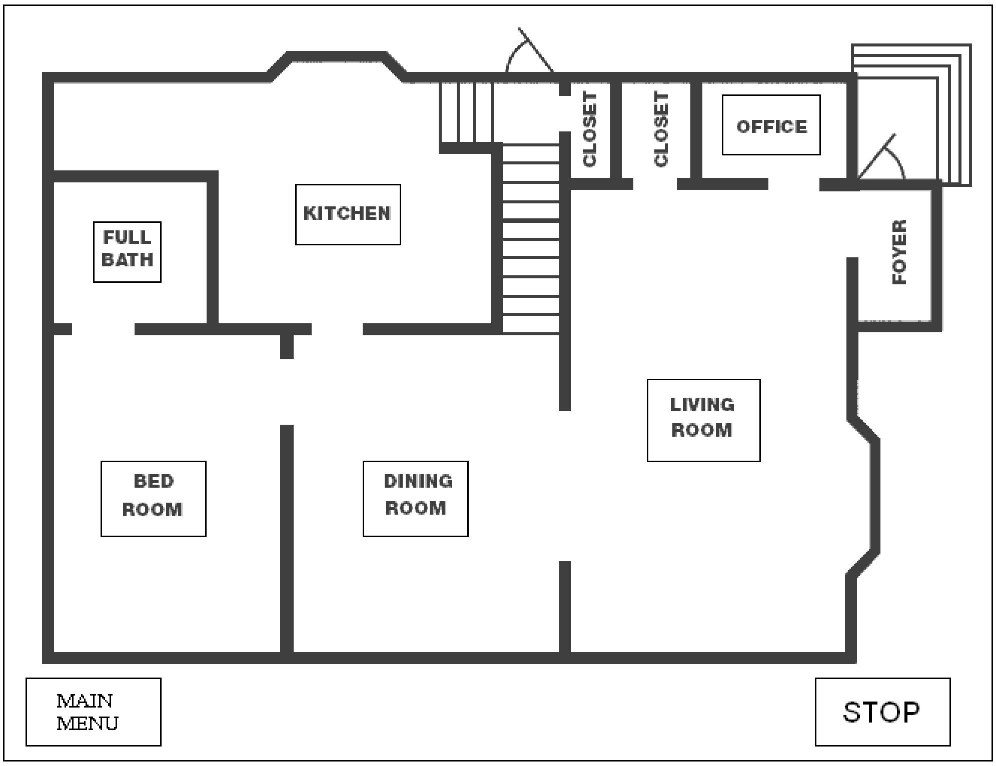

Figure 8: Floor plan of an apartment displayed on the screen for the subject to choose the room that the wheel chair should take him to. Each block containing the name of the room flickers at a specific frequency, which is recognized by the translation algorithm which sends the device command to the WN application to transport the wheel chair to the selected position. The block labelled stop can be used to stop the wheelchair at any desired moment if is in movement. The same STOP block will switch to GO if the wheelchair is still, and it will be used to give the command to start the movement after a location has been selected. The block on the left bottom shifts to the main DCTP menu depicted in Fig. 6.

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APPENDICES

App1 *ADDITIONAL TABLES FROM SECTION B. EEG SPECTRA USING SINGLE AND BI-FREQUENCY STIMULATION*

This appendix contains tables from section B. EEG Spectra using Single and Bi-frequency Stimulation. Table A1 displays Results for single frequency stimulation and Table A2 displays results for bi-frequency stimulation.

TABLE A1
Results for single-frequency stimulation. The first two columns show the letter and its stimulation frequency and the three other columns show the elicited frequencies in the Oz electrode.

Sub.1	Stimulating		Hz / amplitude x 10exp7	
Letter	freq. [Hz]	Fundamental	1st harmonic	2nd harmonic
A	5		10 / 2.6	15 / 2.4
B	7.08	7.2 / 3.5	14.2 / 2.9	
C	7.73	7.8 / 2.2	15.4 / 2.8	
D	8.5	8.4 / 1.01		
E	10.63	10.6 / 0.52		
F	12.14	12 / 0.97		
G	14.16	14.2 / 2.03		
H	17	17 / 1.44		
I	21.25	21.1 / 0.53		
Sub.2	Stimulating		Hz / amplitude x 10exp7	
Letter	freq. [Hz]	Fundamental	1st harmonic	2nd harmonic
A	5	5 / 2.84	10 / 1.68	15 / 1.54
B	7.08	7.2 / 2.05	14.2 / 3.94	
C	7.73	7.8 / 1.28	15.4 / 3.28	
D	8.5	8.4 / 4.2		
E	10.63	10.6 / 4.01		
F	12.14	12.2 / 3.2		
G	14.16	14.2 / 0.16	6.8 / 1.5	
H	17	17 / 3.82		
I	21.25	21.2 / 2.56		
Sub.3	Stimulating		Hz / amplitude x 10exp7	
Letter	freq. [Hz]	Fundamental	1st harmonic	2nd harmonic
A	5			15 / 5.75
B	7.08	7 / 5.05	14.2 / 2.73	21.2 / 2
C	7.73	7.8 / 9.05	15.4 / 2.66	23.2 / 1.37
D	8.5	8.4 / 3.07		
E	10.63	10.6 / 6.17	21.2 / 2.1	
F	12.14	12.2 / 1.96	24.2 / 3.15	
G	14.16	14.2 / 1.07	6.6 / 0.97	
H	17	17 / 1.62		
I	21.25	21.4 / 0.66		

TABLE A2

Results for bi-frequency stimulation. The first two columns show the letter and its stimulation frequencies and the other column shows the elicited frequencies in the Oz electrode.

Sub.1 Letter	Stimulating freq. [Hz]	elicited freq. Hz / amplitude x 10exp6
A	6.8 - 10.63	6.8 / 10.6
B	6.07 - 6.8	6 / 10.8 - 6.8 / 6.6
C	6.8 - 9.44	6.8 / 5.3 - 9.6 / 8.05
D	8.1 - 10.63	8.2 / 6.2 - 10.4 / 5.85
E	6.07 - 8.1	6 / 7.5 - 8 / 8.1
F	8.1 - 9.44	
G	10 - 10.63	10 / 10
H	6.07 - 10	6.4 / 10
I	9.44 - 10	
Sub.2 Letter	**Stimulating freq. [Hz]**	**elicited freq. Hz / amplitude x 10exp7**
A	6.8 - 10.63	6.8 / 1.67 - 10.6 / 2.15
B	6.07 - 6.8	6.8 / 5.08
C	6.8 - 9.44	6.8 / 5.1 - 9.4 / 2.97
D	8.1 - 10.63	8 / 1.8 - 10.6 / 1.6
E	6.07 - 8.1	8.2 / 3.8
F	8.1 - 9.44	8 / 3.25
G	10 - 10.63	10 / 2.7
H	6.07 - 10	10 / 2.23
I	9.44 - 10	9.4 / 1.43 - 10 / 1.44
Sub.3 Letter	**Stimulating freq. [Hz]**	**elicited freq. Hz / amplitude x 10exp7**
A	6.8 - 10.63	6.8 / 3.15 - 10.6 / 5.76
B	6.07 - 6.8	6.8 / 4.9
C	6.8 - 9.44	6.8 / 3.17
D	8.1 - 10.63	10.6 / 4
E	6.07 - 8.1	8 / 2.55
F	8.1 - 9.44	8 / 6 - 9.4 / 3.4
G	10 - 10.63	10 / 1.81
H	6.07 - 10	10 / 2.7
I	9.44 - 10	10 / 3

App2 *ADDITIONAL TABLES FROM SECTION C.* DEVELOPMENT OF THE CLASSIFIER

This appendix contains additional tables from section C. Development of the Classifier. Tables A3 and A4 display classification rates for each stimulation frequency. Tables A5 and A6 display classification rates for each subject.

TABLE A3
Results for 5 seconds of EEG signal over 7 subjects (average accuracy). The numbers in the first column correspond to the frequency the subject looked at. The numbers in the first row correspond to the number recognized by the BCI system.

5 s	5 Hz	7.08 Hz	7.73 Hz	8.5 Hz	10.63 Hz	12.14 Hz	14.16 Hz	17 Hz	21.25 Hz
5 Hz	**100%**								
7.08 Hz		**89.8%**			4.08%		4.08%		2.04%
7.73 Hz		2.27%	**95.46%**		2.27%				
8.5 Hz			2.27%	**97.73%**					
10.63 Hz					**100%**				
12.14 Hz						**100%**			
14.16 Hz	2.04%	2.04%	4.09%	2.04%	2.04%		**87.75%**		
17 Hz	6.82%	2.27%		2.27%				**88.64%**	
21.25 Hz	9,1 %	4.54%			11.36%				**75%**

TABLE A4
Results for 3 seconds of EEG signal, over 7 subjects (average accuracy). The numbers in the first column correspond to the frequency the subject looked at. The numbers in the first row correspond to the number recognized by the BCI system.

3 s	5 Hz	7.08 Hz	7.73 Hz	8.5 Hz	10.63 Hz	12.14 Hz	14.16 Hz	17 Hz	21.25 Hz
5 Hz	**93.19%**	2.27%		2.27%	2.27%				
7.08 Hz		**89.8%**			4.08%		4.08%		
7.73 Hz		4.55%	**90.9%**		4.55%				
8.5 Hz				**100%**					
10.63 Hz	1.85%				**98.15%**				
12.14 Hz					2.27%	**97.73%**			
14.16 Hz	2.04%	16.32%	4.08%				**77.76%**		
17 Hz		2.27%	2.27%	2.27%				**93.19%**	
21.25 Hz		11.36%			13.63%			2.27	**72.74%**

TABLE A5

Individual results using 5 seconds of EEG signal. The average accuracy for each character is shown as well as the average accuracy over the 9 characters.

5s	5 Hz	7.08 Hz	7.73 Hz	8.5 Hz	10.63 Hz	12.14 Hz	14.16 Hz	17 Hz	21.25 Hz	**Total**
Sub.1	100%	85.7%	100%	100%	100%	100%	100%	100%	100%	**98.4%**
Sub.2	100%	100%	100%	100%	100%	100%	100%	100%	57.2%	**95.2%**
Sub.3	100%	57.1%	85.7%	100%	100%	100%	100%	100%	100%	**93.1%**
Sub.4	100%	100%	100%	100%	100%	100%	85.7%	100%	50%	**93.1%**
Sub.5	100%	85.7%	100%	100%	100%	100%	100%	100%	100%	**98.2%**
Sub.6	100%	100%	100%	83.3%	100%	100%	100%	100%	100%	**98.2%**
Sub.7	100%	100%	83.3%	100%	100%	100%	28.6%	16.6%	16.6%	**75.9%**

TABLE A6

Individual results using 3 seconds of EEG signal. The average accuracy for each character is shown as well as the average accuracy over the 9 characters.

3s	5 Hz	7.08 Hz	7.73 Hz	8.5 Hz	10.63 Hz	12.14 Hz	14.16 Hz	17 Hz	21.25 Hz	**Total**
Sub.1	100%	85.7%	100%	100%	100%	100%	100%	100%	100%	**98.4%**
Sub.2	100%	100%	100%	100%	100%	100%	100%	100%	42.87%	**93.7%**
Sub.3	66.6%	71.4%	66.6%	100%	100%	100%	100%	100%	83.3%	**86.2%**
Sub.4	100%	100%	100%	100%	100%	100%	71.4%	100%	33.3%	**89.7%**
Sub.5	83.3%	85.7%	100%	100%	87.5%	100%	85.7%	100%	100%	**93.1%**
Sub.6	100%	100%	71.4%	100%	100%	100%	85.7%	100%	100%	**96.6%**
Sub.7	100%	100%	83.3%	100%	100%	83.3%	14.3%	16.6%	16.6%	**72.4%**

App3 *GUI OF THE ACQUISITION SYSTEM OF THE REAL TIME BCI.*

The stimulation program was developed on visual C running on Windows XP and it is based on the NetReader software provided by Neuroscan for its EEG acquisition systems and it functions together whit Scan 4.3 software. For a user guide of NetReader and Scan 4.3 please refer to the Neuroscan documentation.

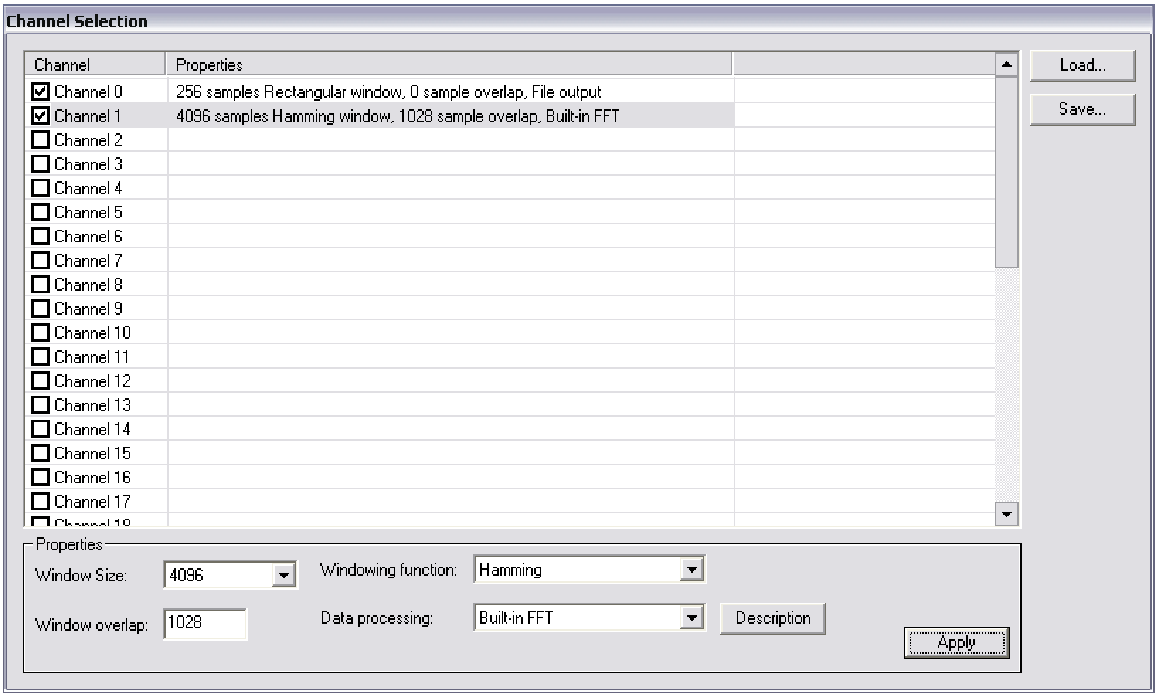

Figure A1: GUI of the acquisition system of the BCI.

Several channels can be selected, as shown in Fig. A1. Each channel has independent settings (except sampling rate that is set in *Acquire*), such as:

- Window size: a size in power of 2, from 32 to 4096. Other window sizes can be also added, if needed;
- Window overlap: set how many samples from current window are included at the beginning of the next window;
- Windowing function: select between *Rectangular*, *Hamming*, *Blackman*, *Flat Top* and *Hann* windows. Other functions can be added, if needed.
- Data processing function: lets the user choose between the '*Built-in FFT'* function, *'File output', 'Discard data'* and other data processing functions. If some valid .DLL libraries are found during program start, they are also added to the list. A description of the selected function can be viewed by pressing *Description* button.

Only checked (enabled) channels can be edited. Summaries of their settings are shown in the channel list, as shown in the figure.
Channel settings can be saved to and loaded from a *.ini* file.
During data acquisition the enabled channels receive data samples. Data buffers are provided for each channel. When the number of received samples becomes

equal to the window size of a particular channel, the selected windowing function is applied and selected data processing function is called. A circular buffer is implemented in order to minimize data moving overhead.

App4 *VISUAL STIMULATION PROGRAM*

The stimulation program was developed on visual C running on Windows Xp. The program is constituted of a dynamic-link library (VisualStimmDLL.dll) an executable file (GUI.exe) and a folder with several text files (Exp1). Place the GUI.exe and the Exp1 folder in the C: drive, the VisualStimmDLL.dll in C:\WINDOWS\SYSTEM32. The VisualStimmDLL.dll dynamic-link library was developed by Judex DataSystems and modified by Casino et al. and the executable file GUI.exe was developed by Wahoun et al. [1] (they do not to work on Windows 95/98). Using DirectX on WindowsXP it was possible to control the content of the monitor at the refresh rate of the screen enabling the programmer to set any pixel of the screen at any refresh cycle to a specific color. This program uses a setup file, with extension txt, to obtain the necessary parameters to run. This setup files must be placed in \c:/Exp1/". An example of a setup file is shown next:

```
numBlocks = 2
#
BiF r; Letter = A
Nred = (1; 9; 1; 10); Ngreen = (1; 6; 1; 7)
P os = (100; 000; 100; 100)
#
BiF r; Letter = B
Nred = (1; 9; 1; 10); Ngreen = (1; 5; 1; 5)
Pos = (400; 000; 100; 100)
#
```

The parameters in the setup file are explained as follow:

- numBlocks specifies the number of blocks that will appear on the screen, the same number of blocks must be describe in the setup file.
- BiFr specifies that this is a block using multi frequency stimulation.
- Letter=A specifies the letter shown inside the block.
- Nred=(Non1;Noff1;Non2;Noff2) specifies the frequency content of the red stimulation signal, where the stimulation frequency is fs= RR/(Non+Noff), whit RR=refresh Rate of the screen.
- Ngreen=(Non1;Noff1;Non2;Noff2) specifies the frequency content of the green stimulation signal, where the stimulation frequency is fs= RR/(Non+Noff), whit RR=refresh Rate of the screen.
- Pos=(x;y;width;height) specifies the position on the monitor and the size of the block.

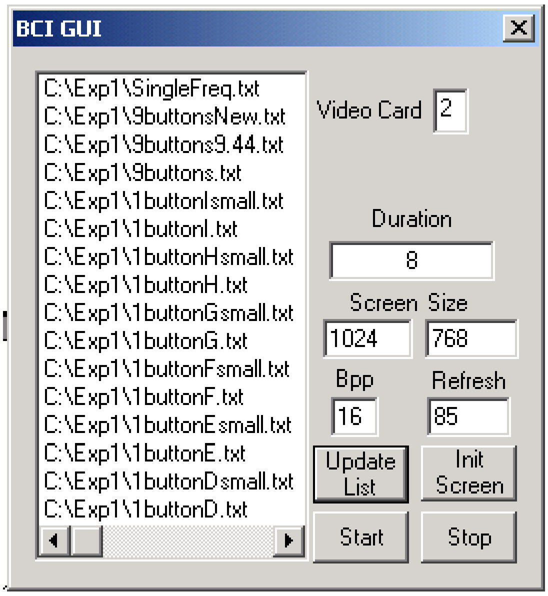

Figure A2: GUI of the visual stimulator.

Using specific functions in the DirectX interface it is possible to generate rectangular blocks of specific colors, which turn on or o at specific refresh cycles, this way different frequencies can be obtained by changing the number of *on* cycles and *off* cycles. As explained before Non and Noff are the number of refresh cycles that the block is *on* and *off* respectively to obtain a specific frequency. All these stimulation frequencies have 50 % duty cycle.
When the program is executed (GUI.exe) the window showed in Figure A2 appears, where it is possible to set the following:

- Video Card: selects which monitor will give the visual stimuli (in case that two monitors are connected to the computer), 1 is the main screen and 2 is the secondary screen, selecting 2 the stimulation will be delivered through the secondary screen and the program will be controlled on the main screen.
- Duration: Sets the duration of the stimulation in seconds.
- Screen Size: Is the screen resolution of the output monitor (default is 1024x768 pixels)
- Bpp: Determines the number of bits per pixel (default is 8)
- Refresh: Sets the refresh rate of the output monitor.
- Update List: Press this button to update the list of setup files in \C:/Exp1/".
- Init Screen Press this button to initialize the output screen.
- Setup File: The setup File can be selected in the text field located on the left side of the GUI window.
- Start: Press this button to start the visual stimulation (after the setup file is selected).
- Stop Press this button to stop the visual stimulation.

This program is only able to produce bi-frequency stimulation. However it is possible to give single frequency stimulation by setting the two stimulation frequencies to the same number.

EOD