# Steady-state visual evoked potential (SSVEP) - based brain computer interface (BCI)

**Research Organisations involved**
**Swinburne University of Technology**
**RMIT University**

Author(s)
Associate Professor Jingxin Zhang
Professor Dinesh Kumar
Mr Behzad Aliahmad

31st August, 2014

Research report #: 075-0814-R01

A joint initiative of

# Table of Contents

## Executive Summary

A brain computer interface typewriter was designed, developed and tested. This device met most of the criteria; it was inexpensive, easy to replicate and portable. The testing on able bodied individuals demonstrated that the device was reliable. However, some participants felt that it was slow and resulted in errors. Testing the device on one patient gave good results, but the second patient's family did not like the flickering lights, an essential aspect of the technology. At this stage, we believe that the device is suitable for the application, though improvements such as reduced time delays are essential for this to gain acceptability.

## Purpose

We report the development and testing of SSVEP based assistive device to help quadriplegic patients, often caused by spinal cord injury in road trauma. They use naturally generated responses from localized brain sources as a result of visual stimulation and translate the detected stimulus frequency into action. This research has developed an SSVEP based Speller BCI system and investigated some limitations of the available technologies as well as reporting the challenges and potential solutions to improve the system for real-world practical application. This work has investigated the following three main areas:

1) As SSVEP concept is based on analysis of Electroencephalogram (EEG) recordings corresponding to brain's visual cortex activity, in the presence of a visual stimulus; the intensity and frequency of the flickering light (stimulus) can cause excessive fatigue in patients. Therefore, the optimum light intensity and flickering frequency range of the stimuli need to be investigated.

2) In order to increase the device functionality of a BCI system, several stimuli are used at the same time, each being mapped into a specific action by the system. Each stimulus is frequency and/or phase coded to be differentiated from the other stimuli as well as increasing the information transfer rate (ITR). However, the minimum physical distance between each stimulus and the optimum dimension to avoid cross-interference between the response signals have not yet been effectively investigated. Understanding this minimum distance and optimum dimension of each stimulus is crucial for implementation on tablet computers with small display size.

3) A complete BCI system includes data acquisition, filtering, feature extraction, feature classification and command translation which apply a time delay in real-time processing. Unoptimized algorithms will increase the time required by the patients to stare at the stimuli, causing fatigue as well as slowing the system performance.

# Rationale

This research has filled the knowledge gap in determination of the relationship between the choice of different stimuli parameters (i.e. Frequency range, phase, light intensity, intra-stimulus physical distance, delays and signal analysis methods) and user fatigue and provided an optimum selection of such parameters. This research has developed innovative algorithms for online data acquisition and information processing and provided a speller BCI system suitable for quadriplegic patients who are unable to speak or use the hands. The system is portable and inexpensive and can be integrated with tablet computers for user's comfort.

# Methods

The proposed prototype speller system was for an inexpensive, user friendly and easy to use system consisting of the following four main parts:

1) EEG headset and dry electrodes.
2) Display tablet.
3) Main controller/interface board.
4) Processing unit.

However, the results with the above were not satisfactory and a modified prototype as described below has been developed:

1) EEG headset with saline wetted electrodes.
2) Purpose built display panel with LEDs.
3) Main controller/interface board.
4) Processing unit.

Block diagram of the proposed system showing its different parts and their interactions is shown in Figure 1.

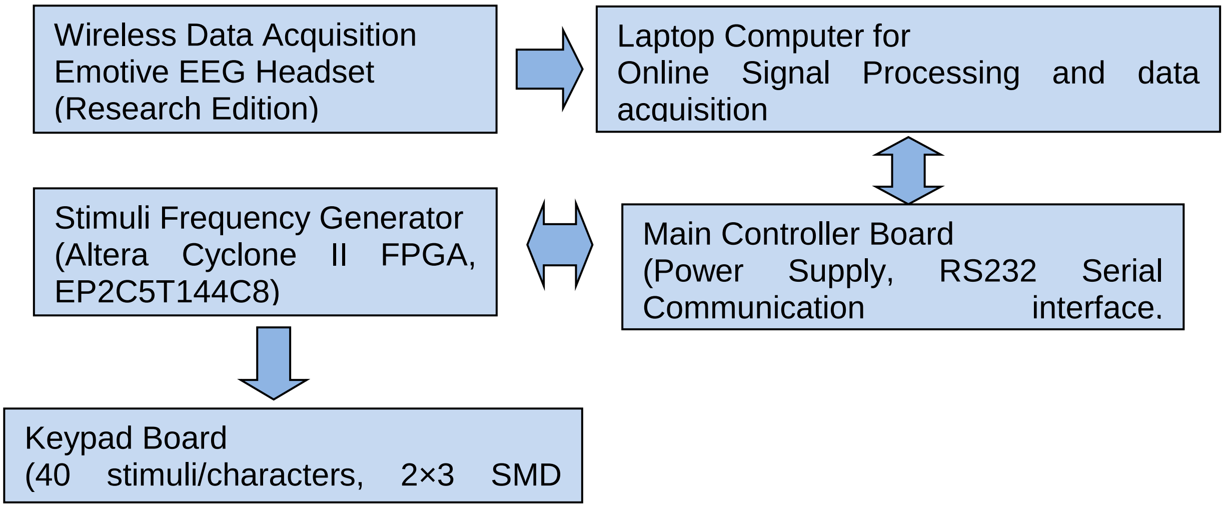


Figure 1: Hardware configuration

## EEG headset

EEG was recorded wirelessly using Emotive EPOC neuro-headset (Research Edition). It features 14 EEG channels (10-20 international location system AF3, F7, F3, FC5, T7, P7, O1, O2, P8, T8, FC6, F4, F8, AF4) of 14 bit resolution (16 bit ADC with 2 bits discarded for instrumental noise floor) plus 2 CMS/DRL reference channels (P3 & P4). The headset wirelessly communicates with a computer at 2.4 GHz band through a USB receiver. It also features wet electrodes and comes with special solution provided by the manufacturer. The device output is sequentially sampled at 128 SPS (2048 Hz internal) and band limited between 0.2 to 45 Hz with two digital notch filters at 50 and 60 Hz. The headset is shown in Figure 2.

Figure 2: Emotive EPOC neuro-headset

## Display/LED panel

The visual stimulator panel contained 40 arrays of 2×3 (2 rows, 3 column, 1×1 $cm^2$) white SMD LEDs (SMT 0603 super bright) each corresponding to a specific character, number and/or a command (i.e. A-Z, 0, 1, ..., 9, space, back space, Enter and Shift key), see Figure 3. All the characters were arranged in 8 (columns) × 5 (rows) cells with 4 cm intervals between LED arrays measured form their margin. The hardware configuration allows for independent triggering of each LED array at a specific frequency, which requires allocation of 40 different frequencies inside a narrow bandwidth. However, due to some other constraints to be discussed later in “Design challenges and limitations” section, the maximum number of required frequencies was brought down to 8 and character detection was performed based on the interaction between SSVEP responses of columns and rows each trigged at specific frequency between 5 to 13 Hz. Each frequency was generated independently using a digital counter configured in an FPGA (Altera Cyclone II, EP2C5T144). 8 different counters corresponding to 8 predefined frequencies were implemented. Each pulse was generated using an independent synchronous counter with 12 bits of resolution and zero phase angle. The hardware was equipped with a 50MHz crystal oscillator as the reference clock and all the train pulses were produced using multiple divisions of the high frequency 50MHz oscillator to obtain good frequency precision. A multiplex based sub-circuit was also considered to switch between the columns and rows of the display panel when a command is received from the interface board. Block diagram of the implemented digital circuit is shown in Figure 4. As shwn in the figure, the clk_in pin is the main clock input connected to the 50MHz oscillator. The Pulse_in is the multiplexer’s select pin which is connected to the interface/controller board. The Pulse_out pin arrays are the 40 bit vector each connected to an LED array


Figure 3: Speller LED panel (Display)

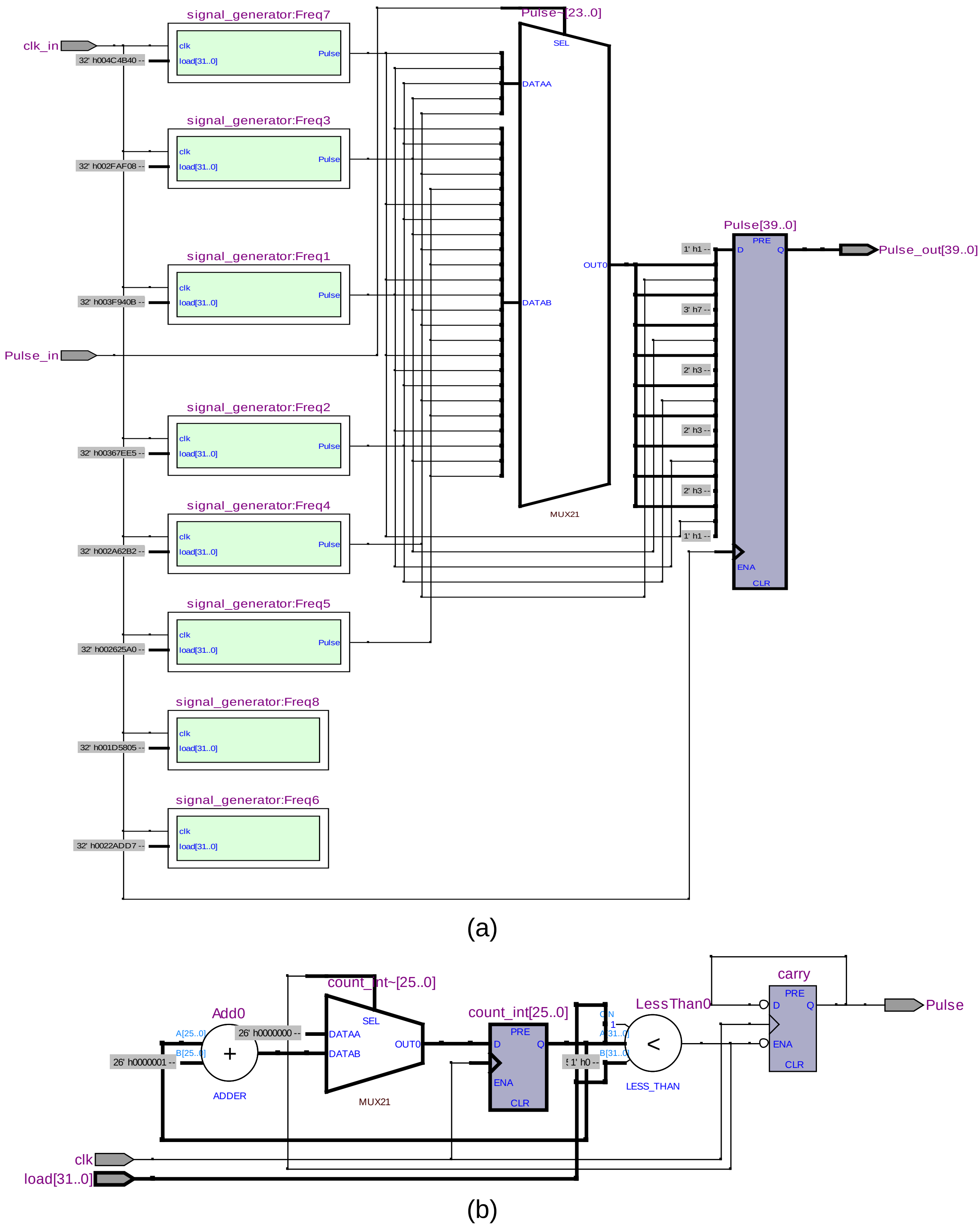


Figure 4: The implemented digital circuit. (a) The entire schematic. (b) The circuit inside the signal generator block.

## Main controller/interface board

An interface circuit was built as the main controller for sending commands to the FPGA, initiating recordings and switching on and off the stimuli. It was equipped with an 8 bit microcontroller (ATMega 8 AVR) and RS232 interface. The controller is mainly used as a communication interface between the LED panel and processing unit. The selection of columns and rows was possible through setting the Pulse_in pin to '1' and '0' respectively based on the commence received from the Processing unit. The communication between the controller board and processing unit which is a software package was provided through USB port and USB to RS232 converter module. The controller board and its different sections are shown in Figure 5.

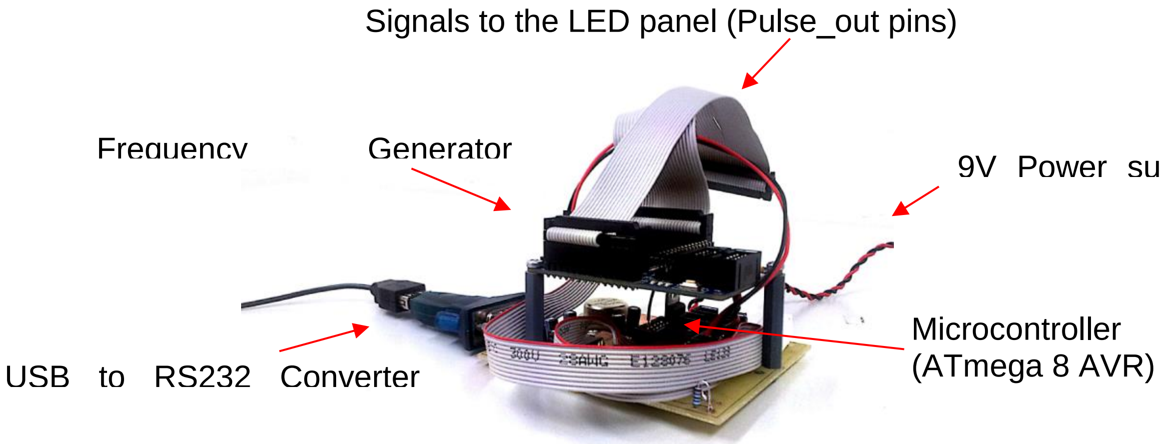


Figure 5: Main Controller/Interface Board

## Processing unit

A software package was written in Visual C++ 2010 express edition to 1) handle the recordings form Emotive wireless USB receiver, 2) perform online signal processing and 3) produce outputs by typing the characters on the screen. It was also equipped with a voice module to speak out each character that gets typed on the screen for user comfort and accuracy evaluation. Mathematical operations and plotting were performed through integration of MATLAB engine with Visual C++ platform and calling it from inside the platform. The software was also designed to send some instructions to the controller board via a separate USB port connected to a USB to RS232 convertor. The instructions included switching between Vertical (columns) and Horizontal (rows) lines of the display panel by sending 'V' and 'H' characters to the interface board.

Two different online signal processing methods were implemented and tested. The first was based on multivariable statistical canonical correlation analysis (CCA) in frequency domain in which two types of reference signals were used. i) Synthetically made sine and cosine expressions with different levels of additive Gaussian noise as reference and ii) natural pre-recorded EEG signals of the same patient as the training sets. The second tested method was based on implementation of a series of matched Gaussian filtering in the frequency domain and taking the maximum output SSVEP response for frequency detection. Described below in detail is the second method which had better performance.

Among 14 available channels, two channels of O1 and O2 corresponding to Bain's visual cortex were used. A buffer of length 5×128 bits was implemented for each channel separately to keep the data for 5 seconds. The buffers were updated with one second intervals by shifting the old data 128 bits towards the Most Significant Bit (MSB) and replacing the new samples in place of Least Significant Bits (LSB). Signal processing was applied to the entire buffers within one second interval between the two updates. Each channel was treated separately until the very last stage which will be explained later. At first the data was normalized by dividing the entire buffers by its maximum value followed by autocorrelation operation. The Fast Fourier Transform (FFT) was obtained and filtered with a band pass filter with 3dB cut-off frequencies of 4 Hz and 15 Hz. The reason for considering the filter bandwidth about 1 Hz wider than the used frequency range was to allow room for slight variations that may happen in the SSVEP response. A set of 8 narrow band Gaussian filters were used to filter out each stimulating frequencies. The magnitude of each filter was set to 1 in order not to apply any gain factor. The mean values were set to centre each filter at a specific frequency corresponding to the used stimuli (i.e. 6, 7, 8, 9, 10, 11, 12, 13 Hz). The spreading factor σ of the filters was set to 0.5 to avoid overlapping with adjacent frequencies. Maximum output of each filter with known centre frequency was buffered for later comparison, providing 16 unique values (2 channels ×8 filters produced) every second. The values of this buffer were sorted from maximum to minimum every 3 seconds (iterations) and centre frequencies of the first three maxima were monitored. If the three frequencies were similar, the corresponding value was selected as the detected frequency. The above process was repeated for each horizontal and vertical scanning and the resulting two frequencies were obtained. As each character was encoded with two frequencies (one horizontal and one vertical), the detected value could be easily mapped to a corresponding character. Diagram of the above process is shown in Figure 6.

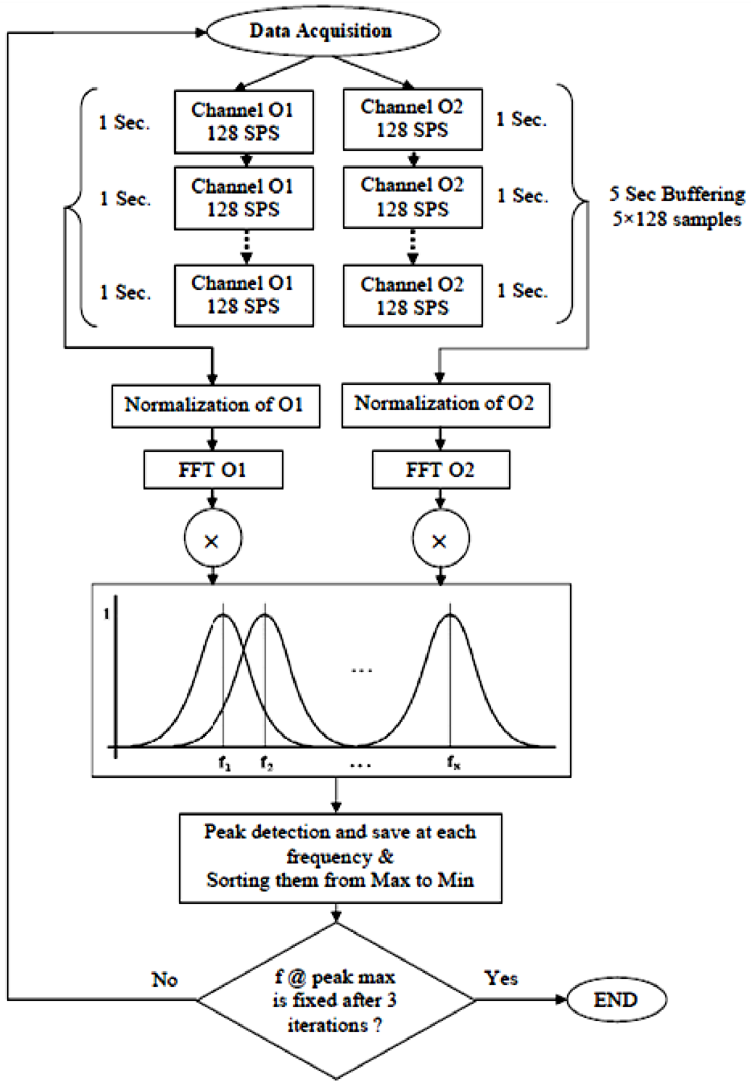


Figure 6: Diagram of the online processing algorithm

# Research findings and implications

Figure 7 shows the spectrum of an example signal stimulated at 7Hz after being passed through the Gaussian filter series. As seen from the figure, the response from the output of the 7Hz Gaussian filter has the highest peak value compared to those from other filters, showing that the stimulation had a frequency of 7Hz.

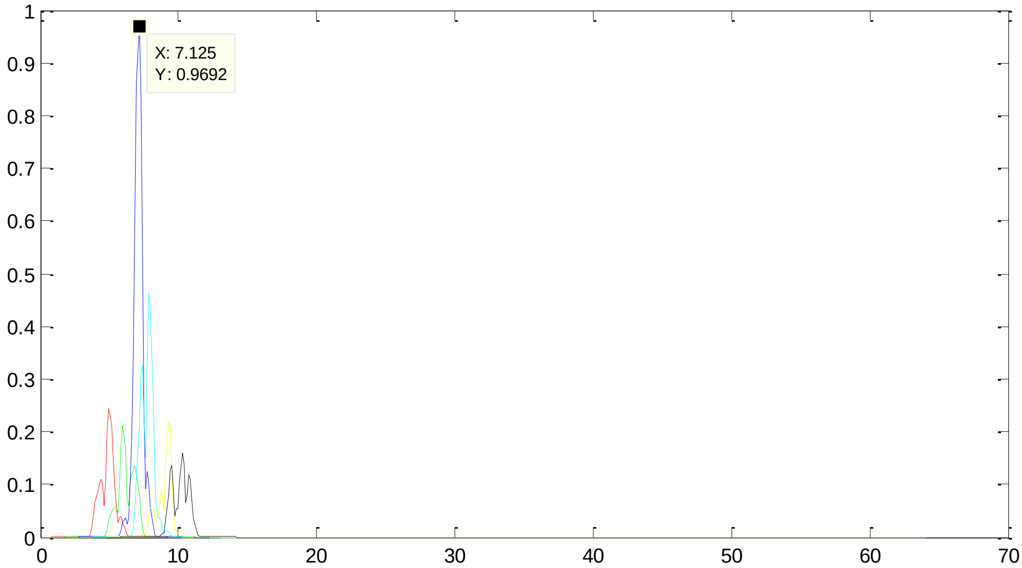

Figure 7: Output of the Gaussian-filter series for channel O1 at the presence of 7Hz stimulation.

## Tests on able-bodied subjects

Four people (3 males and 1 female) aged between 27 and 55 volunteered to participate in the final test. The test was performed in room with normal lighting condition (not in dimmed light). At first all the subjects were trained how to use the speller system. The classification accuracy Acc was estimated based on the percentage of correct character detection among 10 trials.

The estimated time to output one symbol was 4.5 sec/frequency (horizontal/vertical lines) and 8.5 sec/symbol calculated as the average time for each correct output symbol plus the time required for switching between two characters (shifting gaze). The required 2 seconds rest was excluded from this calculation. The result is shown in Table 1.

Table 1: The test result

| Subject No. | Accuracy (Acc) | Raw Signal Quality from headset | Gender |
|---|---|---|---|
| 1 | 90% | Good | Male |
| 2 | 0% (Headset Failed) | Bad (No signal) | Male |
| 3 | 40% | Poor | Female |
| 4 | 70% | Good | Male |

The experimental observations are summarized below:

- In some subjects like subject 1, we found one occipital channel was more dominant than the other in the sense that SSVEP response did not peak at some specific frequencies.

- The use of Parietal channels (P1 and P2) for the purpose of Laplacian Montage, which is defined as the difference between each Occipital electrode and a weighted average of the surrounding electrodes (P7 & P8), did not contribute to any better classification accuracy and therefore channel P1 and P2 were removed from the processing to save computation time.

- The headset did not work on the subjects with thick hair and slightly larger head size.

- The test on one subject was unsuccessful due to limitation of the headset. On this subject the headset signal quality check failed and did not detect good quality signal. This happened due to subject's thick hairs and a round head shape slightly larger than the average people.

- The classification accuracy of the system was 40% when tested on a subject (subject #3) with neuromuscular disorder and very thick hair resulting in poor signal quality for the O1 and O2 channels.

## Tests on subjects with special needs

Two people with special needs volunteered for this study; female, mild cerebral palsy (subject 1) and male with motor neurone disease (subject 2). However, when the careers of subject 2 saw the flashing lights, they decided to withdraw from the experiment. The results of subject 1 were; accuracy = 60%. Subject reported discomfort due to visual stimuli, and delay in the recognition of the key by the system.

## Design challenges and limitations

The design challenges and difficulties we faced with were mainly due to the limitation of Emotive EEG headset for SSVEP based BCI applications. These limitations are listed below:

- Emotive works only with wet electrodes soaked in saline solution. However, it is effective only for the first 20 minutes of the experiment and the pads will become dry quickly causing increase in the impedance and therefore affects signal quality.

- Emotive comes with a test bench software to assist with correct electrode positioning and ensure receiving highest signal quality. However, this test only shows approximate locations inside a region of 1 to 2 cm. Slight displacement of O1 and O2 electrodes within that region resulted in different detection accuracies, from no correct detection to accuracy of 90%.

- As a result of reaction between saline solution and metal bit of the electrodes, the pads and metal parts get easily molded which affects the conduction path. Also the pads pick up dirt and grease which also affect signal quality. Cleaning is necessary after every 2 to 3 times of use. The metal bit need to be scraped with fine sand paper and the pads soaked in hot detergent water.

- The headset does not filter out high frequency components due to any mechanical movement and tapping. Although it is equipped with 50 and 60Hz notch filter, the 50 Hz frequency still appears in the output spectrum of the raw signal with very high magnitude.

We have noticed that further improvements in different areas are needed to gain better classification results which are listed below:

- Application of different scanning method for more effective switching of columns and rows of the display LED arrays. Instead of triggering all the rows or columns at the same time, which will cause interference between SSVEP responses of the target frequency and the ones observed in the background due to impact of other adjacent stimuli, an approach similar to the scanning method used in matrix keypad boards can be taken. In this method only one column or row at a time will be switched on and flickered.

- Our experiment showed that applying 2 to 3 seconds pause between detection of each frequency can improve classification accuracy. This pause was applied by training the patient to close his/her eye for 2 seconds before moving onto looking at another character. This pause could also be implemented by turning off all the LEDs for 2 to 3 seconds after detection of each frequency, and switching them back on. But such delay caused fatigue and discomfort among the users.

- We found arrangement of frequencies and different allocation order to columns and rows can impact on the output accuracy. At first allocation of frequencies to columns and rows was not in order to make sure two consecutive frequencies do not appear next to each other. The reason was to keep the frequency distance between two adjacent columns and rows as large as possible to avoid any interference in the output SSVEP response and filtering problem. Therefore, for the 8 columns the frequencies were ordered as 13, 9, 12, 8, 10, 7, 11, 6 Hz respectively. However, this was problematic, as higher frequencies resulted in lower SSVEP amplitudes. When the patient stared at a frequency like 12 Hz which is bounded between two lower frequencies (e.g. 9 and 8 Hz), SSVEP responses due to those lower ones were be observed in the background and become comparable with the target stimulus frequency. Therefore, to overcome this issue the frequencies were arranged in the orderly manner as 13, 12, 11, 10, 9, 8, 7, 6 Hz.

- As one Occipital channel may be dominant in some people, frequency allocation should be adaptive and modified for each subject, followed by the system training for the selected frequency range.

# Use of the research

Most BCI applications focus on proving assistive care for the people with lack of functional motor control to help them better communicate with their surrounding environments. However, the application of BCI is not only limited to quadriplegic patients. For healthy people, BCI systems can be incorporated with life science technology as a powerful tool providing hands-free interaction between user and a system. Some potential applications of this research are outlined below:

- This work has provided a summary of parameters for optimum design of SSVEP based speller system to be used by quadriplegic patients. However, the findings are applicable for any other control devices, including hands-free wheelchair and robotic controls.

# Potential impact of the research

In this research, the use of Emotive Epoch neuro-headset has enabled non-invasive and cost efficient acquisition of EEG signals as well as easy electrode placement on scalp. Also, the designed methodology (hardware and software) is suitable for implementation on tablet computers which makes the whole system inexpensive, portable, user friendly and suitable for commercialisation. The choice of stimulus frequency and minimum light intensity prevents user fatigue and tiredness. However, the excessive delays made the device unsuitable for some applications and there is a need for further development to reduce this delay. An improved version of this would be suitable for people such as spinal injury patients.