# Performance Analysis of Multi-frequency SSVEP-BCI Using Clear and Frosted Colour LED Stimuli

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***Abstract*— Among the many paradigms used in brain-computer interface (BCI), steady state visual evoked potential (SSVEP) offers the quickest response; however it is disadvantageous from the point of view of visual fatigue, which prevents subjects from prolonged usage of visual stimuli especially when LEDs are used. In this paper, we propose a visual stimulator using readily available RGB LEDs with clear and frosted glass, with the latter being tested for performance and qualitative user comfort using electroencephalogram (EEG) data from four subjects. Furthermore, we also compare frosted and clear stimuli for three colours Red, Green and Blue with frequency values of 7, 8, 9 and 10 Hz. The results using band-pass filtering and Fast Fourier Transform showed that 7 Hz Green clear LED stimuli gave the highest response in general, although all the subjects indicated that they were more comfortable with frosted LED stimuli.**

## I. Introduction

Brain-computer interfaces (BCI) give users the capabilities to communicate and control various devices by establishing a direct communication channel between human brain and external devices, independent of muscular actions [1]. Signals produced by brain activity (known as electroencephalogram, EEG) are recorded non–invasively from the scalp using electrodes positioned at various locations. Non-invasive BCIs use different methods such as P300, motor imagery and steady state visual evoked potential (SSVEP). Researches in BCI have identified that SSVEP based BCI needs less training time, but provides faster response and higher information transfer rate [2-4] and hence it is suitable for implementing real time applications.

SSVEP based BCIs are evoked by repetitive visual stimuli and widely used in many applications [5-8]. The evoked EEG is an oscillatory component at the frequency same as the stimulus and this response is known as SSVEP. Research studies have shown that the amplitude of the response in the specific stimulus frequency varies with the different subjects, colour, intensity and the type of stimulus [9-16]. Often SSVEP signals are corrupted with other noise such as background EEG, artifacts and external noise such as power-line interference and specific signal processing techniques will need to be employed to reduce these undesired effects.

Even though SSVEP responses are sufficiently high for practical purposes, it is not always comfortable for subjects for longer periods of time especially when the stimulus is presented using LEDs. In this study, we have analysed the effect of different colours over different frequency values (7, 8, 9 and 10 Hz) using conventional clear glass and our proposed frosted glass, which we hope will reduce eye fatigue/strain thereby allowing longer usage of LED based SSVEP-BCIs. Three colours, namely red, green and blue from single one Watt RGB LED, were used to produce the stimulus flickering at fixed frequency and controlled by a microcontroller and high current driving circuit.

## II. Materials and Methods

### A. Experiment Setup

To explore the effects of different colour, frequency and glass texture on SSVEP, participants were seated 60 cm from the stimulus, which was fixed at eye level. One EEG bipolar channel using gtec Mobilab+ along with active electrode driver box was used to record the data with electrodes positioned at $O_z$ (midline occipital) and $F_{pz}$ (midline frontal) with $A_2$ (right mastoid) as reference. The visual stimulus flickered at fixed frequency and colour during a complete recording cycle of 30 seconds. Fig. 1 shows a typical trial of EEG recorded for 30 seconds. For each colour and frequency, five trials were recorded for both the conventional clear glass and the proposed frosted glass, which gave 150 segments, with each segment consisting of one second of SSVEP signal. Four healthy subjects (three females, one male) in the age group 25 – 45 volunteered for this study and none of the subjects had any previous experience with BCI. All subjects had perfect vision or corrected vision.

### B. Visual Stimulus

The visual stimulus was realised with a 5 mm RGB LED using common-anode configuration connected to a microcontroller and driven by a high current MOSFET. The RGB LED is rated at 5000 mcd according to the manufacturer. The microcontroller was programmed for flickering outputs at 7, 8, 9 and 10 Hz. These frequencies were chosen as the lower frequencies give better responses [17, 18].The accuracy of the frequency was verified using a digital oscilloscope with a frequency error of less than 0.012 Hz at room temperature.

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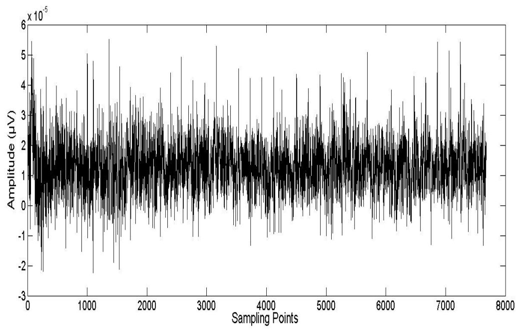


Fig 1. SSVEP from green 7 Hz clear LED stimulus

The complete hardware for visual stimulus was powered by a 5V DC battery source to avoid AC component being induced in the light source. For each trial, one of the RBG LED cathodes was connected to the microcontroller for the desired frequency and colour. This process was repeated for all three colours (red, green and blue) and frequencies 7, 8, 9 and 10 Hz. The complete set of trials were performed similarly for the proposed frosted glass RGB LEDs and repeated for all the subjects.

### *C. Data Aquisition*

EEG cap fitted with gtec active electrodes at the specified locations with electrode conductive gel were used on all subjects, producing single channel bipolar SSVEP data. This setup does not require any skin preparation. Fig. 2 shows the electrode positions used for this study.

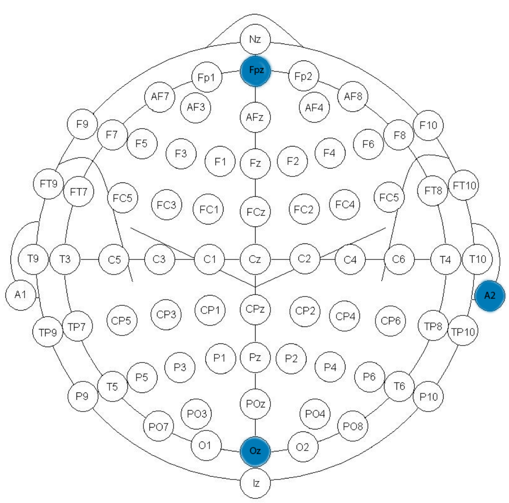


Fig 2. The electrode positions used in this study to collect the EEG data

The study was approved by the ethics committee and all subjects were shown a short demonstration/training on visualising the stimulus in the experiment. The recording time was set to 30 seconds for each trial with a rest time of one minute between each trial. Our preliminary investigation showed that a break of one minute was sufficient to completely allow the previous responses to subside. Each trial began with a five second pause and 30 seconds of data recording. The sequence for data recording was 7 Hz red clear glass followed by 7 Hz green clear glass and 7 Hz blue clear glass. The same step was repeated for frequencies 8, 9, and 10 Hz using clear glass LED. The sequence was alternated on different trials to avoid colour habituation effects. Following this, the visual stimulus was replaced with the proposed frosted glass and all the above steps were repeated.

After starting the visual stimulus, EEG data were recorded with a sampling frequency of 256 Hz. Each trial had duration of 30 seconds, thus it lasted 1800 seconds for three colours and four different frequencies, with five trials for each colour and frequency. Hence the total time required for completing the EEG recording for each subject was about 90 minutes for 60 trials of conventional clear glass and similar amount of time for the proposed frosted glass.

### *D. Signal Processing*

Each 30 seconds of EEG recording was filtered with a band-pass filter and segmented into one second EEG segments and analysed with Fast Fourier Transform (FFT). Since this was a pilot study to compare conventional clear and proposed frosted LEDs, standard FFT was employed rather than advanced features. Table 1 shows the filter parameters used. The maximum amplitudes of the FFT using the filtered SSVEP signal for all the 150 segments were computed and stored for further analysis. This process was repeated for all the four frequencies and three colours in both conventional clear and proposed frosted visual stimuli.

TABLE I
VALUES OF PARAMETERS USED IN DATA PROCESSING

| Frequency | Order | Pass band edge frequencies | Stop band edge frequencies | Max pass band ripple (dB) | Min stop band attenuation (dB) |
|---|---|---|---|---|---|
| 7 | 4 | 6,8 | 5,9 | 0.1 | 30 |
| 8 | 4 | 7,9 | 6,10 | 0.1 | 30 |
| 9 | 4 | 8,10 | 7,11 | 0.1 | 30 |
| 10 | 4 | 9,11 | 8,12 | 0.1 | 30 |

Initially, the experiment was to decide the best colour to use and then the chosen colour was fixed for the rest of the experiments. Next, the frequency was analysed before finally testing the LED types. Statistical t-test was used to compute the p-values to obtain the significance when comparing the different parameters.

TABLE II
T-TEST SIGNIFICANCE (P-VALUE) RESULTS COMPARING FFT AMPLITUDES FOR FROSTED AND CLEAR LED STIMULI (R, G, AND B DENOTES RED, GREEN, AND BLUE RESPECTIVELY)

| Subject | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| S1 | | | S2 | | | S3 | | | S4 | | |
| Frequency (Hz) | Hypothesis | Significance | Frequency (Hz) | Hypothesis | Significance | Frequency (Hz) | Hypothesis | Significance | Frequency (Hz) | Hypothesis | Significance |
| 7-Clear | G > R | 0 | 7-Clear | G > R | 0 | 7-Clear | G > R | 0 | 7-Clear | R > G | 0.0048 |
| 7-Clear | R > B | 0.087 | 7-Clear | R > B | 0.97 | 7-Clear | R > B | 0.95 | 7-Clear | B > R | 0 |
| 7-Clear | G > B | 0 | 7-Clear | G > B | 0 | 7-Clear | G > B | 0 | 7-Clear | G > B | 0 |
| 7- Frosted | R > G | 0.26 | 7- Frosted | R > G | 0.55 | 7- Frosted | R > G | 0.55 | 7- Frosted | G > R | 0 |
| 7- Frosted | R > B | 0.14 | 7- Frosted | R > B | 0.21 | 7- Frosted | R > B | 0.21 | 7- Frosted | B > R | 0 |
| 7-Frosted | B > G | 0.68 | 7-Frosted | B > G | 0.87 | 7-Frosted | B > G | 0.87 | 7-Frosted | G > B | 0 |
| 8-Clear | G > R | 0 | 8-Clear | R > G | 0.92 | 8-Clear | R > G | 0.92 | 8-Clear | G > R | 0 |
| 8-Clear | R > B | 0.78 | 8-Clear | B > R | 0 | 8-Clear | B > R | 0 | 8-Clear | B > R | 0 |
| 8-Clear | G > B | 0 | 8-Clear | B > G | 0.95 | 8-Clear | B > G | 0.95 | 8-Clear | B > G | 0.48 |
| 8- Frosted | R > G | 0.84 | 8- Frosted | R > G | 0.62 | 8- Frosted | R > G | 0.62 | 8- Frosted | R > G | 0.01 |
| 8- Frosted | R > B | 0.19 | 8- Frosted | B > R | 0 | 8- Frosted | B > R | 0 | 8- Frosted | B > R | 0 |
| 8-Frosted | B > G | 0.98 | 8-Frosted | G > B | 0 | 8-Frosted | G > B | 0 | 8-Frosted | G > B | 0 |
| 9-Clear | R > G | 0.05 | 9-Clear | G > R | 0 | 9-Clear | G > R | 0 | 9-Clear | G > R | 0 |
| 9-Clear | R > B | 0 | 9-Clear | R > B | 0.94 | 9-Clear | R > B | 0.93 | 9-Clear | B > R | 0 |
| 9-Clear | G > B | 0 | 9-Clear | G > B | 0 | 9-Clear | G > B | 0 | 9-Clear | G > B | 0 |
| 9- Frosted | G > R | 0 | 9- Frosted | G > R | 0 | 9- Frosted | R > G | 0.92 | 9- Frosted | G > R | 0 |
| 9- Frosted | R > B | 0.05 | 9- Frosted | R > B | 0.25 | 9- Frosted | R > B | 0.25 | 9- Frosted | B > R | 0 |
| 9-Frosted | G > B | 0 | 9-Frosted | B > G | 0.95 | 9-Frosted | B > G | 0.94 | 9-Frosted | B > G | 0.63 |
| 10-Clear | G > R | 0 | 10-Clear | G > R | 0 | 10-Clear | G > R | 0 | 10-Clear | G > R | 0 |
| 10-Clear | R > B | 0.99 | 10-Clear | R > B | 0.68 | 10-Clear | R > B | 0.68 | 10-Clear | R > B | 0.05 |
| 10-Clear | G > B | 0 | 10-Clear | G > B | 0 | 10-Clear | G > B | 0 | 10-Clear | G > B | 0 |
| 10- Frosted | R > G | 0.99 | 10- Frosted | R > G | 0.27 | 10- Frosted | R > G | 0.27 | 10- Frosted | G > R | 0 |
| 10- Frosted | R > B | 0.38 | 10- Frosted | B > R | 0 | 10- Frosted | B > R | 0 | 10- Frosted | B > R | 0 |
| 10- Frosted | G > B | 0 | 10- Frosted | G > B | 0 | 10- Frosted | B > G | 0.94 | 10- Frosted | G > B | 0 |

## III. RESULTS AND DISCUSSION

As mentioned earlier, three different parameters were tested for performance using SSVEP; *(a)* colour significance, *(b)* LED glass significance, and *(c)* frequency significance. FFT amplitudes for each frequency and colour were compared with t-test statistical test to compute the significance to identify the most significant colour for SSVEP stimulus with the significance value (alpha) set to 0.1. Two colours were compared at a time for the same frequency and LED glass type. Table 2 gives the significance test results for all the subjects in the colour comparison experiment. For eg., G > R means that the FFT amplitudes from green LED is tested as being higher than red. From the multiple t-test comparison results in Table 2, it can be seen that the highest SSVEP performance for all four subjects is from the green LED visual stimulus for all frequencies.

Table 3 shows the results from comparing conventional clear glass and the proposed frosted glass. For three subjects, it shows clear glass results are significantly higher than frosted glass. For one subject, there was no notable significance in glass type.

TABLE III
T-TEST SIGNIFICANCE (P-VALUE) RESULTS COMPARING FFT AMPLITUDES FROM CLEAR VERSUS FROSTED LEDS USING GREEN STIMULI

| Hypothesis tested (LED type) | Frequency (Hz) | Subject | | | |
|---|---|---|---|---|---|
| | | S1 | S2 | S3 | S4 |
| Clear>Frosted | 7 | 0 | 0 | 0.07 | 0.25 |
| Clear>Frosted | 8 | 0 | 0.03 | 0.06 | 0.01 |
| Clear>Frosted | 9 | 0.41 | 0.88 | 0.05 | 0.92 |
| Clear>Frosted | 10 | 0 | 0.05 | 0.08 | 0 |

Table 4 shows the results of the frequency analysis: subjects S1, S2, and S3 gave statistically highest SSVEP response to 7 Hz visual stimulus as compared to other frequencies. For subject S4, both 7 Hz and 8 Hz gave statistically similar performance.

It can be seen that SSVEP performance increased as the visual stimulus frequency decreased, which confirms previous research findings [17, 18]. All four participants felt that the green stimulus was more comfortable followed by blue and the least comfortable was red. The green stimulus also gave the highest SSVEP response, confirming the results of a previous study on flashing lights which found green had more robust effect when compared to white [19], and our study extends the result by studying the other two prominent colours, blue and red. The subjects felt that blue stimulus was relaxing and made them sleepy, whereas red was not comfortable for prolonged usage. All participants strongly recommended frosted glass for visual stimulus as opposed to clear glass even though clear glass gave higher SSVEP response.

TABLE IV
T-TEST SIGNIFICANCE (P-VALUE) RESULTS COMPARING FFT AMPLITUDES FOR DIFFERENT FREQUENCIES USED IN LED VISUAL STIMULI

| Hypothesis tested (Hz) | Subject | | | |
|---|---|---|---|---|
| | S1 | S2 | S3 | S4 |
| 7 > 8 | 0 | 0.024 | 0 | 0.12 |
| 7 > 9 | 0 | 0.37 | 0 | 0.19 |
| 7 >10 | 0.01 | 0.01 | 0.06 | 0.01 |
| 8 > 9 | 0 | 0.54 | 0 | 0.11 |
| 8 >10 | 0.09 | 0.99 | 0.05 | 0.01 |
| 9 > 10 | 0 | 0 | 0 | 0.17 |

## IV. CONCLUSION

In this paper, we have investigated how different colours, frequencies, and type of glass affect the performance of SSVEP in BCI. According to the participants in this study, green stimulus was the easiest to concentrate upon, and was less of a strain on the eyes when used for longer periods. The results also indicated that green stimulus gave higher responses than the other two colours. Even though conventional clear glass gave higher responses than the proposed frosted glass, the participants were more comfortable with frosted stimulus for prolonged data recording. Participants also mentioned blue stimulus as relaxing and sleepy, whereas red was not comfortable for longer periods. In the frequency comparison, the lowest studied frequency of 7 Hz gave the highest SSVEP performance when compared to 8, 9 and 10 Hz.

To conclude, green coloured 7 Hz frequency conventional clear LED stimulus gave the highest performance even though subjects were more comfortable with the proposed frosted stimulus. Further work may include the study of light intensity influences in SSVEP with clear and frosted stimulus to reduce visual fatigue using dry electrodes.

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