Comparison of Steady-State Visual Evoked Potential (SSVEP) with LCD vs. LED Stimulation

Jing Mu, David B. Grayden, Ying Tan, and Denny Oetomo

Abstract— **The steady-state visual evoked potential (SSVEP) is a robust brain activity that has been used in brain-computer interface (BCI) applications. However, previous studies of SSVEP-based BCIs give contradictory results on which stimulation medium provides the best performance. This paper describes a comparison of electroencephalography (EEG) decoding accuracy between using an LCD screen, clear LEDs, and frosted LEDs to deliver flashing light stimulation. The LCD screen and frosted LEDs achieved similar mean accuracies, and both of them were significantly better than clear LEDs. Background contrast with the LEDs did not significantly influence SSVEP decoding accuracy. A strong correlation was found between SSVEP accuracy and frequency domain magnitudes of EEG measurements.**

I. Introduction

Brain-computer interfaces (BCIs), also known as brain-machine interfaces (BMIs), are communication interfaces between humans and external devices that use direct measurement of brain activity for people with movement impairments. The steady-state visual evoked potential (SSVEP) is one of the most robust brain activities detected through electroencephalography (EEG), a non-invasive brain imaging technique. SSVEP is a frequency-locking behaviour of the brain that is most strongly detected over the occipital lobe when the subject is presented with periodic visual stimulation.

Several media of stimulation can be used to obtain SSVEP responses. Light emitting diodes (LEDs) and screens are the most commonly used devices. In recent years, liquid crystal display (LCD) screens are the most common option among types of screens. Compared to the LCD screens, LEDs are generally brighter, easier to attach to physical objects, and are able to display a wider range of frequencies. However, LCD screens are easier to set up and program, more flexible in tuning the size of stimuli, better at displaying high resolution patterns, and more versatile in presenting multi-layered interactive stimuli. Hence, screens are preferred in tasks where no physical actions are required [1], [2], while LEDs serve an important role when the task is not confined to the screen [3], [4]. For tasks where high level commands are required, both LEDs and screens have been utilised in the literature [5], [6], [7], [8]. Both media have their advantages in different applications so it is important to study both LEDs and screens.

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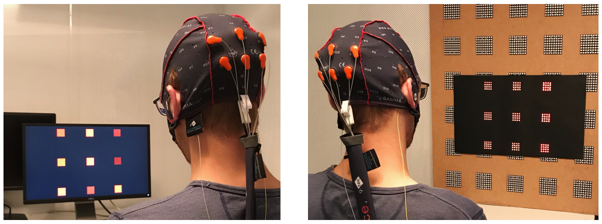
Comparisons of the performances of LEDs and LCD screens in SSVEP applications in the literature give inconsistent results, which could be partially due to the differences in experimental setups and evaluation criteria. Classification accuracy and frequency domain magnitudes are measures used in different studies. Some results show that LEDs perform better in evoking SSVEP [9], [10], [11], which contradict other results [12], [13]. It is challenging to compare results in the literature due to unreported details. In [9], experimental setups on size, shape, and the type of lens of the LEDs were not reported. Arrangements of LED stimuli were explained in [10], [11], but the setups of LEDs and LCD screen were different in size, pattern, spatial arrangement, etc., which may have affected LED vs. LCD screen comparison. In [12], LED model number and size in pixels on the LCD screen were documented, but the size of the LCD screen and the pixels were not clearly specified. Study [13] compared seven SSVEP stimulation properties; size, colour, and brightness between LEDs and LCD screen were kept as similar as possible but details on LEDs were not provided. In the papers where LED specifications were detailed [10], [11], [12], frosted LEDs were used in all three papers, yet contradictory conclusions on whether LED or LCD screen worked better were reported. One study was found to explicitly compare the effect of using clear or frosted LED lenses for a SSVEP-based BCI [14], and reported that clear LEDs were found to evoke stronger SSVEPs. However, only four subjects participated in this study and the t-test results did not show a consistently significant difference between the clear and frosted LED lens conditions. In [9], [14], performance was measured by comparing the resulting frequency domain magnitude of the recorded SSVEP signals. This is in contrast with [10], [11], [12], where decoding accuracy was used as the means of comparison. Since decoding accuracy is dependent on the decoding algorithm, it should be noted that it may not directly correlate with the performance using frequency domain magnitudes.

Hence, this paper focuses on comparing LCD screen, clear LEDs, and frosted LEDs as SSVEP stimulation media. The results are presented as both decoding accuracy and frequency domain magnitudes. A variation in LED background colour was also included in the experiment to investigate the potential effect of having different contrast between our LED and LCD screen setups.

II. Methods

A. Hardware setup

1) LCD screen: A Dell P2417H LCD screen (1920×1080, 23.8 inch, 60 Hz) with LED backlight was used in this



(a) (b)

Fig. 1: Hardware setups. (a) Setup with the LCD screen. (b) Setup with the LEDs with the black background on. The black cardboard was cut into the same size as the LCD screen. The LEDs that were stimulated are those within the open squares of the black board for both LED conditions, with and without the black board.

experiment as shown in Fig. 1a. The screen was connected to an Alienware R4 (Dell) with NVIDIA GeForce GTX 1070 graphics card through an HDMI port. Visual stimulation was generated by MATLAB with Psychtoolbox-3 [15].

2) LED board: The LEDs used in this experiment were Adafruit NeoPixel 8×8 RGB LED panels. The LED panels were mounted on a light brown medium-density fibreboard (MDF) as shown in Fig. 1b. In the setup where the LEDs were frosted, two layers of Pillär Premium Static Solar Frost Window Film were applied immediately over the LEDs. A 210 gsm black cardboard with the same size as the LCD screen was used to alter the background contrast (Fig. 1b).

3) Stimulation setup: Fig. 2 illustrates the layout of the nine stimuli/targets in this experiment. Each target consists of a 4×4 matrix of LEDs on the LED board, or 111×111 pixels on the LCD screen. The spacing between adjacent targets is 91.5 mm or 333 pixels on the screen. Each target was stimulated with a different frequency ranging from 10 Hz to 14 Hz with 0.5 Hz interval as labelled in red font in Fig. 2. All targets were simultaneously stimulated and the subjects were instructed to attend to each one in the order indicated by the orange arrows in Fig. 2.

Red was selected as the stimulation colour. The subjects were asked to match the colour and brightness of the LCD screen and LEDs before the experiment started.

Square waves (LEDs/pixels fully on or fully off) instead of sine waves were used to ensure a fair comparison of the LCD screen and LEDs because the brightness matching process reduced the colour depth of the LEDs and, therefore, resulted in fewer discretisation steps.

During the experiments, subjects sat 80 cm away from the stimulation medium with the centre of the stimuli in the sagittal plane of the subject (Fig. 1). This resulted in an estimated 19° field of view in both horizontal and vertical directions for the entire nine targets, and 2° for each target. The spacing between adjacent stimuli is approximately 7°, which follows the suggestion of [16].

B. EEG data recording

EEG data were recorded using a g.USBamp system with g.SAHARA dry electrodes (g.tec medical engineering

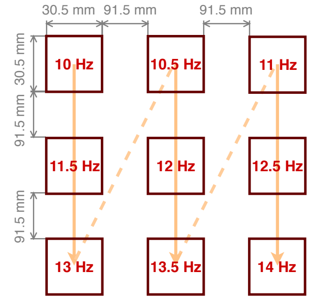


Fig. 2: Stimuli layout. Frequency of each target is labelled in red. Orange arrows indicate the sequence that targets were visited during each test. (Figure not to scale)

GmbH, Austria) sampled at 512 Hz. A 50 Hz notch filter and a $0.5 - 100$ Hz bandpass filter were applied in g.USBamp when collecting EEG measurements. The six selected EEG electrode locations were PO3, POz, PO4, O1, Oz, and O2 (Fig. 1) according to the international 10-20 system. Reference and ground electrodes were placed on the left and right mastoids, respectively. Experiments were conducted in a Faraday shielded room located in the Department of Biomedical Engineering, The University of Melbourne.

C. Subjects

Twelve healthy subjects (six females and six males, aged 20-29 years) participated in the experiment. All subjects had normal or corrected-to-normal vision and no self-reported colour deficiency. Six subjects were naïve to SSVEP-based BCIs. This experiment was approved by the University of Melbourne Human Research Ethics Committee (Ethics ID 1851283).

D. Experimental protocol

The experiment consisted of two parts and included 10 sessions in total. The first part compared LCD screen and clear LED on light brown (neutral) background as stimulation media; the second part compared different LED setups. The sequence of the sessions is depicted in Fig. 3.

In each session, there were three tests. Each test had nine trials where the nine targets were visited from top to bottom, left to right, as labelled in orange in Fig. 2. The trials started with a 0.5 s target prompt with a green square frame, followed by 5 s of stimulation, and ended with a 0.5 s blank period. To ready subjects at the beginning of each test, a 2 s blank period was presented.

E. Data processing

EEG data were first cut into segments of 5 seconds in accordance with the length of each trial. Canonical correlation analysis (CCA) [17] was used to identify the target. CCA calculates and compares the correlation between the measured EEG signal and a set of predefined artificial reference signals. The set of reference signals includes one reference signal for each stimulation frequency candidate. Each reference signal is then constructed as an array of sinusoidal signals (both sine and cosine) of the fundamental

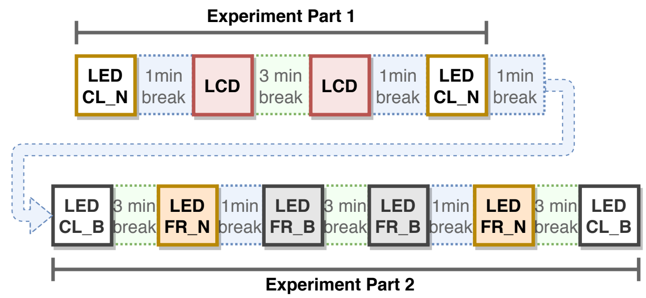


Fig. 3: Experimental protocol. CL: clear; FR: frosted; N: light brown (neutral) background; B: black background.

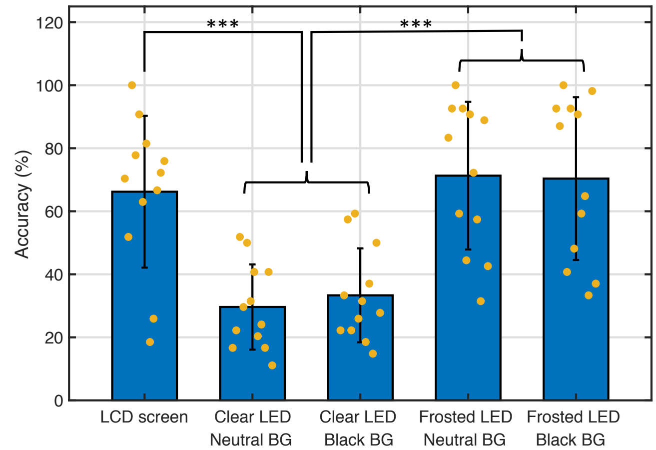


Fig. 4: Accuracies for 12 subjects. The heights of the bars indicate the mean accuracies. Error bars show ± 1 standard deviation. Individual subject results are shown as yellow dots. *** indicates significant difference ($p < 0.001$) between the two groups with paired sample t-tests. (BG: background.)

frequency and its harmonics. After calculating the correlation of the measurement with all reference signals, the one with the highest correlation is selected as the classification output. Here, we have used up to the third harmonic in our CCA algorithm. The accuracy from each session could then be obtained from the CCA.

The fast Fourier transform (FFT) was used to obtain frequency domain magnitudes of the EEG measurements. The whole $5\,s$ measurement was used to calculate FFT magnitudes. As the bin size of frequencies in FFT depends on the length of input signal, the data was first zero-padded to $10\,s$ for finer (0.1 Hz) frequency resolution. Then the average across all channels was calculated as the input to FFT. The resulting magnitudes are read at the fundamental frequency.

Note that, in some LCD sessions, a 0.2 Hz offset was applied to the reference frequencies to correct for a frequency shift sometimes observed on the LCD screen. This is further discussed in Section IV-D.

III. Results

Two comparisons are reported in this paper: SSVEP classification accuracy with CCA and the signal-to-noise ratios (SNRs) of the SSVEP signals.

Fig. 4 compares results with a measure of the SSVEP classification accuracy using CCA. The Jarque-Bera Test was first done for the accuracy from each setup option, and all the five groups of data were shown to be normally distributed. Paired sample t-tests with Bonferroni correction for multiple comparisons were then done for the following null hypotheses (all written in the context of SSVEP accuracy):

- $H_{0,1} : Neutral\ background = Black\ background$
- $H_{0,2} : LCD = Clear\ LED$
- $H_{0,3} : Clear\ LED = Frosted\ LED$
- $H_{0,4} : LCD = Frosted\ LED$

$H_{0,1}$ was not rejected at the 5% significance level ($p = 0.50$). $H_{0,2}$ and $H_{0,3}$ were rejected with $p = 9.8 \times 10^{-5}$ and 9.0×10^{-6}, respectively. $H_{0,4}$ was not rejected ($p = 0.59$).

Since the FFT magnitudes are a relative measure and the SNR reflects how distinct the signal is, we present our frequency domain magnitudes as SNRs. Table I lists the SNR at the fundamental frequencies for each subject in each setup. The SNR is calculated as the ratio of the FFT magnitude at fundamental frequency and the average FFT magnitudes within a neighbourhood of the fundamental frequency. Here, the neighbourhood was selected as 10 frequency samples on each side, which makes 20 samples in total.

Correlation analysis was done of accuracy vs. SNR from all subjects in all setups. The result showed a strong correlation between accuracy and SNR ($\rho = 0.7850$, $p = 1.15 \times 10^{-13}$, where ρ is the correlation coefficient). Fig. 5 depicts the correlation between accuracy and SNR.

IV. Discussion

A. Comparison of LCD screen, clear LEDs, and frosted LEDs

As shown in Fig. 4, the LCD screen and frosted LEDs significantly outperform clear LEDs by a large margin. The difference between LCD sessions and frosted LED sessions was not statistically significant. However, the mean and distribution indicate that it could be possible to get a slightly higher accuracy with frosted LEDs compared to an LCD screen.

Based on our observations, we suspect that low accuracy with clear LEDs is associated with their punctate character. The frosting film acts as a diffuser, which could distribute the light more evenly.

B. Comparison between black and neutral background contrast on LEDs

The results in Fig. 4 demonstrated that similar results were obtained from sessions with neutral and black background contrasts, and no significant difference was observed when varying LED background contrast. This suggests that background contrast in LED setups does not have a strong impact on SSVEP performance.

C. Correlation between SSVEP accuracy and frequency domain magnitudes

It was observed from Fig. 5 that the SSVEP accuracy using CCA and the SNR were strongly correlated ($\rho = 0.7850$, $p =$

TABLE I: Signal-to-noise ratios (dB) at fundamental frequency. CL: clear lens; FR: frosted lens; N: neutral background; B: black background.

Subject	LCD	LED			
		CL N	CL B	FR N	FR B
1	0.40	-0.26	-1.65	0.17	2.13
2	0.82	0.36	1.97	6.51	7.29
3	5.15	2.75	3.25	8.22	7.79
4	6.22	0.99	0.76	5.70	3.70
5	10.22	7.06	7.32	10.52	11.34
6	3.67	0.88	1.35	1.99	5.51
7	6.35	1.02	0.49	7.31	7.76
8	0.60	-1.56	-1.02	4.43	4.65
9	1.35	-1.28	-0.42	2.78	1.88
10	1.10	0.04	-0.92	-1.11	-1.54
11	5.28	0.15	3.21	3.76	5.51
12	3.57	0.57	1.30	1.86	0.52
Mean±SD	3.73±3.04	0.89±2.24	1.30±2.47	4.35±3.44	4.71±3.61

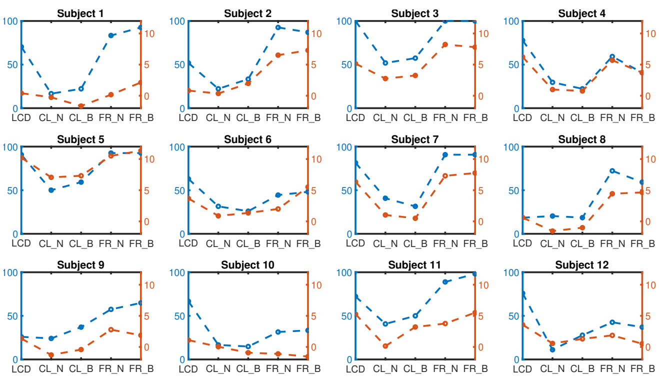


Fig. 5: SSVEP accuracies and SNRs for each subject. Blue and orange show accuracies and SNRs, respectively. CL: clear LED; FR: frosted LED; N: neutral background; B: black background.

10^{-13}), while a weaker correlation was also found between the FFT magnitudes and the accuracy ($\rho = 0.5331$, $p = 10^{-5}$). The weaker correlation may be due to changes in the level of noise during the experiment especially with dry electrodes, which are more sensitive to noise and artefacts.

D. Observed frequency offset on the LCD screen

During the experiment, a randomly occurring frequency offset on the LCD screen was noticed. With the help of a photodiode (Vishay BPW34), the size of the offset was identified to be around 0.2 Hz (lower). It is suspected that this is due to the engagement of the Windows desktop window manager (DWM), which may introduce a delay in frame timing. It is unclear under what condition this frequency shifting behaviour will happen. Detailed information on the laptop configuration is thus provided for people who would like to further investigate this issue: the Alienware laptop used runs 64-bit Windows 10 Home V.1903, with Intel® Core™ i7-7700HQ CPU at 2.80 GHz, and 16 GB RAM.

V. Conclusion

This paper compared SSVEP performance with different stimulation media with a focus on comparing LCD screen, clear LEDs, and frosted LEDs. It was found that the LCD screen evokes stronger SSVEP than clear LEDs, but when frosting films are applied to LEDs, the performance is similar. Background contrast on LEDs was also tested and the result showed no significant difference between neutral and black background on LEDs. Last but not least, strong correlation was observed between SSVEP accuracy with CCA and the SNR of the recorded EEG data.

A 0.2 Hz frequency shifting appeared on the LCD screen randomly to some subjects. Therefore, we suggest that researchers who use a screen as the SSVEP stimulation medium always measure and check the actual displayed frequency on the screen.

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