EVALUATION OF DIFFERENT STIMULI COLOR FOR AN SSVEP-BASED BCI

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Abstract: This paper presents the evaluation and comparison of different colored stimuli used in flickering with different frequencies in order to develop an SSVEP-BCI reliable and comfortable. Four LEDs of different colors (red, green, blue and yellow) flickering at four different frequencies (8, 11, 13 and 15 Hz) were used. Ten subjects, with ages from 21 to 33 years old participated in this study. The results shown that the red color obtains the highest rate of Information Transfer Rate (ITR), but it was not mentioned by any of the volunteers as the most comfortable. The most reliable and comfortable color for an SSVEP-BCI to use is the green one with an ITR of 17.69 ± 3.69 bits/min, followed by yellow and blue color. This election is based in a rule proposed in this work.

Keywords: SSVEP-BCI, color stimuli, EEG signals.

Introduction

About 40 years ago, Regan [1] started experimenting with long visual stimuli trains consisting of sinusoidally modulated monochromatic light. These stimuli produced a stable Visual Evoked Potentials (VEP) of small amplitude, which could be extracted by averaging over multiple trials. These EEG waves were termed as "Steady-State" Visually Evoked Potentials (SSVEPs) of the human visual system.

The amplitude and phase of the SSVEP are highly sensitive to stimulus parameters, such as repetition rate, color, contrast or modulation depth, and spatial frequency.

SSVEP-based BCI activates commands or targets using the control of gazing at flashing lights with defined frequency. SSVEP-BCI has higher accuracy and Information Transfer Rate (ITR) than other kind of BCIs [2. 3]. In addition, short/no training time and few EEG channels are required.

Flickering stimuli can elicit epileptic responses in case of combination of colors. The chromaticity of the stimulus also has a strong impact on the human eye response, and low luminance chromatic stimuli using red colors can induce epileptic responses. Also, red/blue and green/blue flickers have the strongest effect on both pupil contraction and epileptic responses [4].

Figure 1 shows a form of representing isolate basic response. In this graphic is shown the fundamental color response curves of the human eye, according to the theory of W. D. Wright [5]. These represent the absorption curves of the three color-sensitive cone pigments.

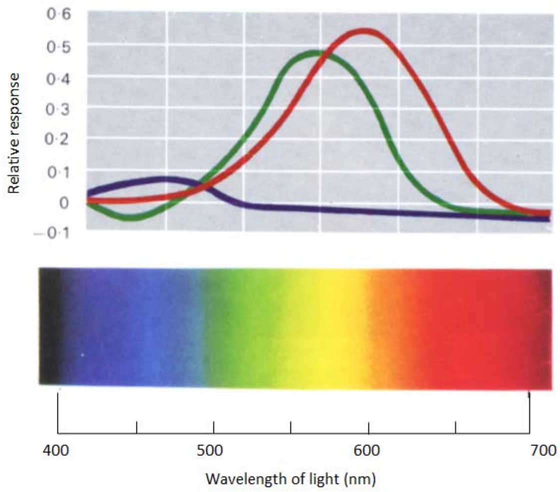

Figure 1: The fundamental color response curves of the human eye, according to W. D. Wright. Adapted from [5].

Many authors agree that lack even more studies related to colors in flicker stimulation. There are some studies mentioned in the literature for example, in [6] is shown that green color gets the highest rate of ITR in comparison with red and blue, while blue offers greater comfort. In this work, the stimuli were displayed on a screen LCD. In [7], four different colors of stimulus: green, red, blue and violet were displayed on a LCD monitor and their performances were evaluated. In this work, the violet color obtained better performance. Finally in [8], white color shown in a LCD monitor achieves the highest accuracy and ITR, followed by gray, red, green and blue colors.

Although the ITR can evaluate the effectiveness of each color, it is dependent on the signal processing technique used. However, there is not a study about the effect of color stimulus on the SSVEP using LEDs as visual stimulator. In this study, four stimuli with different colors flickering were presented by LEDs at different frequencies of independent form (without color combination). This analyze allows to evaluate the performance of such specific frequencies and color and also the degree of comfort of these stimuli. It leads to the development of a reliable, safe and comfortable BCI.

Methods

Subjects– Ten subjects (nine males and one female), with ages from 21 to 33 years old, which were recruited to participate in this study. The mean and standard deviation of the ages were 27.5 and 3.34, respectively. The experiments were performed according to the rules of the ethics committee of UFES/Brazil, under registration number CEP-048/08.

All measurements were noninvasive and the subjects were free to withdraw at any time without any penalty. Previously, a selection of volunteers was performed and topics related to precautions as visual problems, headaches, family history with epilepsy and problems related to brain damage were consulted.

System architecture and visual stimulus– For the development of this study, 12 channels of EEG signal with the reference electrode at the left ear lobe were recorded at 600 samples/s, with 1 to 100 Hz pass-band filter. The ground electrode was placed on the forehead. Using the extended international 10-20 system, the electrode positions chosen were P7, PO7, PO5, PO3, POz, PO4, PO6, PO8, P8, O1, O2 and Oz (Figure 2).

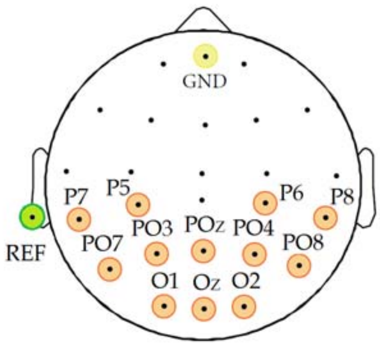

Figure 2: Electrode placement on the scalp during the experiments.

The equipment used for EEG signal recording was the BrainNet-36, manufactured by Lynx Tecnologia Ltd. The volunteers sat on a comfortable chair, in front of a stimulator system, 70 cm far from this. For the evaluation of this type of visual stimulation, a coupling structure of small boxes (4cm x 4cm x 4cm) containing four Light-Emitting Diodes LEDs (Figure 3) was mounted.

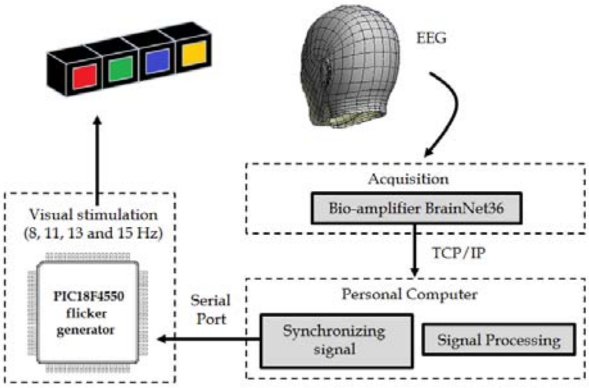

Figure 3: Block diagram of the system.

The participants were asked to observe the stimuli generated by a microcontroller (PIC18F4550, Microchip Technology Inc., USA) with 50/50 % on-off duties. Four Light-Emitting Diodes (LEDs) (part number: NCM: 85414022) with four different colors and luminous intensity of: yellow (31 lux), red (47.5 lux), green (49.7 lux) and blue (33.7 lux) color, all covered with thin white papers diffusers. The flickering frequencies were 8.0 Hz, 11.0 Hz, 13.0 Hz and 15.0 Hz.

Experimental Tasks– The experiments were performed in offline mode. Each color stimulus was shown in the following order: red, green, blue and yellow. The time for observation of each stimulus was 15 seconds to avoid fatigue. Each stimulus with its respective color flickered at four different frequency in the following order: 8, 11, 13 and 15 Hz. In order to improve the analysis of colors, a structure to equitably enhance the intensity of the colors and keep them in the same pattern was designed, as shown in Figure 4.

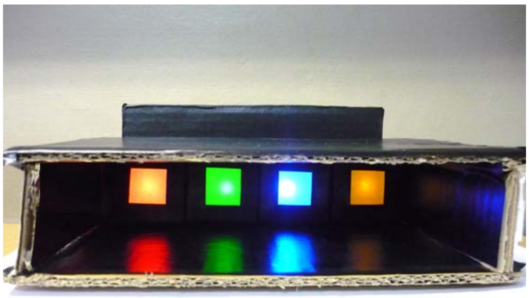

Figure 4: Structure designed to enhance the intensity of the colors.

Data Analysis

The data from twelve EEG channels were segmented and windowed. The window lengths were 1, 2, 4 and 6s, each one with an overlapping of 50 %. Subsequently, a spatial filtering was applied using a Common Average Reference (CAR) filter, and a band-pass filter between 3-60 Hz was also applied for the twelve electrodes.

Although the twelve EEG channels were used during the spatial filtering process, just the three occipital channels (O1, O2 and Oz) were used in the evoked potential detection analysis (feature extraction and classification). According to previous results of our research group, it was found that the Multivariate Synchronization Index (MSI) provides the best performance to extract EEG signal features related to SSVEP [10].

MSI is a method to estimate the synchronization between mixed signals and reference signals, which provides a potential index for recognizing the stimulus frequency. For more details, see [9]. The three harmonics were used in the EEG signal analysis. The synchronization index between the signals from the occipital electrodes (O_1, O_2 and O_Z) and each reference signal was calculated. Then, k indices and their respective classes $(S_1, S_2, \dots, S_k)$ were obtained. Finally, the class was obtained through a criterion of maxima amongst of the S_k classes.

Experimental Results

In addition to the accurate rate, the Command Transfer Interval (CTI) and Information Transfer Rate (ITR) were also computed. Then CTI was defined as the total experimental time (Ttotal) divided by the number of total output digits or letters (Ntotal), i.e., Ttotal/Ntotal. The most common measure to assess the performance of a BCI system is the Shannon's Information Transfer Rate (ITR) [4], which are defined by Equation 1 and 2:

$$\frac{Bits}{Command} = \log_2 K + P \log_2 P + (1 - P) \log_2 \left(\frac{1-P}{K-1}\right), \qquad (1)$$

$$ITR = \frac{Bits}{Command} \cdot \frac{60}{CTI} \qquad (2)$$

Table 2 represents the mean of all cases analyzed, represented in windows lengths *versus* colors with their respective frequencies.

Figure 5 represents the Analysis of Variance (ANOVA) in terms of the accuracy rate for different colors and frequencies used from Table 2. Table 3 shown an information of paramount importance, considering that indicates values ITR averages calculated and this will be one of the indicators in choosing the most suitable color stimulus.

Table 3: Average ITR for all cases analyzed, according to the color coding.

Color	Blue	Yellow	Green	Red
Average ITR	13.45 ± 5.47	17.44 ± 6.46	17.69 ± 3.69	27.06 ± 15.47

In addition to the bit rate, we also consider the comfort of the stimuli on a 7-point scale ranging from low to high comfort, based on the subjective observations of the subjects before the experiments. These results are shown in the graph illustrated by Figure 6:

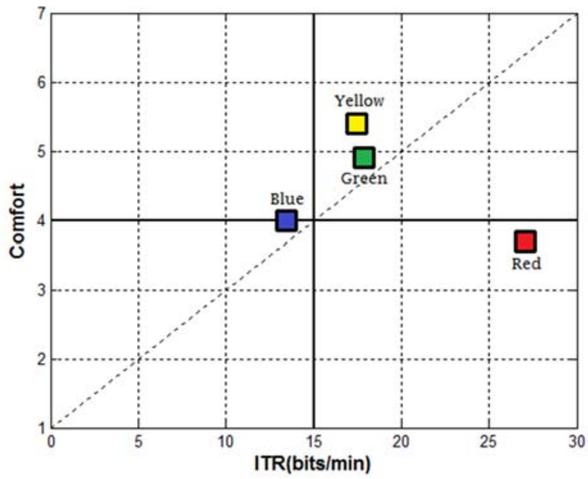

Figure 6: Visualization of the results of ITR vs comfort for each stimulus.

Discussions and Conclusions

Based on the results, it can be confirmed that the red color stimulus presented at different frequencies obtained the highest rate of accuracy and highest ITR for detection of SSVEP. These results confirm the theory proposed by W. D. Wright [5], mentioned in Introduction Section.

According to Figure 6, the red color got the highest value of ITR compared to other colors, although it turned out to be the least comfortable for the use of a BCI. Both yellow and green had good ITR rate and acceptable level of comfort. For all colors, it can be seen that the performance for low frequencies (8.0 and 11.0 Hz) is higher than at middle frequencies (13.0 and 15.0 Hz), which confirms the literature [4].

Moreover, as aforementioned, red color can be dangerous in combination with other colors by the fact that it could be generator of seizures. For this reason, its use requires some care. Thus, the green color would be more suitable for the use of a reliable SSVEP-BCI for having a high rate of ITR and an acceptable level of comfort, followed by yellow and finally blue. This decision was taken according to the following rule: it was taken as reference the point of the diagonal line that is closest to any condition with higher value (high ITR and comfort). Starting from that point, the measured distances to each condition indicate the order of best choice. Finally, it shows that green is suggested as the best choice for a comfortable, safety and accurate BCI. The importance of this study is based in order to help in improve the performance of an SSVEP-BCI.

As future work, tests will be conducted in order to validate our results. In these tests changes in the order of colors and frequencies will be conducted randomly.

Acknowledgment

Richard Godinez would like to thank CAPES/Brazil for the scholarship granted.

Table 2: Average of all cases analyzed, represented in windows lengths *versus* colors with their respective frequencies.

	8 Hz	**11 Hz**	**13 Hz**	**15 Hz**	**8 Hz**	**11 Hz**	**13 Hz**	**15 Hz**	**8 Hz**	**11 Hz**	**13 Hz**	**15 Hz**	**8 Hz**	**11 Hz**	**13 Hz**	**15 Hz**
	RED				**GREEN**				**BLUE**				**YELLOW**			
1s	79.06	65.33	62.35	62.56	77.93	61.63	45.92	30.58	82.33	59.59	42.00	24.32	80.97	69.48	44.76	25.67
2s	84.66	81.22	84.28	79.61	84.47	80.01	66.49	47.14	86.10	70.72	60.71	42.85	89.94	79.28	66.96	41.86
4s	96.66	98.33	96.66	91.66	93.33	88.33	79.99	66.68	88.33	80.00	71.66	54.99	93.33	96.66	83.56	51.68
6s	97.50	100	100	93.33	97.50	95.00	88.33	75.00	97.50	87.50	92.50	67.50	92.50	92.50	90.00	52.50
Acc	**89.47**	**86.22**	**85.82**	**81.79**	**88.31**	**81.24**	**70.18**	**54.85**	**88.57**	**74.45**	**66.72**	**47.42**	**89.19**	**84.48**	**71.32**	**42.93**
Std	**9.09**	**16.31**	**17.05**	**14.20**	**8.80**	**14.44**	**18.51**	**19.95**	**6.45**	**12.05**	**21.10**	**18.39**	**5.66**	**12.45**	**20.19**	**12.48**

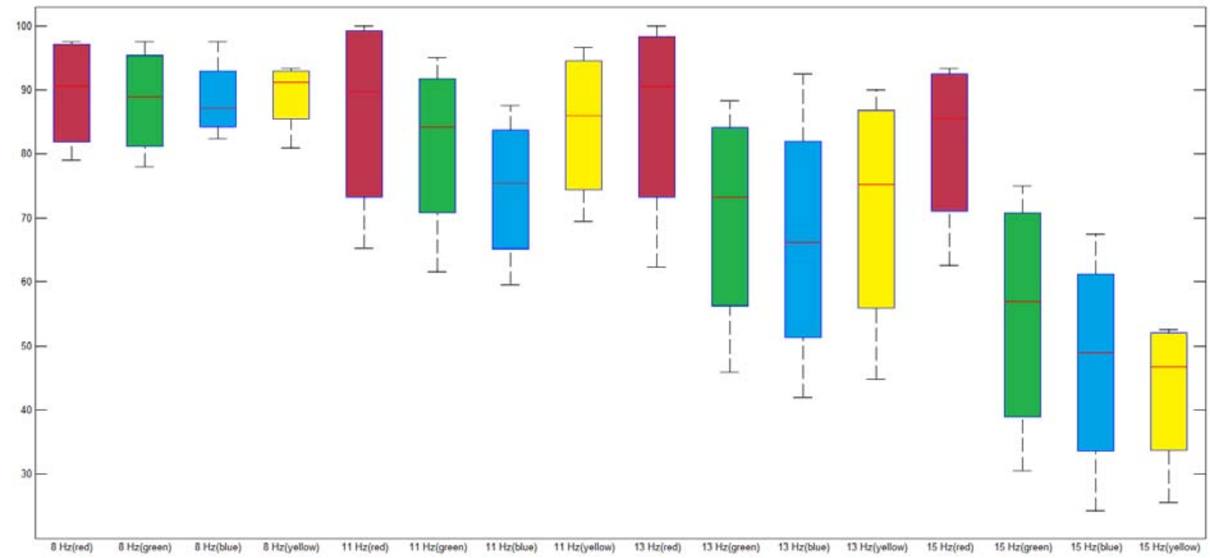

Figure 5: Analysis of Variance (ANOVA) in terms of the accuracy rate for different colors and frequencies from Table 2.

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