Analysis About SSVEP Response to 5.5–86.0 Hz Flicker Stimulation

G. S. Ferreira, P. F. Diez and S. M. T. Müller

Abstract

This paper introduces an analysis about the Steady State Visual Evoked Potential (SSVEP) present in electroencefalogram (EEG) signals. This analysis was performed under some features. Firstly, the flickering stimuli varied along the 5.5–86.0 Hz range, and two types of settings were used, a monopolar and a bipolar. The analysis outputs were SSVEP amplitude response and its signal-to-noise ratio (SNR). These features were discriminated according to the three frequency ranges: low, medium and high frequency. Moreover, a subjective discomfort evaluation was performed through a questionnaire, which was answered by the 20 participating volunteers. Finally, it is shown that this study is in accordance with the literature statements about the SSVEP's power and SNR behavior regarding the oscillating stimuli frequencies.

1 Introduction

When an individual stares at a flickering light, which flickers at a constant frequency, or visualizes a sudden light change, electrical potentials are generated on his scalp via visual pathways neurons [1, 2]. These so-called Visually Evoked Potentials (VEPs) can be understood as a reorganization of spontaneous brain oscillations due to exterior stimuli [3] and some authors call this a *resonance* phenomena [4, 5]. VEPs can be subdivided into two types: *Transient* VEPs and *Steady-State* VEPs, which will be used in this study. For more information on how these potentials are understood and classified, please check [6].

In 1966, Regan [7] published a pioneer study on stimulating the human retina with long sinusoidal modulated monochromatic light. By averaging the achieved signal response he was able to obtain the then-called average steady state response. The study demonstrated that after a 12–20 s period of repetitive light stimulation, the average response was remaining rather constant in amplitude and phase. This behavior was then later attributed to Steady State Visually Evoked Potentials (SSVEPs). However, what really gives SSVEPs its name is under the frequency domain. Vialatte et al. [3] highlights that an organized response with stationary periodic oscillations is the main difference between steady state and transient VEPs.

The way that SSVEP response varies its amplitude along the stimulation frequency axis has been demonstrated by many authors. Regan [8] divided the SSVEP response frequency spectrum into three regions: low-, medium- and high-frequency ones, presenting peaks at 10 Hz, 16 Hz 50 Hz, respectively. Wang et al. [9] also divided it into three regions named just like Regan's, but with peaks at 15 Hz, 31 Hz 41 Hz. Other studies used stimulus frequency beyond the conscious perception threshold, also called critical flickering frequency (CFF), such as [5, 10] and [11]. These works showed evidences for SSVEP response appearance at stimuli frequencies higher than 50 Hz. Note that CFF is understood as the limit at which humans start to perceive flickering light as continuous.

Among possible applications, SSVEPs are used in Brain-computer interfaces (BCIs) development. A SSVEP-based BCI uses EEG signals as input to command output devices. Nevertheless, there are some issues related to the SSVEP-based BCI development, which are the number, location and selection of EEG channels to be used, and noise reduction of EEG recordings. Former studies such as [12, 13] affirm that a bipolar electrode setting has the most suitable response for

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SSVEP-based BCIs. Moreover, [9] also suggests that a bipolar electrode setting diminishes the noise present at SSVEPs responses.

Thus, the current study analyzes the SSVEP response produced by a blinking green-light emitter LED [14] stimuli in the range from 5.5 to 86.0 Hz. This way, the experiment includes the low-, medium- and high-frequency stimuli ranges and also proposes a new nomenclature to high-frequency stimuli beyond the critical flickering frequency, such as [15] but with a higher resolution inside this range. Another subject studied in this work is the phenomena related to SSVEP's Signal-to-Noise Ratio (SNR). Here, the spontaneous EEG signal is taken as noise because it is not an event-related VEP. According to [9], this noise decreases with increasing stimuli frequency, as well as the signal itself, allowing to maintain the SNR approximately constant throughout the studied frequency range.

Considering the importance of analyzing the subjective influence that tiredness and other subjective feelings has upon SSVEP amplitude as presented in [16], a subjective analysis was performed from volunteers' responses to an applied questionnaire. Finally, besides analyzing SSVEP amplitude and SNR behaviours, they are analyzed under monopolar and bipolar settings. With this, the paper aims to study and describe the behavior of the human SSVEP response in a large range of frequencies and to have data on how people feel when using a SSVEP-based BCI system.

2 Methods

This section describes the experimental procedures, the EEG signal acquisition equipment and the volunteers characteristics.

2.1 Volunteers and EEG Signal Acquisition

Twenty volunteers (nine female) took part on the experiment. The average age and its standard deviation are 24.75 and 7.37 years. Seven volunteers wear glasses and 2 are left handed.

The EEG signals were recorded with a Grass 15LT bioamplifier system, composed of 15A54 Quad-amplifier (Astromed, Inc.) with opto-coupled inputs, and digitized with a NI-DAQPad6015. The sample frequency 512 Hz and 12 EEG channels in occipital region were placed as shown in Fig. 1a. The volunteers sat on a comfortable chair at 60–70 cm away from a computer monitor with a box (2.5 cm × 2.5 cm) on top of the screen, illuminated by high-efficiency green-light-emitting diodes (LEDs) controlled with precision by a FPGA Xilinx Spartan2E.
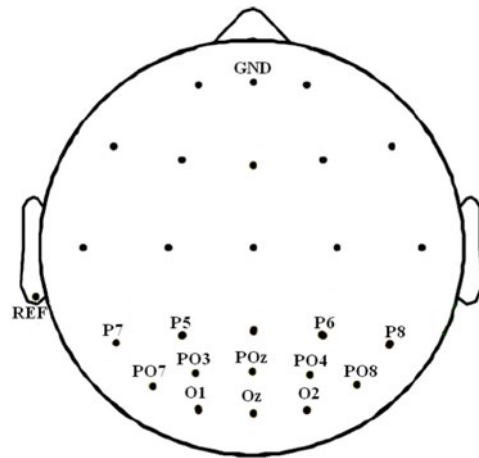
(a) Twelve EEG electrodes used at the experiments
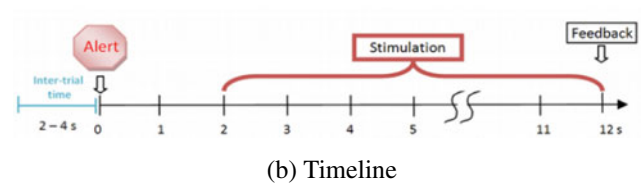
(b) Timeline

Fig. 1 Electrodes positioning and experiment timeline

2.2 Experimental Procedure

The experiment was composed by three sessions, which were classified regarding the LED flickering frequency (low-, medium- and high-frequency), as shown in Table 1. The high-frequency range, at the data analysis, was subdivided into two ranges since there are different frequency steps for each range. Moreover, this subdivision is justified due to some volunteers report that they perceived the flickering stimulus as continuous for frequencies higher than 45 Hz, as it is of interest dividing the high-frequency range below and above the CFF.

Each session has a number of trials according to its frequency range as shown in Table 1. The timeline for each trial is illustrated in Fig. 1b. Before each trial there is a resting (or inter-trial) interval, without stimulation. Then, an audible warning allowed the volunteers to be attentive to the coming stimulus. Two seconds later, the stimulus begins and at the

Table 1 Flickering stimulus frequency range

Range	Subgroups	From (Hz)	Up to (Hz)	Step (Hz)	Number of trials
Low		5.5	12.0	0.5	14
Medium		12.5	29.5	0.5	35
High	High	30.0	45.0	0.5	31
	Ultra-high	46.0	86.0	2.0	21

end of the trial a sound indicated whether the frequency was correctly identified.

2.3 Applied Questionnaire

The volunteers were asked to fill out a questionnaire. This was done with the purpose of having information on how people subjectively feel while undergoing the experiment. Initially and after each session, the volunteers had to give graduated answers to the following questions:

Q1   How much discomfort did the cap cause to you? (0—None, 10—Great discomfort);
Q2   What is your current state of mind? (1—Very sad, 10—Very happy);
Q3   What is your current calmness level? (1—Very calm, 10—Very altered);
Q4   What is your current self-esteem level? (1—Little confident, 10—Very confident);
Q5   What is your current tiredness level? (0—Well rested, 10—Very tired);
Q6   How much discomfort did the stimuli from the last session cause to you? (0—None, 10—Great discomfort);
Q7   What was your concentration level during the last session? (0—None, 10—Very concentrated).

2.4 Signal Processing

After data collecting, the raw EEG signals were processed in some steps. First, the signal DC component has been removed; after, it was spatially filtered using a Common Average Reference (CAR) filter, which used the signal from all of 12 EEG channels. Then, an elliptic Infinite Impulse Response (IIR) band-pass filter was used, with a pass-band of 3–90 Hz plus a notch filter 50 Hz due to the country line frequency.

In this work, two variables were used to study the SSVEP behavior: the response amplitude and the signal-to-noise ratio (SNR). The SSVEP amplitude response over the frequency was determined by the data normalization at the amplitude spectrum, as shown in Eq. (1).

$$P = \frac{|FFT(x)|}{\sum |FFT(x)|}. \tag{1}$$

where x is the processed EEG signal containing the SSVEP information, FFT(x) is the fast Fourier transform of x and $\sum |FFT(x)|$ represents the summation of the amplitudes over all the frequency spectrum, thereby normalizing the sum of the amplitude spectrum to one. Moreover, the signal-to-noise ratio (SNR) was defined by Wang et al. [9] as the ratio of FFT(f) to the mean value of the n adjacent points to the stimulus frequency f, as shown in Eq. (2).

$$SNR = \frac{n \times F(f)}{\sum_{k=1}^{n/2} F(f + k\Delta f) + \sum_{k=1}^{n/2} F(f - k\Delta f)}. \tag{2}$$

where f is the stimulus frequency, F is the Fourier power of the signal, and Δf is the Fourier transform precision or frequency step. The number of adjacent points to the frequency of stimulation f was of 20 in this data processing. Since the frequency resolution is of 0.1 Hz, 10 neighbor points to the stimulus frequency analyzed can give results when compared to numbers up to 1 Hz difference, to each side of it. Previous studies such as [17–19] have used a frequency resolution of 0.2 Hz and 8 adjacent points, reaching a range of ± 0.8 Hz with the stimulus frequency as reference.

After using Eqs. (1) and (2) for all stimulus frequency of all volunteers, an average value of amplitude response and SNR were determined for each stimulation frequency.

3 Results and Discussion

The results can be analyzed regarding two aspects: qualitative and quantitative evaluations. The qualitative assessment concerns the values presented in the questionnaire by the volunteers. This allows to assess the discomfort influence in the experiment execution, which is presented and discussed in Sect. 3.1. The quantitative analysis concerns the SSVEP amplitude response as well as its SNR value. These results are presented in a graphical mode in Sect. 3.2.

3.1 Questionnaire Results

The self-assessment questionnaire results are presented at Tables 2 and 3. Each column number represents the answer for one of the questions presented at Sect. 2.3, according the graduation given by the volunteer.

Table 2 presents the volunteers answers before the experiment starting. The average values were Q1:1.2, Q2: 7.2, Q3: 1.85, Q4: 5.5, Q5:2.35. It means that the cap caused little discomfort at the experiment starting for all the volunteers. Moreover, an average current state of mind of 7.2, plus an average calmness level of 1.85, indicate volunteers' willingness to participate in the experiment. An average current self-esteem level of 5.5 can represent the volunteers' expectation of what will happen during the experiment. Finally, an average current tiredness level of 2.35 may be related to a good night sleeping the day before. Thus, a scenario of good conditions for the volunteers was set up.

The experiment was conducted using the three ranges presented in Table 1, which were randomly presented to the volunteers. Here, the high-frequency range comprises the High and Ultra-high ranges. Each volunteer had its own randomly generated sessions' order, as presented at Table 3. Moreover,

Table 2 Self-assessment answers before the beginning of the experiment

Vol	Q1	Q2	Q3	Q4	Q5
A1	1	7	1	7	2
A2	2	9	1	9	4
A3	0	9	1	9	6
A4	2	5	1	1	6
A5	0	8	2	7	1
A6	3	9	5	3	8
A7	0	7	1	3	5
A8	3	8	4	7	0
A9	2	5	1	1	4
A10	2	7	1	5	2
A11	1	5	1	7	0
A12	0	7	1	9	0
A13	2	8	1	3	1
A14	1	5	3	1	1
A15	1	7	1	5	1
A16	3	7	1	7	2
A17	0	9	1	7	1
A18	1	7	3	6	1
A19	0	8	2	8	0
A20	0	7	5	5	2
Average	1.2	7.2	1.85	5.5	2.35

Table 3 Self-assessment answers after each session of the experiment

Vol	Frequency range order	Q1	Q5	Q6	Q7
A1	L, M, H	2, 4, 8	4, 3, 1	4, 3, 1	6, 6, 7
A2	L, H, M	3, 6, 7	4, 4, 6	4, 5, 9	9, 9, 10
A3	M, L, H	5, 9, 9	5, 8, 9	0, 8, 5	8, 8, 9
A4	M, H, L	4, 7, 8	7, 8, 8	3, 6, 8	8, 6, 9
A5	H, L, M	3, 4, 7	2, 2, 3	2, 3, 4	8, 7, 8
A6	H, M, L	3, 4, 5	7, 8, 8	4, 5, 6	8, 8, 7
A7	L, M, H	0, 1, 1	0, 1, 1	0, 0, 0	5, 9, 9
A8	L, H, M	1, 2, 1	2, 3, 3	3, 4, 1	9, 7, 9
A9	M, L, H	3, 7, 9	4, 5, 9	5, 6, 1	9, 5, 7
A10	M, H, L	0, 0, 0	5, 8, 8	6, 8, 9	8, 3, 9
A11	H, L, M	2, 4, 5	0, 1, 1	0, 0, 0	4, 4, 4
A12	H, M, L	0, 0, 0	0, 1, 1	2, 0, 0	9, 9, 9
A13	L, H, M	4, 5, 6	3, 4, 6	4, 5, 5	9, 9, 7
A14	L, H, M	1, 5, 6	1, 4, 4	3, 4, 5	9, 5, 5
A15	M, L, H	2, 3, 4	1, 1, 1	1, 4, 4	8, 8, 8
A16	M, L, H	3, 4, 7	4, 6, 7	5, 5, 4	7, 6, 8
A17	H, L, M	1, 1, 1	3, 3, 2	2, 3, 2	7, 9, 9
A18	H, M, L	3, 2, 3	2, 2, 3	1, 1, 2	8, 8, 8
A19	M, H, L	0, 1, 5	1, 5, 4	0, 6, 3	5, 4, 5
A20	L, M, H	0, 0, 1	2, 4, 4	1, 3, 3	5, 7, 5

Table 3 shows how the discomfort increased for most part of the volunteers throughout the experiment. The average values are Q1: 2.0,3.45,4.65; Q5: 2.85,4.05,4.45; Q6: 2.5,3.95,3.6; Q7: 7.45,6.85,7.6.

As expected, the average cap discomfort increased over time, as shown in Q1 answers. Starting with a 1.2 grade (see Table 2), it increased to 2.0 after the first session, then it changed to 3.45 after the second session and kept rising until the last session, which had a grade of 4.65. The same reasoning can be applied to the Q5 answers, which means that the tiredness level also increases over time. Initiating at the grade of 2.35 (see Table 2) and going up to 2.85, 4.05 and 4.45 along the sessions.

However, the graduations for Q6 and Q7 answers do not present an increasing or decreasing characteristic. This was already expected since these questions refer to the stimulus discomfort and concentration level at certain frequency range. Both questions are dependent on the stimuli frequency region, which were presented randomly to the volunteers.

Considering then an average for each frequency range, the low-, medium- and high-frequency ranges present a discomfort (Q6) equal to 3.8, 2.9 and 3.35, respectively. This shows how the volunteers had minimal discomfort at the medium-frequency region frequencies. However, it is important to highlight here that the high-frequency region was composed by frequencies above and below the critical flickering fre-

quency, and this should be studied later. For Q7 question, if the average is taken for each frequency range instead of averaging the values along the experiment, the calculated values were 7.3, 7.55 and 7.0 for low-, medium- and high-frequency ranges, respectively. This probably shows that the subjects felt as they were not able to focus on the stimulus at the high-frequency levels as much as on the low- and medium-frequency ones.

However, a new analysis is necessary and this analysis must consider the separation of the ultra-high-frequency range values from the high-frequency range ones.

3.2 SSVEP Amplitude Response and SNR

As presented in Sect. 1, studies already known in the literature have shown peaks at SSVEPs' amplitude spectra in three frequency regions. Namely, Regan [8] with peaks at 10, 16 50 Hz, and Wang et al. [9] with peaks at 15, 31 41 Hz. The current work seeks to confirm these statements in addition to complementing them with an increase in the frequency range analyzed. Moreover, the results are presented for monopolar and bipolar settings, with the monopolar setting or EEG channel chosen was Oz and the bipolar setting chosen was the POz-Oz. These choices were made from the conclusions obtained in [12].

Fig. 2 Average SSVEP amplitude response to the flickering stimuli
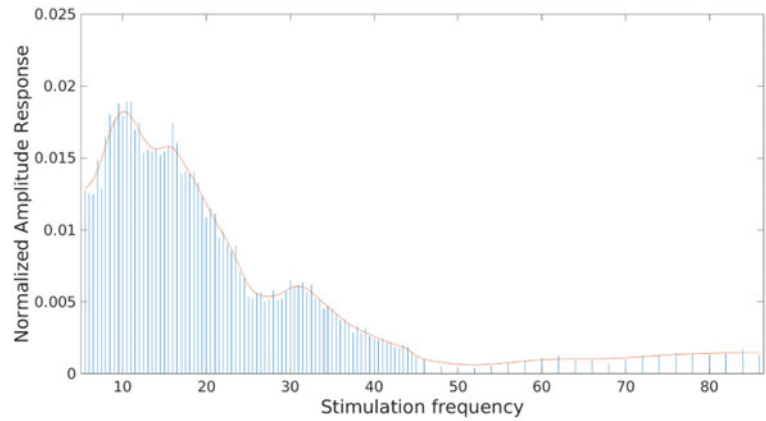
(a) Frequency spectrum for monopolar electrode setting (Oz)
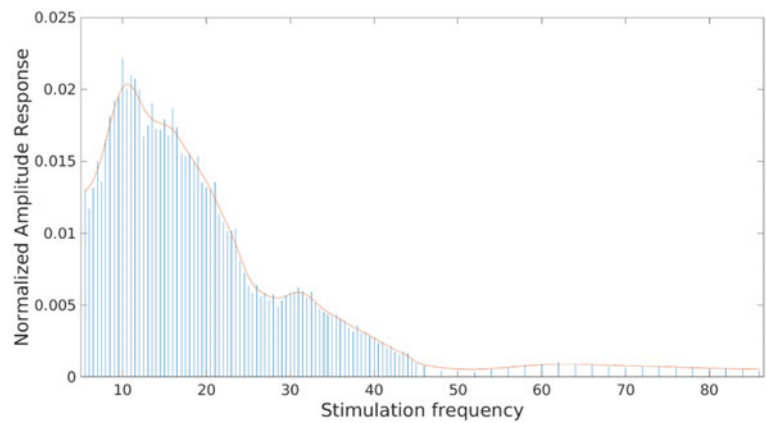
(b) Frequency spectrum for bipolar electrode setting (Oz-POz)

Thus, Fig. 2 shows the averaged SSVEPs normalized amplitude spectra, which the response for monopolar setting (Oz) is presented at Fig. 2a and for the POz-Oz bipolar setting is pictured at Fig. 2b. It can be observed that the bipolar setting has a higher amplitude response until the end of High-1 region (45 Hz, see Table 1) comparing to the monopolar setting. Then, this bipolar setting was chosen for discussing the averaged amplitude spectrum analysis.

Figure 2b shows peaks 10 Hz 16 Hz, as pointed out by Regan [8]. Unfortunately the electric line had 50 Hz frequency and it did not allow to check the SSVEP amplitude at this stimulation frequency, showed at that study as the high-frequency peak. Using Wang's study [9] for comparison, it also can be seen a peak at 31 Hz. However, the 41 Hz peak showed by him was not the peak here, and it was assumed that 38 Hz stimulation frequency would be the established peak for the high-frequency region.

At the ultra-high-frequency region (45 Hz), the monopolar setting shows a higher amplitude response, so the Fig. 2a will be used for the SSVEP amplitude response analysis. This region could be subdivided into two regions: one with a local

peak 62 Hz and another with a peak 84 Hz. The 62 Hz peak remains visible also at the bipolar setting amplitude spectrum (Fig. 2b), while the 84 Hz peak does not. Herrmann's study [5] states the existence of a peak around 80 Hz stimulation frequency, which is close to the 84 Hz peak appearance here, but it leads us to a new peak at the now-called ultra-high-frequency region. All these evidences show that the current work is in accordance with the literature on the appearance of three (and now four) different frequency regions.

Regarding the SNR analysis, Wang's study [9] shows peaks at 16 Hz, 32 Hz 43 Hz. However, in the current work, considering bipolar setting, the SSVEP SNR presents peaks at about 6.5 Hz, 10 Hz, 15.5 Hz, 20 Hz, 21.5 Hz, 31 Hz, 35.5 Hz, 40 Hz 42 Hz, as seen at Fig. 3b. The SNR remains rather constant until the end of the high-frequency region, which can explain the appearance of so many local peaks, in contrast with the amplitude spectrum.

Moreover, just like the averaged amplitude response, the SNR shows the same behavior for stimuli frequencies at the ultra-high-frequency region having a higher value at the monopolar setting and then diminishing significantly when

Fig. 3 Average SNR response along the frequency spectrum
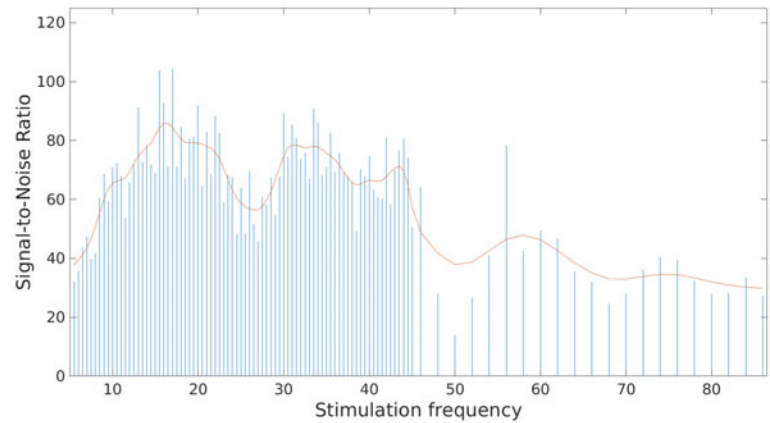
(a) SNR for monopolar electrode setting (Oz)
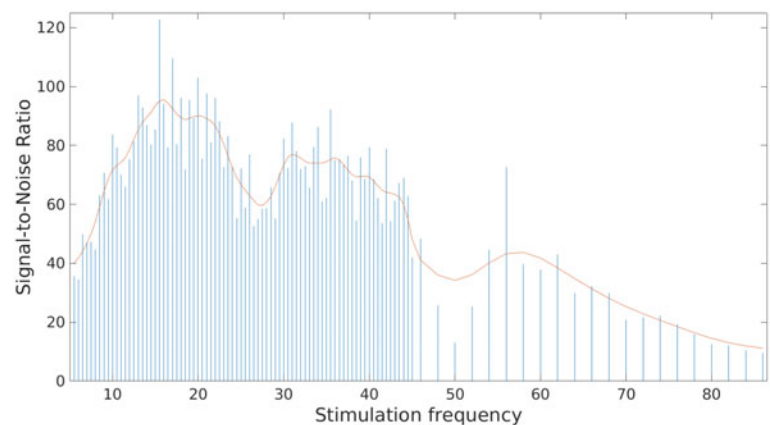
(b) SNR for bipolar electrode setting (Oz-POz)

compared to the other regions. Checking the Fig. 3a it can be seen peaks at 56 Hz, 74 Hz and a peak at 84 Hz. Values close to the one pointed by Herrmann's study [5].

4 Conclusion

Two analysis were performed at this current work, a quantitative and a qualitative one. The quantitative analysis presented new evidences on the SSVEP response amplitude and SNR, supporting the current literature about the division of its spectra into three regions (low, medium and high). It was also proposed the definition of a new region, called here as *ultra-high-frequency* region. The qualitative analysis presented a complementary study related to the volunteers feelings on each frequency region throughout the experiment.

If a correlation is performed between the quantitative and qualitative analysis some conclusion can be taken. Despite having the highest levels of response amplitude and SNR, the low-frequency region presents the most discomfortable stimuli for the participants, and it shows that this frequency

range might not be a good option for SSVEP-based applications. The study also shows that although having the minimal SNR and response amplitude among all the regions, the high-frequency SNR levels still have values that show that this region might be a good option for a SSVEP-based tools. This region analysis presented 80 Hz stimulus frequency local peak, showing slight accordance with Herrmann's work [5].

The study showed a 3.55 grade of discomfort for high-frequency region, but a separation between the high- and ultra-high-frequency regions was not made, and it must be done in further work to check if the stimuli above the critical flickering frequency could be a good option for an application. The attempt for using the ultra-high-frequency region is important, since humans perceive the flickering light as continuous which might lead to a region of minimal discomfort.

Even more, the current work provided information about the peaks at each frequency region for SSVEP response amplitude and SNR. It was in accordance with two of Regan's [8] peaks (10 and 16 Hz), and one of Wang's [9] (31 Hz). However, peaks at different, but close, stimuli frequencies also appeared, such as the one 38 Hz (in contrast with Wang's [9]

41 Hz and Herrmann's [5] 40 Hz peaks for the high-frequency region).

Subsequent studies can be performed but now dividing the high-frequency stimuli region during the experiment into two different regions, enabling to accomplish a more detailed analysis of the human SSVEP response behavior to 5.5–86.0 Hz flicker stimulation.

Compliance with Ethical Requirements Conflict of Interest The authors declare that they have no conflict of interest.

Statement of Human Rights The experiments were performed according to the rules of the Consejo de Bioetica from the Facultad de Ciencias Exactas Fisicas y Naturales, at the Universidad Nacional de San Juan (Ata N7).

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