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EEG-based characterization of flicker perception

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Abstract:

Steady-State Visual Evoked Potential (SSVEP) is an oscillatory electrical response appearing in the electroencephalogram (EEG) in response to flicker stimulation. The SSVEP manifests more prominently in electrodes located near the visual cortex and has oscillatory components at the stimulation frequency and/or harmonics. The phase and amplitude of the SSVEP are sensitive to stimulus parameters such as frequency, modulation depth, and spatial frequency. Research related to SSVEP and the human visual system has mainly focused on brain computer interfaces (BCI) applications, cognitive and memory performance, pathophysiology of diseases. Some other research has been focus in the influence of light properties (i.e. colour and size of stimuli) on brain activity.

Sensitivity to flicker can be studied from a perception viewpoint. By presenting flickering light to an observer it is possible to find the frequency and modulation depth that is required to detect that the light is flickering rather than steady. The sensitivity varies between people and change due to factors like age, concentration and fatigue, while for the stimulus; colour, background an intensity of the light have an influence on the perception. Also, we can find various studies on the response of human visual perception to flicker. However, very little re-
search has been investigated about the SSVEP sensitivity base on the influence of the frequency and modulation depth of flicker.

In this work, we present ZEER unit, a criterion to measure the intensity of SSVEP. This unit allows us to quantify the oscillatory response of the brain to flicker. With the ZEER unit we are able to make the estimation of the SSVEP sensitivity curve according to the frequency and modulation depth of flicker. We implemented an experiment to acquire the visual perception and SSVEP response to the flicker stimulation with goal of characterizing the link between visual perception of flicker and the corresponding SSVEP response.

An experiment was conducted where 25 flicker stimuli with different properties were presented to 12 voluntary participants. The flicker stimuli result from the combination of five different frequencies and five different Modulation Depths (MDs). The MDs were selected around the values defined by a perception curve which defines the relation between perception and MD for a given flicker frequency.

In the study, the EEG and the visual perception data from each participant were collected. The EEG data was pre-processing by peak-filtering, subsampling, artifact correction and averaging the result. Then we applied statistical analysis on the distribution of the samples before and during stimulation. The results were spatially analysed all over the scalp and we used 2 different methods for the estimation of SSVEP sensitivity and flicker perception curve: absolute modulation depth and psychometric method.

The results of the estimated curves indicate that visual perception of flicker and the SSVEP sensitivity are not aligned. We can start to see entrainment at stimuli frequencies below ~35 Hz only for flicker that are perceived by the observer. On the contrary, for higher stimuli frequencies it is possible to elicit oscillatory responses below the visual perception of flicker.

Conclusions:

In this work, we defined a criterion to determine whether the observer’s brain activity is entrained or not by oscillating light. The defined criterion was used to define an entrainment intensity measure called ZEER and to estimate an SSC. The entrainment intensity measured with the ZEER unit allows us to: evaluate the effects of the frequency and MD on the brain activity, characterize the SSVEP response of a certain subject a compare it with others, and improve BCI system designs by selecting stimulus that avoid negative repercussions of flicker on user comfort and safety.

Our results suggested that the statistical analysis on the sample distributions of PSD before and during stimulation combined with the optimal selection of electrodes’ locations is a robust criterion to determine whether the brain is entrained or not by flicker. The robustness is reflected by the consistency of between subject and within subject
results. The selected method can be applied independently to any conditions for an observer. In addition, the criterion allows the comparison between the flicker perception curve and the SSC.

Two methods were used to estimate the SSC: the absolute modulation depth and psychometric method. With the data available the SSC has been successfully estimated in the range of 24-40 Hz with both methods. However, for data obtained at 6 and 60Hz of stimulation we can expect that the curve lies above the tested MDs. The results show that the spectral power at the stimulation frequencies is proportional to the MD and variable across frequencies.

Based on the defined criteria, we found that there is no alignment between the SSC and the FPC. Results showed that it is possible to get entrainment at flicker frequency and MD below the FPC. For frequencies below ~35 Hz it is possible to get an entrainment only with flicker that can be consciously perceived by the observer. For frequencies higher than ~35 Hz the SSC is below the flicker perception curve. This suggests an interaction between the SSC and FPC. However, the entrainment intensity is proportional to the modulation depth.

Despite the current advances in defining a robust measure of entrainment and relating it to the observer’s visual perception of flicker, to fully model the phenomenon further work is needed. One reason to work with low MD conditions was to see if there is any entrainment below the FPC at each condition’s frequency. However, results showed very low or almost no entrainment for 0.002, 0.008 and 0.0014. We proposed for further work to keep the 2 highest MD (0.020 and 0.026) and add 3 points above 0.026. Following the distance between MD conditions, the next three points would be 0.032, 0.038 and 0.044 MD. In addition, to complete the shape of the SSC would be convenient to add high frequencies values like 70Hz. We expect to obtain higher entrainment intensity in order to have appropriate data for the estimation.
Management Summary

Steady-State Visual Evoked Potential (SSVEP) is an oscillatory electrical response appearing in the electroencephalogram (EEG) in response to flicker stimulation. The SSVEP manifests more prominently in electrodes located near the visual cortex and has oscillatory components at the stimulation frequency and/or harmonics. The phase and amplitude of the SSVEP are sensitive to stimulus parameters such as frequency, modulation depth, and spatial frequency. Research related to SSVEP and the human visual system has mainly focused on brain computer interfaces (BCI) applications, cognitive and memory performance, pathophysiology of diseases. Some other research has been focus in the influence of light properties (i.e. colour and size of stimuli) on brain activity.

Sensitivity to flicker can be studied from a perception viewpoint. By presenting flickering light to an observer it is possible to find the frequency and modulation depth that is required to detect that the light is flickering rather than steady. The sensitivity varies between people and change due to factors like age, concentration and fatigue, while for the stimulus; colour, background an intensity of the light have an influence on the perception. Also, we can find various studies on the response of human visual perception to flicker. However, very little research has been investigated about the SSVEP sensitivity base on the influence of the frequency and modulation depth of flicker.

In this work, we present ZEER unit, a criterion to measure the intensity of SSVEP. This unit allows us to quantify the oscillatory response of the brain to flicker. With the ZEER unit we are able to make the estimation of the SSVEP sensitivity curve according to the frequency and modulation depth of flicker. We implemented an experiment to acquire the visual perception and SSVEP response to the flicker stimulation with goal of characterizing the link between visual perception of flicker and the corresponding SSVEP response.

An experiment was conducted where 25 flicker stimuli with different properties were presented to 12 voluntary participants. The flicker stimuli result from the combination of five different frequencies and five different Modulation Depths (MDs). The MDs were selected around the values defined by a perception curve which defines the relation between perception and MD for a given flicker frequency.

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<td>FPC</td>
<td>Flicker perception curve</td>
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<td>SSVEP</td>
<td>Steady-State visual evoked potential</td>
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<td>MD</td>
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<td>CFF</td>
<td>Critical flicker frequency</td>
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<td>ICA</td>
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<td>CAR</td>
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<td>ROC</td>
<td>Receiver operating characteristic</td>
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1. Introduction

Brainwave entrainment refers to the brain activity that is modulated by an external stimulus. Flicker stimuli evoke the so-called Steady-State Visual Evoked Potential (SSVEP) which is an oscillatory electrical response appearing in the electroencephalogram (EEG) in response to flicker stimulation.

The analysis of distributed patterns of brain activity has led to novel insights about the mapping of brain area functions, the diagnosis of diseases in the visual pathway and the links between the different oscillatory system signals and mental states [6]. Multiple studies have shown that SSVEP is related to different psychological outcomes such: stress, migraines, mood, memory, behavioural problems, attention, cognitive performance and overall intelligence and achievements [7]. In addition, researchers have demonstrated that brainwaves are linked to mental states; they can induce or stimulate a change in the conscious state of a person.

Similarly, important research has been done on the psychophysics of human visual perception. Various light properties (i.e. frequency, MD, colour, etc.) have been investigated in order to understand the human visual perception, and to define the conditions at which a periodic light stimulus appears to be steady (flicker fusion) to the observer.

Despite the great advances achieved in this domain in understanding and modelling the human sensitivity to flicker there is little work on linking the visual perception of flicker to the oscillatory response of the brain. This study aims at bridging the two topics.

1.1. Objective

The aims of this project are:

- Defining a criterion to determine whether the observer's brain activity is entrained by repetitive visual stimulation.
- Estimating an SSVEP sensitivity curve which implies the definition of an entrainment intensity measure.
- Finding a link between the estimated SSVEP sensitivity curve and the visual perception of flicker.

1.2. Problem description

In this study we want to know how light properties influence brain activity in humans and the links between the visual perception and the oscillatory response of the brain to light flickering stimuli.

The problem lies on the inexistency of a metric to quantify the SSVEP intensity. Any of previous researches has proposed a standard criterion applicable to any subject and based on the properties of the flicker like frequency and modulation depth. There are proposed methods that only cover the detection of SSVEP in different studies and applications and they are limited or adapted to their particular objectives.
Furthermore, similarly to the flicker perception curve, there is not an SSVEP sensitivity curve which allows us to describe the SSVEP response according to the frequency and modulation depth of the flicker. In addition, excluding the recent studies about SSVEP based on perception insights [2] there is not more studies related to the links between visual perception and SSVEP. In this context, it is important to mention that flicker can be annoying to people and even become dangerous for the ones that are photo sensible, suffer migraines or epilepsy.

1.3. Solution approach

In order to solve this problem, we conducted an experimental study where 25 different flicker conditions were presented to 12 volunteers. The conditions were a combination of five different frequencies and five Modulation Depths (MDs). All of them were selected in the proximities of the visual perception sensitivity curve to flicker. During the experiment, we acquired the brain activity and the visual perception data from each participant. During the experiment, the EEG and the visual perception data from each participant were collected. We proceed with the pre-processing of the data by filtering, subsampling, removing artifacts and averaging the signal. Then we applied statistical analysis on the distribution of the samples before and during stimulation. In addition, feature extraction has been done in the spectral content at the stimulation frequencies. The results were spatially analysed all over the scalp and we used 2 different methods for the estimation of SSVEP sensitivity and flicker perception curve: absolute modulation depth and psychometric method.

1.4. Document organization

This document is structured in 4 main chapters. In Chapter 2, the scientific background and previous results are introduced. In chapter 3, we present a detailed description of the setup and the data processing and analysis. In chapter 4, the results are discussed and interpreted. Finally, in chapter 5 we present the conclusions and suggestions for future research.
2. Background

The first experimental studies on visual stimuli varying sinusoidally in radiance as a function of time were introduced by Ives in 1922 [8], followed by Lange [9] in 1952-1957 with his work about elaborating series of small-filed, photopic amplitude sensitivity measurements. Few years later, in 1961 Kelly used the contrast of the flicker as the threshold variable and took measurements at different frequencies in order to define a curve of relative amplitude sensitivity versus frequency [10]. Then, in 1974, Kelly studied the visual perception of flicker to define the highest rate of flicker perceived by the human. Kelly called Critical Flicker Frequency (CFF) to the flicker rate when flicker get fused as continues light. Under optimal conditions humans can perceive flicker till 80-100Hz.

Regarding the oscillatory brain response insights, SSVEP has been used in many brain-computer interface (BCI) system studies. BCI is a system that allows the user to execute commands to the system without involving the use of his/her peripheral nerves and muscles [11]. BCIs are can be very helpful for people with reduced motor abilities. In addition, new applications are emerging for different fields like entertainment, safety, and security.

In non-invasive BCIs, electroencephalography is becoming very popular because of its high time resolution, high signal to noise ratio, it is easy to acquire, and its implementation is cheaper compared to other brain activity monitoring modalities. Some electrophysiological sources for non-invasive BCIs systems are: event-related synchronization/desynchronization, visual evoked potentials, SSVEP and others [12].

The aim of an experiment study results presented by Philips Research Laboratory in 2011 [2], was to connect the research on SSVEP with the insights of human visual perception of flicker. The selection of stimulus was based in psychophysical researches [10] to present to the observers flickering stimuli with properties that are around the human visual perception curve of flicker. Ten participants were exposed to five different square-wave frequencies (8, 24, 32, 40 and 48Hz) combined with five different MD settings, all fractions of the visual perception curve of flicker (0.6, 1.8, 1.0, 1.2 and 1.4). Figure 3.4 in chapter 3, shows the condition with blue crosses in the frequency and MD dimension.

Results of this study proved that it is possible to entrain the brain with stimulus below the visual perception curve, specifically at 32, 40 and 48 Hz. In addition, results indicated that the higher the frequency and MD of the flicker is, the higher the intensity of SSVEPs is. On the contrary, it was not possible to elicit SSVEP responses at frequencies lower than 32 Hz. Regarding the relation between SSVEP and the visual perception curve of flicker, they concluded indicating that they are no aligned and the intensity of entrainment changes with frequency [15].
3. Methods

In this chapter we provide a complete description of the procedures undertaken to come up with the research results. This chapter is organized in 7 sections: 1) experimental setup, 2) hardware and software, 3) stimulus selection, 4) stimulus design, 5) data acquisition, 6) data pre-processing and 7) data analysis.

3.1. Experimental setup

Twelve participants (9 males, 3 females; age 20-26 years) were recruited in this experiment. The inclusion criteria were as follows: 1) No history of epilepsy and 2) no history of migraines.

Experiment presentation was controlled by a JAVA program running under Windows XP. Experiment session consisted of 250 trials separated into two 18-minute duration and one break of 10 minutes in between. One trial is the presentation of one waveform light to the observer. The trial is composed of 4-seconds long of DC light followed by 3 seconds-long of flicker light at a certain frequency and MD. The purpose of DC light is to prevent adaptation.

During the experiment the Subjects sat in a chair at 150cm distance from a white wall and were instructed to maintain visual fixation on a black central cross placed on the wall at a distance of 150 cm from the floor.

Figure 3.1 The picture shows the location of the Subject seated in front of the wall and the black cross (visual fixation point) below and between the lamps. The monitor station is placed behind the subject.
Subjects were instructed to attend the stimuli and respond Yes or No on a keyboard depending on whether they see flicker or not. Their answer was based on their individual flicker perception.

The whole experimental stimuli sequence consisted of 25 conditions composed by the combination of 5 different frequencies (6, 24, 32, 40 and 60Hz) and 5 different MDs (0.2, 0.8, 1.4, 2 and 2.6%) shown in Figure 3.4. Each condition was repeated 10 trials resulting in a total of 250 trials.

Each trial began with the onset of a DC light that remained on for 4.0 s. Then, an auditory cue (beep) informed the subject of the starting of the flicker stimuli for 3.0 s followed by two beeps indicating the end of the stimuli and prompting the subject to respond by pressing one of two buttons (with the thumb or index finger of their dominant hand). The protocol is described in Figure 3.2.

![Figure 3.2 Time-line describing the protocol of the experiment.](image)

### 3.2. Hardware and Software

The experimental setup consists on the following hardware:

- a) 2 LED Lamps equipped with strips of cold and warm and cold LEDs.
- b) Agilent N3300A System DC Electronic Load.
- c) EA Elektro-Automatik EA-PSI 9300-25 rack mount programmable power supply.
- d) Agilent 33522A Function Generator.
- e) BioSemi ActiveTwo EEG signal acquisition system [14].
- f) 32 electrode setup placed on a textile cap according to the international 10-20 system [15].
- g) Photodiode.
- h) PC with Windows XP operating system.
- i) 18-Key USB Numeric Keypad.

The PC sends the commands to the function generator to load and display the waveforms through a TCP/IP interface. The waveforms sent by the function generator pass through the DC Electronic Load before they reach the Lamps in order to regulate the current load. The lamps are powered by an EA power supply and controlled by an Agilent 33522A function generator. In addition, the USB numeric Keypad is connected to the PC with a large USB cable to cover the distance between the subject and the PC.
The BioSemi ActiveTwo EEG Acquisition System receives and digitizes the signals from the 32 electrodes and the photodiode. Then, the data is sent to the PC by an USB cable.

MATLAB was used to generate and store the waveforms. The EEGLAB toolbox was used to process the data [16].

![Figure 3.3 Experiment Hardware Schematic](image)

### 3.3. Stimulus selection

SSVEP can be elicited by presenting to the subject a repetitive visual stimulus (RVS) or flicker at frequencies in the 1 to 100 Hz range rendered by external light sources able to emit modulated light or alternating graphical patterns in a computer screen. Colour, frequency and MD are flicker properties that depend on the rendering device which influence the SSVEP characteristics [17]. Flicker at high brightness level may affect subject’s vision, and if they are modulated at certain frequencies can provoke epileptic seizures and induce fatigue [18].

The selection of the stimuli was based on previous experiments [2] conducted at Philips Research and on the aims of this project. Taking into account the interest of defining the SSC in frequency and MD dimension and its relation with the general FPC it is suitable to locate the conditions at the proximities of the general FPC. See Figure 3.4.
3.4. Stimulus design

In this experiment, light stimuli are rendered using LED Lamps with white light modulated at a specified frequency and MD. The light stimuli consisted of 25 waveforms generated using Eq. 3.1.

All waveforms are square waves with a length of 6248 samples and an average light level of 1000 [Lux] and colour temperature of 4000K. The output was carefully controlled and the correct output was ensured through the calibration of the system.

\[
\text{Waveform} = \text{ALL} + \text{Square}(T \times F) \times \text{MD} \times \text{ALL}, \quad \text{Eq. 3.1}
\]

where:

- ALL = Average Light Level [Lux]
- Square() = Square wave
- T = Time [seconds]
- F = Frequency of stimuli [Hz]
- MD = MD of stimuli [%]
Figure 3.5 Design of a single wave frequency wave. Square wave generated at 24Hz and 0.002 MD. The voltage and offset parameters computed for this waveform are on the top of the figure.

From the lighting measurements, the modulation depth (MD) was calculated using:

$$MD = \frac{(a + m) - (a - m)}{(a + m) + (a - m)}$$  \hspace{1cm} Eq. 3.2

where:

- MD = Modulation depth (%)
- a = average luminance
- m = modulation amplitude

with \((a + m)\) and \((a - m)\) representing the highest and lowest luminance respectively. High MDs of flicker has more chances to be perceived than low MDs [20].

### 3.5. Data acquisition

Electrical brain activity was recorded from 32 scalp sites using electrodes mounted on an elastic cap (international 10-20 system [15]). All the recording were referenced to the CMS and DRL electrodes [21], the data was digitized at 2048 Samples/s and stored on a PC for further analysis.

The Photodiode sensor was placed below the right LED lamp and connected to the AUX 1 input of the BioSemi ActiveTwo acquisition system. The purpose of recording this signal is to precisely register in the time domain the start and end time of each trial. It is important to know that the EEG and the photodiode signal are recorded simultaneously and the ActiView software allows us to monitor and register both signals in a common EEG data structure.

Furthermore, the Yes/No flicker perception input are also recorded in a text file together with the condition, frequency and MD.
3.6. Data Pre-processing

For all results in this paper, data were pre-processed by Matlab scripts, the signals were Notch filtered at power-line frequency (50Hz) and subsampled at 256 sample/sec. In addition, signals were High Pass filtered at 2Hz, the blinks were removed by Independent Component Analysis (ICA) and the signals were referenced to common average reference (CAR) excluding T7 and T8. Then, data was separated into non-overlapping epochs time-locked to each stimulus.

![Signal Pre-Processing Flow Chart](image)

Figure 3.6 Signal Pre-Processing Flow Chart

3.6.1. Notch filter at power-line frequency (50 Hz)

EEG recording is vulnerable to different sources of noise, which present brings complications to the analysis and interpretation of data. The pre-processing starts with a 50 Hz notch filter to remove the external noise coming from the AC power line. See Figure 3.7.
Figure 3.7 Notch filter response at 50Hz. The top and bottom graphs show the Magnitude (dB) and Phase (degrees) of the Notch Filter Response respectively.

3.6.2. Resample

We refer to sample as each measurement point recorded by the data acquisition system. Originally, the recording sample rate was 2048 Hz. In order to decrease the data time costs of the processing the number of samples was reduced by resampling it at 256 Hz.

3.6.3. High pass filter (2 Hz)

Slow changes in the measured voltage can be produced by sweating and drifts in electrode impedance. For that reason, the data was high pass filtered at 2 Hz by a linear-phase FIR filter in order to eliminate DC shifts. See Figure 3.8.
Figure 3.8 High pass filter response at 2Hz. The top and bottom graph shows the Magnitude (dB) and Phase (degrees) of the High Pass Filter Response respectively.

### 3.6.4. Independent Component Analysis (ICA)

A serious problem for EEG interpretation and analysis is the contamination of EEG activity by eye movements, blinks, muscle, and heart and line noise [22]. ICA can remove a wide variety of artifacts by eliminating the contributions of artifactual sources onto the electrodes.

ICA is a method used for the artifact correction of EEG signals. The artifact correction consists in extracting from the recorded signal (signal from artifactual and cerebral sources) the information that corresponds exclusively to cerebral sources. The recorded signal can be represented with the following model:

\[
\text{EEG}_{\text{rec}}(t) = E\text{EG}_c(t) + \sum_{n=1}^{N} E\text{EG}_n(t),
\]

where:

- \( E\text{EG}_{\text{rec}}(t) \): recorded EEG signal
- \( E\text{EG}_c(t) \): signal from cerebral sources
- \( E\text{EG}_n(t) \): signal from artifactual sources

ICA is a component-based method which means the data can be alternatively represented by transforming the information contained in multiple channel recordings. This multivariate data analysis is able to estimate the ocular artifact. Component-based method can be explained with the cocktail-party problem [23], which models the signal as the following linear system.
\[ x_i(t) = a_{i1}s_1(t) + a_{i2}s_2(t) + \cdots + a_{in}s_n(t) \quad \text{for all } i = 1, \ldots, n \]  

Where:
- \( n \): number of people speaking simultaneously in a room and number of microphones
- \( x_i(t) \): microphone measure
- \( s_n(t) \): speech signal emitted by the speaker
- \( a_{ij} \): distance (parameter) between the microphones and speakers

The objective is to estimate under general assumptions the mixing components and coefficients from the recorded signal. Using a vector-matrix notation, the model can be written as:

\[ x = Ms \]  

\[ x = \sum_{i=1}^{n} a_is_i \]  

Where:
- \( x \): is a vector with \( x_1(t), \ldots, x_n(t) \) as elements
- \( M \): is an \( n \times n \) Matrix with \( a_1(t), \ldots, a_n(t) \) as elements
- \( s \): is a vector with \( s_1(t), \ldots, s_n(t) \) as elements

Inversely, the components \( s_i(t) \) are given by

\[ s = Wx, \]  

where \( W \) is the inverse of \( M \), called the unmixing matrix. Then, by assuming certain restrictions on \( s \) and \( M \) it is possible to estimate them [23]. The assumptions of ICA on the sources \( s_n \) are:

- All the sources are mutually independent to estimate \( W \)
- All but one component must have non-Gaussian distributions
- The number of independent components is equal to the number of observed mixtures

The artifact components of an EEG signal can be estimated by ICA. If we assume that the potentials of artifactual EEG are independent from cerebral EEG potentials, the artifacts and signals from the brain can be resembled by the independent components. In that way, the artifacts can be removed from the EEG recording.
3.6.5. Common Average Reference (CAR)

CAR is a spatial filter in which the average value of all the electrodes on the scalp (the common average) is subtracted from the channel of interest. CAR functions as a high-pass spatial filter by reducing the components that are present in a large proportion of the electrodes [24].

The CAR was computed according to the formula

\[ V_{i}^{\text{CAR}} = V_{i}^{ER} - \frac{\sum_{j=1}^{n} V_{j}^{ER}}{n} \]  

Eq. 3.8

where \( V_{i}^{ER} \) is the potential between the \( i \)-th channel and the reference and \( n \) is the number of channels in the montage.

3.6.6. Cutting and rejection of Epochs

The continuous data was separated into 8-second long epochs starting 4-sec before and ending 4-sec after the onset of each stimulus and stored in a Matlab structure. The onset of each trial is detected using the photodiode signal. See Figure 3.9.

![Flowchart](image.png)

Figure 3.9 Processing flow to get the epochs.
Figure 3.10 Starting time detection and epochs (left graph). The method to obtain the epochs consists of detecting the onset of the stimuli in the photodiode channel and using this time as a reference. We create 2 set of epochs: 4 seconds (1024 samples) before stimulus onset and 4 seconds (1024 samples) after stimulus onset. This procedure is repeated for all the channels and trials.

Afterwards, artifacts were rejected after analysing the energy of the signal. For instance, if a trial has more than 30 channels with an epoch’s variance that satisfy the condition in Eq. 3.11 then the trial is accepted, otherwise it is rejected. The signal with peaks higher than the sum of the mean of the signal, and four times the standard deviation of the signal are rejected in order to dismiss motor artifacts.

\[ \text{EpochVar} < \{ \text{meanVar(channel)} + 4 \times \text{stdVar(channel)} \} \], \quad \text{Eq. 3.9} \\

where:

Channel = Channel number  
EpochVar = Variance of the current epoch  
meanVar(channel) = Variance’s mean of the current channel across all conditions  
stdVar(channel) = Variance’s standard deviation of the current channel across all conditions

3.7. Data Analysis

SSVEPS can be detected through a series of signal processing steps including pre-processing, artifact detection/correction, feature extraction (spectral content at the stimulation frequencies), and feature classification [17]. The first step of the analysis is to look at the spectral content of the signal by estimating the power spectral density using Welch’s method [25].
3.7.1. Welch’s method

For estimating power spectra we used Welch’s method. In this method, the signal is divided into successive time blocks, creating the periodogram for each block, and averaging them across time. The window function \( w(n) \) reduces side-lobe level in the spectral density estimate.

Denote the \( m \)th windowed, zero-padded frame from the signal \( x \) by

\[
x_m(n) = w(n)x(n + mR), \quad n = 0, 1, \ldots, M - 1, \quad m = 0, 1, \ldots, K - 1,
\]

where

- \( R \) = window hop-size
- \( K \) = number of available frames.

The periodogram of the \( m \)th block is given by

\[
P_{x_m,M}(w_k) = \frac{1}{M} |FFT_{N,k}(x_m)|^2
\]

and the Welch estimate of the power spectral density is given by,

\[
\hat{S}_x^W(w_k) = \frac{1}{K} \sum_{m=0}^{K-1} P_{x_m,M}(w_k)
\]

In this case, we use a non-rectangular analysis window, it means that the window hop-size \( R \) cannot be larger than the half the frame length \( M/2 \) and windows are overlapped \([25]\). For an epoch’s PSD of 768 samples length (three seconds), we set a window length of 256 samples (one second) and an overlap window of 128 samples (0.5 seconds), which gives 5 half overlapped windows of 3 seconds long epoch. Then, the PSD during and before stimulus are compared in order to find any relevant difference in their contents throughout the spectra, especially at the frequency of stimulation and its harmonics.

In order to plot the PSD, we start selecting the channel of interest. Then, we take the data from a Matlab structure where the PSD \([\mu V^2/0.33Hz]\) values are stored in a 129 length vector. Each index corresponds to one frequency (1-128 Hz). Finally, we take the mean of all the epochs’ PSD that belongs to one condition and we plot it in the frequency domain. This procedure is applied to the signal before and during the stimuli. See Figure 3.11.
Figure 3.11 Power spectrum density of Subject #3 at location Pz. Blue and red line represent the PSD during and before the stimulation respectively. Vertical green line represents the frequency of stimulation. Columns show different MDs, rows show different frequencies. The unit in vertical axes is $\mu V^2/0.33Hz$ and in horizontal axes [Hz]

### 3.7.2. Z-score

In order to measure the strength of the SSVEP, the z-score is introduced to the analysis. A standard score of 1 is considered significant at the 84% level. It is computed as follows:

$$Z_{score} = \frac{x - \mu}{\sigma} \quad \text{Eq. 3.13}$$

where:
- $x$ = mean of epochs’ PSD from one condition during the stimulus
- $\mu$ = mean of epochs’ PSD from all conditions before the stimulus
- $\sigma$ = standard deviation of epochs’ PSD from all conditions before the stimulus

The standard score is derived by subtracting the mean of the baseline (epochs’ PSD before stimulus) from epochs’ PSD during stimulus and then dividing the difference by the standard deviation of the baseline. The baseline is computed for each channel and composed of epochs’ PSD before stimulus (DC light) from all conditions.
Figure 3.12 Standard score of Subject #3 at location Pz (blue) and Oz (red). Vertical green line represents the frequency of stimulation. Columns show different MD, rows show different frequencies.

In order to visualize the z-score values in a topographic map, we take the standard score from each channel for one condition and then we plot it by an EEGLAB Matlab function at its respective location on the scalp. The same procedure is applied for all the conditions. Finally, we select the range of values that are going to be represented with a colour bar.
3.7.3. Receiver operating Characteristic (ROC) curve

The criteria to define the FPC from the binary visual perception input ("Yes"/"No") lies on finding the MD for each frequency which has at least 5 out of 10 trials answered with a ‘Yes’ (visible flicker). Then, it is appropriate to look at the distribution of the data by analysing the Receiver Operating Characteristic (ROC) Curve, plotting the false positive (FP) rate on the X-axis and the false negative (FN) rate on the Y-axis and finding the point on the ROC curve that define the equal error rate (EER). At this point we have equal amount of FP and FN. Figure 3.14 shows the ROC curve and the distribution of epochs before (in red) and after (in blue) the stimulus onset for Subject #3 for the location Pz and Oz at 40 Hz and 0.020 MD.

Figure 3.13 Standard score topoplots Subject #3 at the frequency of stimulation for each of the 32 channels. Columns show different MD, rows show different frequencies. At the right side is located the colorbar bounded from -3 to +3 standard deviation.
Figure 3.14 Receiver Operating Characteristic (ROC) Curve and distribution. Top-left graph) ROC curve of the Subject #3 for the location Pz at 40 Hz and 0.020 MD with the black line represents the ROC curve, the green line is the Equal Error Rate line and the red point the intersection of the EER line and ROC curve with its corresponding threshold and standard score in the legend. Bottom-left) Histogram based on the data of top-left graph. Blue line represents the PSD at the frequency of stimulation from epochs during stimulation and with red line the epochs before stimulation. Green vertical line represents the threshold value of the EER point in top-left graph. In addition, FN is the number of False Negative values and FP is the number of False Positive values. Top-right graph) ROC curve of the Subject #3 for the location Oz at 40 Hz and 0.020 MD. Bottom-right graph) Histogram based on the data of top-right graph.

3.7.4. ZEER unit

The conclusion after analysing the distribution of the data with the ROC curves and the histograms is that EER values and their respective standard score are suitable parameters to combine in order to create an entrainment measurement unit.

The Zscore is a powerful method to determine the existence of statistically significant difference between two samples normally distributed. This statistically significant difference indicates the probability that the difference in the means of the distributions occur as a result of the intervention rather than by a chance. However, there is a problem with the use of Zscore because the analysis of the histograms suggests that the data is not necessarily normally distributed. Similarly to the Zscore method, we can calculate a standard score to serve as a measure of distance between the current distributions.
Then, in order to improve the feature extraction of the data, we introduced ZEER definition the results of the EER analysis. The EER analysis allows us to characterize the distribution of the power at the frequency of the stimulation during and before stimulation. Then, the multiplication of standard score and EER gives us a balance combination of both extracted features to define the entrainment intensity measure. The entrainment intensity measure, based on a low standard score (e.g. negative values) can be boosted by the EER in case that the distribution of the samples during and before stimulus has a small overlap. On the contrary, a high entrainment intensity measure based on a high standard score can be reduced if there is a big overlap in the distributions. In this way EER below chance level (<50%) and negative standard scores would not be considered entrainment. By doing this we capture the differences in the distributions before and during stimulation and reduce the influence of chance.

We introduce a new unit called ZEER (from standard score and EER) as follows:

\[ ZEER = \begin{cases} 
0, & EER \geq 0.5 \\
0, & Zscore \leq 0 \\
Zscore \cdot (1 - EER) & \text{otherwise}
\end{cases} \]  \hspace{1cm} Eq. 3.14

The condition proposed in Eq. 3.14 make a classification (whether there is entrainment or not) that depends on whether EER or standard score exceeds their respective threshold. If the EER value for a condition is bigger than or equal to 0.5 or its standard score is smaller than or equal to 0 the group is classified as 'no entrained'. The ZEER value for 'no entrained' group is zero. Otherwise, if EER value is smaller than 0.5 and the z-score is positive, the multiplication of their values gives an entrainment intensity measure.

![Figure 3.15 Surface map values for ZEER unit](image)
3.7.5. Effects of ZEER unit on different signal techniques

ZEER unit was applied to 6 different filtering techniques in order to extract the features from the processed data that allows us to enhance the signal to noise ratio and SSVEP sensitivity across the conditions. We considered a peak filter, power and combinations of harmonics with the goal of getting the best possible resolution beyond the FPC.

The ZEER unit was calculated on the data using 6 different filtering techniques:

a) Non-filtered signal (Original pre-processed signal)
b) Peak filtered signal at the stimulation frequency
c) Power of the peak filtered signal
d) Sum of 2 PSD harmonics values from non-filtered signal
e) Sum of 3 PSD harmonics values from non-filtered signal
f) Sum of 5 PSD harmonics values from non-filtered signal

a) Non-filtered signal (Original pre-processed signal)
In this method the ZEER unit it is applied to the Non-filtered signal. The Non-filtered signal is the signal obtained after the pre-processing steps explained in Figure 3.6

b) Peak filtered signal at the stimulation frequency
The peak filter is a linear-phase FIR filter placed at the frequency of stimulation. The filter is applied to the row signal just after the signal pre-processing (see Section 3.6) in order to improve the signal-to-noise. See Figure 3.16.

![Figure 3.16 Peak filter response at 6Hz. The top and bottom graph shows the magnitude (dB) and phase (degrees) of the peak filter response respectively.](image-url)
c) Power of the peak filtered signal
The signal power corresponds to the signal squared after peak filtering (Eq. 3.17). To describe the power of the signal more globally an averaging over a time-slice is performed, mathematically expressed as integration over time (Eq. 3.18)

\[ P(t) = x^2(t) \]  
\[ Eq. 3.15 \]

\[ P_a = \frac{1}{T} \int_{t_o}^{t_o+T} P(t) \, dt, \]  
\[ Eq. 3.16 \]

where \( P(t) \) is the instantaneous power of the peak filtered signal \( x(t) \), \( P_a \) is the averaged power and \( T \) is the length of the time-slice. The time-slice corresponds to the before and during the stimulation period are 256:1024 (3 seconds) and 1024:1792 (3 seconds) respectively for a sampling frequency of 256 samples per second.

d), e) and f) Sum of 2, 3 and 5 PSD harmonics values from non-filtered signal
In order to see how the number and entrainment intensity of the harmonics affect the ZEER values, we performed three different analysis methods including 2, 3 and 5 harmonics. To do that we sum the PSD values at the fundamental frequency and its harmonics with a spectrum range from 0 to 128 Hz. Table 3.1 shows the selected harmonics by method.

<table>
<thead>
<tr>
<th>Harmonics method</th>
<th>2 Harmonics method</th>
<th>3 Harmonics method</th>
<th>5 Harmonics method</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 Hz</td>
<td>6 and 12 Hz</td>
<td>6,12 and 18Hz</td>
<td>6, 12, 18, 24 and 32 Hz</td>
</tr>
<tr>
<td>24 Hz</td>
<td>24 and 48 Hz</td>
<td>24, 48 and 72 Hz</td>
<td>24, 48, 72 and 96 Hz</td>
</tr>
<tr>
<td>32 Hz</td>
<td>32 and 64 Hz</td>
<td>32, 64 and 96 Hz</td>
<td>32, 64, 96 and 128 Hz</td>
</tr>
<tr>
<td>40 Hz</td>
<td>40 and 80 Hz</td>
<td>40, 80 and 120 Hz</td>
<td>40, 80 and 120 Hz</td>
</tr>
<tr>
<td>60 Hz</td>
<td>60 and 120 Hz</td>
<td>60 and 120 Hz</td>
<td>60 and 120 Hz</td>
</tr>
</tbody>
</table>

Table 3.1 Table of harmonics methods. It shows the frequencies selected for each stimuli frequency and harmonic group taking into account the spectrum range from 0 to 128Hz.

3.7.6. Estimation methods for sensitivity curves
In this section we introduce 2 methods for the estimation of sensitivity curves: absolute modulation depth method and psychometric method.

3.7.6.1 Absolute Modulation Depth Method
This method consists of finding the lowest MD from the conditions that is above a certain threshold for each frequency. This method defines the curve on the condition points. For instance, Table 3.2 shows the number of “Yes” that Subject #3 answered for each condition for the Flicker Visual Perception Input, and according to a threshold of 5, the curve would be defined in the points represented by the green cells. In the case of 60Hz, because of the limited resolution, the expectation is to find the corresponding point above the highest MD (0.026).
Table 3.2 Number of ‘Yes’ answers of Subject #3. MD in the rows and Frequency in the columns. Green cells represent the defined curve base in a threshold 5. Red cell indicates an expectation of the curve’s point at 60 Hz higher than 0.026 MD.

The same method is applied to the ZEER values. In this case, the threshold is 0. As explained before, it means that a ZEER value higher than 0 indicates that there is an entrainment, otherwise there is not entrainment. If there is not any ZEER value higher than 0 for a certain frequency, in the same manner, the expectation is to find the point of curve above the highest modulation depth condition.

3.7.6.2 Psychometric method

The second method which we refer to as psychometric method is based in a regression analysis in which the observational data is modelled by a parametric function in order to estimate the coefficients of a nonlinear regression function. The coefficients are estimated using iterative least squares estimation. This method was applied to perceptual data in order to estimate the FPC and to the ZEER values in order to estimate the SSC.

Psychophysics is a mathematical approach that investigates the relationship between sensations and physical stimuli [26]. To obtain the FPC, we defined a detection threshold at which the observer is able to perceive the presence of the flicker some proportion of the time. For our particular yes-no design, 50% is a suitable threshold because it is the point where yes-no responses are equally expected [26].

The analysed data have continuous predictors with a continuous nonlinear response. In order to find the threshold we need to estimate the coefficients of a nonlinear regression function, using least squares estimation. For estimating the relationship between the predictors and the response we used a statistical technique called, nonlinear regression analysis [27]. With nonlinear regression the data are modelled by a function which is a nonlinear combination of the model parameters. An important application in data fitting is least squares method. Least squares find the best fit by minimizing the sum of squared difference between the observed value and the fitted value provided by the model.

Plotting the cumulative response of the outcomes from one frequency against the 5 different MDs results in a Psychometric function. For this study, the parametric template for the psychometric function is the logistic distribution that is defined as follow [26]:


\[ L(x; \alpha, \beta) = \frac{1}{1 + e^{-\beta}} \]

where:
- Definition range: \( x \in (-\infty, +\infty) \)
- Parameter set: \( \theta = (\alpha, \beta) \)

with:
- \( \alpha \in (-\infty, +\infty) \) position parameter
- \( \beta > 0 \) spread parameter

Figure 3.17 shows an example of the psychometric function.

![Psychometric Function Illustration](image)

Figure 3.17 Illustration of the psychometric function and the underlying binomial distribution at 32Hz and 0.002, 0.008, 0.014, 0.020 and 0.026 MD. Here, the yes-answer percentage of the observer against MD has been plot.
4. Results and discussion

The presentation of the results is divided in five sections: 1) Power spectral density, 2) Z-score, 3) Receiver operating Characteristic (ROC) and Equal Error Rates (EER), 4) ZEER unit and 5) Curves estimation.

4.1. Power spectral density

The analysis of EEG signals in the frequency domain allows us to quantify the power of entrainment originated by an oscillatory visual stimulation at a certain frequency and MD. Thus, we compare the EEG power spectrum density (PSD) during stimulation with the PSD before the stimulation.

Figure 4.1 shows the PSD \( [\mu V^2/0.33Hz] \) average at location Pz for each of the conditions ordered by frequency in the rows and MD in the columns. The vertical green line indicates the frequency of stimulation in each graph. The location Pz was selected because the entrained activity manifests more saliently there as compared to other locations. Relevant power peaks at the first and second harmonics are visible for the following stimulation frequencies: 24, 32 and 40 Hz and MDs 0.014, 0.020 and 0.026. On the contrary, the stimulations at 6 and 60 Hz do not appear to elicit any brain response for any MD. Furthermore, in each of the figures one can observe an attenuation of the power in the Alpha range (8-12Hz) during the stimulation. This is expected because a reduction in alpha at a certain location in the scalp is indicative of brain activity in the cortical areas that influence the EEG signal at that location.

The PSD values are standardized to facilitate statistical interpretation. A standard score is derived by subtracting the mean baseline response composed by all condition's samples 3 seconds before the stimuli at a specific location from the mean of the epochs during the stimulation and then dividing the difference by the standard deviation of the baseline.

4.2. Z-score

Figure 4.2 illustrates the standard score values at location Pz Channel (blue) and Oz (red) for each of the conditions spatially ordered as in Figure 4.1. In this figure, the peaks at the frequency of stimulation and harmonics are more salient as compared to Figure 4.1. The high peaks at 24, 32 and 40 Hz for MDs 0.014, 0.020 and 0.026 are indicative of a large difference between the PSD during the stimulation and the PSD during baseline. For instance, the Pz channel’s peak at the frequency of stimulation (24Hz) in the 24Hz/0.026MD condition shows one standard deviation distance from the Baseline and at the second harmonic (48Hz) the Oz channel has a peak of more than 2 standard deviation distance from the Baseline. These results show that there are significant differences between the PSD during and before the stimulation. In addition, results show small peaks at the frequency of stimulation and harmonics at 6 Hz for a MD of 0.020 and 0.026, which they were not visible in the PSD analysis.
Figure 4.1 Power spectrum density average across subjects for each of the conditions at Channel Pz. Blue and red line represents the FFT during stimuli and the FFT before stimuli respectively. Columns show different MD, rows show different frequencies. The unit in vertical axis is $\mu V^2/0.33Hz$ and in the horizontal axis [Hz].
Figure 4.2 Standard score average across subjects at channel Pz (blue) and Oz (red). Vertical green line represents the frequency of stimulation. Columns show different MD, rows show different frequencies.
The spatial distribution of the standard score on the scalp is useful to identify the regions where relevant brain activity takes place.

Figure 4.3 shows a topographic representation (topoplot) of the z-score averaged across subjects. The Colour Bar is set from 0 to 1.5, which excludes negative values from the analysis because they correspond to the situation where the average power at the frequency of stimulation is lower during stimulation compared to the baseline. The topoplots show high z-scores for 24, 32 and 40 Hz and MDs 0.014, 0.020 and 0.026, in parietal and occipital locations (Pz, PO3, PO4, O1, Oz and O2) which are located near the cortical area responsible for visual information processing.

In addition, there are other clear spots in centro-parietal locations which may appear because of the propagation of the brain waves that have originated in occipital sites.

![Figure 4.3 Standard score average across subjects at the frequency of stimulation for each of the 32 channels. Columns show different MD, rows show different frequencies.](image-url)
4.3. Receiver operating Characteristic (ROC) and Equal Error Rates (EER)

In order to find a criterion (or set of criteria) that determines whether there is entrainment or not, we focused our analysis to sample’s distribution. At this point, the distribution of the power at the frequency of the stimulation during and before stimulation is analysed on a per-trial basis and characterized by the equal error rate (EER). In this case the false positives are the baseline recordings that have a high power at the frequency of interest (at least higher than the threshold) which makes them be considered as being recorded during stimulation. The false negatives are the recordings during the stimulation that have a power lower than the threshold which makes them be considered as being recorded before the stimulation.

The EER and its related standard score (with before stimuli samples for a certain condition as baseline) are computed for each condition and subject. The results are presented in Figure 4.4 where each of the 5 boxplots belongs to a condition frequency value incrementally ordered from left to right. Each boxplot compares the 5 MDs with their EER distribution bar across subjects and its median value indicated by the horizontal red line.

Results show that the higher the MD, the lower the EER. This approach seems to separate better the before and during the stimulation samples at 24, 32 and 40 Hz. This is not the case for 6 and 60 Hz where the EER value is between 0.5 and 0.6 for each of the MDs representing overlapped distributions and confirming the low scores obtained in the PSD and standard score analysis where both methods show a low entrainment at 6 and 60 Hz in all MDs.
Figure 4.4 Distribution of EER values for channel Pz across subjects separated by frequency. Boxplots incrementally ordered from left to right. In each boxplot, the distribution and median value for each MD represented by blue colour boxes and horizontal red lines respectively. On each box, the edges of the box are the 25th and 75th percentiles, the whiskers extend to the most extreme data points not considered outliers, and outliers are plotted individually.

Figure 4.5 shows the EER average topoplots across subjects with a colour range from 0 to 0.5. The lowest EERs are localized around the visual cortex and are centered at channel Pz for the frequency of stimulation at 24, 32 and 40 Hz for MD equal and bigger than 0.014.
Figure 4.5 EER average topoplots across subjects for each condition. Colour range is from 0 to 0.5 in order to reject values bigger than 0.5 because they represent substantial overlapped distributions. Columns show different MD, rows show different frequencies.

Thus far, EER results show a significant correlation with the scores and topoplots obtained from the PSD and standard score. To extend the analysis, a standard score is computed for the EER values with a baseline composed by all the epochs' PSD before stimulus of one condition. The results are shown in Figure 4.6 where data is presented in the same format as Figure 4.4. Two types of values can be observed from the figure, the negative values corresponding to average power during stimulation that is lower than the average power in the baseline and the positive values which correspond to average power during stimulation that is higher than the average power in the baseline.

A correspondence arises for the standard score and EER at 6 and 60Hz where high EER values are reflected as negative standard scores. This indicates that besides the overlapped distributions of these signals, the standard score is below the baseline and consequently those conditions could be good candidate to be classified as not entrained samples. On the contrary, for low EER values the obtained z-score values are positive at 24, 32 and 40 Hz for MD equal and bigger than 0.014 excluding the 24Hz/0.014MD condition.
Figure 4.6 Distribution of standard score for channel Pz from EER values across subjects separated by MD. Boxplots incremental ordered from left to right.

Standard score average from EER values across subject results are presented by topoplots in Figure 4.7. In this Figure the negative values are rejected by the range of the colour bar (from 0 to 0.5) due to their irrelevance. Positive standard score are located in the visual cortex and centred in Channel Pz at 24, 32 and 40Hz for 0.020 and 0.026 MD and 32 and 40Hz for 0.014 MD. The remaining conditions do not show any positive standard score.
Figure 4.7 Standard score average from EER values across subject. Columns show different MD, rows show different frequencies.

The analysis of EER and standard score is used to compare the distribution of the samples per condition before and during the stimulation in order to find: any relevant differences produced by the visual stimuli, an EER threshold that separates the distributions at equal proportion the False Positive and False Negative Rate, and analyse statistically its characteristics. Consequently, due to the correlation of the different results, the EER and standard score can be defined as entrainment criteria. It is suitable to combine EER and Z-score into a new entrainment index with thresholds that follow the criteria of the analysis and classification applicable to all frequencies and MD. The first threshold is applied on the EER and considers as entrainment the conditions with EER smaller than 0.5. The second threshold is applied on the standard score and considers as entrainment the conditions with a positive value.
4.4. ZEER unit

The results of combining the EER and Z-score in a new unit called ZEER (see chapter 3.7.4) are shown in Figure 4.8. The topoplots represent the ZEER average across subjects for each location on the scalp. The ZEER unit gives an intensity measurement of the entrainment in a scale represented by the colour bar from 0 to 0.5 where red spots illustrate the regions with highest entrainment and dark blue spots illustrates the region with low entrainment. It means that for any sample with a ZEER value bigger than zero the condition would be classified as entrainment and a value equal to zero as not entrainment.

Like previous figures, relevant entrainment can be localized in sites near the visual cortex at 24, 32 and 40Hz for MD equal and bigger than 0.014.
The results of ZEER application in the 5 signal techniques in chapter 3.7.5 are shown in Figure 4.11. The graphs represent the distribution of the ZEER value across subjects for each of the conditions. The non-filtered signal method represents higher entrainment across the conditions, especially at low MD in comparison with other methods. In addition, the 2 harmonics group showed the highest entrainment between the harmonics groups in most of the conditions, and the signal power has the lowest entrainment. As a result, the non-filtered signal is the selected method to continue with the analysis.

Figure 4.9 Results of ZEER application to 5 proposed signal techniques at channel Pz
Due to wide range of ZEER values across electrodes, the presence of noise in the front part of the brain and once the entrainment intensity has a unit of measurement it is convenient to isolate the contributions from a set of electrodes. According to ZEER average across subject in Figure 4.8 channels which show a high entrainment and deserve special attention are localized near the visual cortex, it means that Pz, P3, P4, O1, Oz and O2 channel should be part of the electrodes set. The selected channels group is shown in Figure 4.9.

Figure 4.10. Relative placement of 29 scalp electrodes. Red square surrounding the selected channels to isolate the contribution from this particular set of electrodes [28].
Subsequently, the maximum two ZEER values from the group channels are averaged to isolate the contribution from this particular set of electrodes (near the visual cortex). Figure 4.10 shows the group channel ZEER average across subject results in 5 boxplots incrementally ordered by frequency from left to right. According to ZEER scores, the highest median entrainment values are between 0.25 and 0.5 for MDs: 0.020 and 0.026 at 24, 32 and 40Hz.

Figure 4.11 Distribution across subjects of the Group Channel ZEER average. The channels that belong to the group are Pz, P3, P4, O1, Oz and O2
4.5. Sensitivity curves estimation

In this chapter we show the results of the FPC and SSC estimation for each particular subject and the average across subject. The results were obtained by two different methods: absolute modulation depth and psychometric method. Then, we make results comparisons between both methods.

4.5.1. Absolute Modulation Depth (AMD) method

Figure 4.12 show the individual flicker perception curve (FPC) in blue and SSVEP sensitivity curve (SSC) in red. The curves were estimated with the AMD method. The general FPC in green and the condition's points (magenta) are used as references. Most of the FPCs show a good approximation to the general FPC, especially at low frequencies. Then, due to the limited resolution of the conditions it was not possible to find the point of the FPC at 60Hz. Nevertheless, we expect that the value is above 0.026 (indicated with a blue circle on the condition's point). The SSCs show a characteristic repeated in 6 subjects. The characteristic indicates the intersection of the SSC and the FPC between 32 and 40Hz and 0.008 and 0.014 MD. The Subjects with this characteristic have entrainment with no visible flicker at 40 and 60 Hz. Then, at 6 Hz half of the subjects got entrainment below the highest MD (0.026) and for the other half we expect to have entrainment above 0.026 MD. For all the subjects, the SSC curve is well defined in 24 to 40 Hz range and 0.002 and 0.026 MD range.

![Figure 4.12 Curves obtained by AMD Method. The x-axis is the Frequency and the y-axis is the MD.](image)

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The average across subject of the SSC and FPC are plotted in Figure 4.13. The SSC is above the FPC for frequencies approximately below 35 Hz, where both curves intersect and then the SSC goes below the FPC. Despite the low resolution of the experiment’s conditions there is a good approximation of the FPC to the general FPC. In addition, it is valid to expect that the value at 60 Hz is above the 0.026 MD. Furthermore, the tendency of the SSC going below the FPC means that it is possible to reach an entrainment even if subjects don’t perceive the visual flickering stimulus. It is worth highlighting that because of the ZEER sensitivity the SSC reaches a low MD value at 60 Hz.

Figure 4.13 Results obtained by the Absolute Modulation Depth Method for SSC and FPC. Magenta crosses represent the experiment conditions.

4.5.2. Psychometric method

This method was applied to subjective flicker perception input and EEG data. The obtained curves are showed in Figure 4.14. Analysing the FPCs individually, they show a better approximation to the FPC than the AMD method despite that once again we have to expect the FPC’s point at 60Hz to be above 0.026 MD. Regarding the SSC, the characteristic of the data did not permit to estimate properly the curve’s point in some of the conditions. With this method, the entrainment seems to be above the FPC and there is not any intersection between the curves. Nevertheless, basing on the segments of the curve where the points were successfully estimated by the psychometric method the SSC is defined between 24 and 40Hz and 0.015 and 0.035 MD. Psychometric method works better for the flicker perception data than the EEG data.
The average across subject of the SSC and FPC are plotted in Figure 4.15. It is important to note that the average is computed only with the values that could be satisfactory estimated. This reduces the amount of data processed in comparison with AMD method. The results depict an entrainment above the FPC at frequencies below 35 Hz and below the FPC at higher frequencies. This results are similar to the one described with the previous method on Figure 4.13. The main differences occur at the frequencies of 6 and 60 Hz. In the FPC there is a deviation of the curve towards higher MDs at 6 and 60 Hz. However, it was possible to estimate a value at 60 Hz with a good approximation to the general FPC. The psychometric method was not capable to estimate the values for the SSC at 6 and 60Hz due to the characteristics of the data but the points of the curve obtained at 24, 32 and 40 Hz are quite similar to the ones obtained in previous method.
Figure 4.15 Final results obtained by the Psychometric Method for SSC and FPC
5. Conclusions and future work

In this work, we defined a criterion to determine whether the observer’s brain activity is entrained or not by oscillating light. The defined criterion was used to define an entrainment intensity measure called ZEER and to estimate an SSC. The entrainment intensity measured with the ZEER unit allows us to: evaluate the effects of the frequency and MD on the brain activity, characterize the SSVEP response of a certain subject a compare it with others, and improve BCI system designs by selecting stimulus that avoid negative repercussions of flicker on user comfort and safety.

Our results suggested that the statistical analysis on the sample distributions of PSD before and during stimulation combined with the optimal selection of electrodes’ locations is a robust criterion to determine whether the brain is entrained or not by flicker. The robustness is reflected by the consistency of between subject and within subject results. The selected method can be applied independently to any conditions for an observer. In addition, the criterion allows the comparison between the flicker perception curve and the SSC.

Two methods were used to estimate the SSC: the absolute modulation depth and psychometric method. With the data available the SSC has been successfully estimated in the range of 24-40 Hz with both methods. However, for data obtained at 6 and 60Hz of stimulation we can expect that the curve lies above the tested MDs. The results show that the spectral power at the stimulation frequencies is proportional to the MD and variable across frequencies.

Based on the defined criteria, we found that there is no alignment between the SSC and the FPC. Results showed that it is possible to get entrainment at flicker frequency and MD below the FPC. For frequencies below ~35 Hz it is possible to get an entrainment only with flicker that can be consciously perceived by the observer. For frequencies higher than ~35 Hz the SSC is below the flicker perception curve. This suggests an interaction between the SSC and FPC. However, the entrainment intensity is proportional to the modulation depth.

Despite the current advances in defining a robust measure of entrainment and relating it to the observer’s visual perception of flicker, to fully model the phenomenon further work is needed. One reason to work with low MD conditions was to see if there is any entrainment below the FPC at each condition’s frequency. However, results showed very low or almost no entrainment for 0.002, 0.008 and 0.0014. We proposed for further work to keep the 2 highest MD (0.020 and 0.026) and add 3 points above 0.026. Following the distance between MD conditions, the next three points would be 0.032, 0.038 and 0.044 MD. In addition, to complete the shape of the SSC would be convenient to add high frequencies values like 70Hz. We expect to obtain higher entrainment intensity in order to have appropriate data for the estimation.
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References


