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STEADY STATE VISUAL EVOKED POTENTIALS AT THE BOUNDARIES OF VISUAL PERCEPTION

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ABSTRACT: Steady-state visual evoked potentials (SSVEP) are electrical brain responses that oscillate at the same frequency, or harmonics, of rapid repetitive visual stimulation (RVS). SSVEP are widely used in practice, however, the exposure to RVS is associated with discomfort and safety risks. Those negative effects can be overcome by understanding how properties of the stimulation, such as frequency and modulation depth (MD) affect the SSVEP.
In order to explore whether SSVEP can be elicited by barely perceptible RVS and potentially safer stimulation, we used MDs around the visual perception thresholds (VPT), the lowest threshold at which people perceive RVS. SSVEP were detected only for frequencies higher than 19 Hz with MDs close to the VPT. In addition, an increase in MD was associated with an increase in the amplitude of SSVEP. These findings can help designing a quasi-imperceptible stimulation able to elicit SSVEP, reducing the discomfort associated to with the RVS.

INTRODUCTION

Steady-state visual evoked potentials (SSVEP) are electrical brain responses associated with the stimulation of the retina by rapid repetitive visual stimulation (RVS), also known as flicker [1]. SSVEP are oscillatory responses at the same frequency, or harmonics, as that of the driving stimulation [2]. SSVEP have a very stable amplitude and phase over time and are most prominent over parieto-occipital cortical areas [3]. SSVEP have a high signal to noise ratio [4] and are not very susceptible to artifacts and noise contamination [5, 6].
SSVEP are largely used in research and practical applications. In cognitive neuroscience, they are used to estimate the propagation of brain activity during a cognitive task [7]. In clinical settings, SSVEP are used as a diagnostic tool to study pathological brain dynamics [8]. However, the main application of SSVEP is in brain-computer interfaces (BCI). SSVEP are used to establish a direct communication between a brain and a computer without the need of muscular intervention [9] by identifying the frequency of the RVS [10] in the EEG recorded from a participant scalp.
One of the main disadvantages of SSVEP is the discomfort and safety issues associated with the prolonged exposure to RVS. Epileptic seizures [11] and migraines [12] are examples of side effects associated to continuous exposure to flickering light. Among various characteristics of the RVS, people are very sensitive to its frequency and modulation depth (MD). MD is a measure of light contrast that quantifies the relation between the spread and sum of two luminances during periodic oscillations [13]. For a time-varying luminance, MD is an indication of the ratio between the average light level and the amount of change in the light. The equation to calculate MD can be found below:

$$MD = \frac{L_{max} - L_{min}}{L_{max} + L_{min}} * 100 \quad (1)$$

where:

MD = modulation depth

L_{max} = maximum luminance

L_{min} = minimum luminance

The relationship between MD, frequency and visual perception of RVS has been described by the contrast sensitivity curve (CSC) [14]. The curve defines the visual perception thresholds (VPT): the lowest MD for a particular frequency at which people perceive RVS as discontinuous for at least 50% of the attempts. In recent years an updated version of the CSC, using the entire visual field and controlling for adaptation was created [13] (Fig. 1).

Contrary to the vast volume of research on visual perception there is little known about the effect of the frequency and MD of the stimulation on SSVEP. There is not a CSC describing the lowest MD necessary to elicit SSVEP at different frequencies. If there is a relationship between frequency, MD and SSVEP strength as in visual perception research, the MD of the RVS can be adjusted at different frequencies to reduce discomfort.

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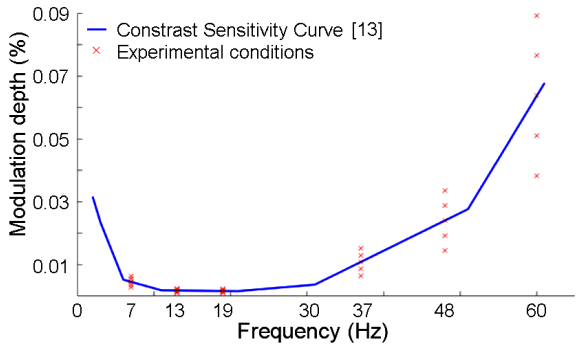

Figure 1: Contrast sensitivity curve (CSC) [13], and the experimental conditions in the current study.

To our knowledge, there are only two studies that have investigated the effect of frequency and MD on SSVEP [15, 16]. One study used RVS with frequencies from 8 to 48 Hz at MDs relative to the VPT described by the first version of the CSC [14]. They found SSVEP for frequencies higher than 24 Hz and MDs below the VPT [15]. In another study, five frequencies from 6 to 60 Hz at five absolute MDs from 0.002 to 0.026 were used. They found SSVEP only for the frequencies 24 and 32 Hz at MD starting at 0.008 and for 40 Hz at MD starting at 0.002 [16].
In this study, we aim to investigate the effect of frequency and MD on the SSVEP response and to find the lowest MDs necessary to elicit SSVEP for frequencies in the range of the CSC (1 to 70 Hz). For this purpose we employed the full field CSC described in [13] (see also Fig. 1). Furthermore, to get a better resolution, we expanded the sampling area around the VPT, compared to the previous two studies, and included conditions (i.e. frequency-MD pairs) that were not tested earlier.

MATERIALS AND METHODS

Participants: Twenty-four healthy volunteers with normal or corrected to normal vision were included in the study: 17 males and 7 females (mean age = 26.4; SD = 6.0). Participants were recruited among the Philips employee population at High Tech Campus, Eindhoven. Before the study, participants signed a written consent letter. The research protocol was approved by the Philips Research Ethics committee board.

Experimental task: The flicker perception task consisted of 300 trials. A trial started with 3 seconds of continuous light, followed by a beep, and 3 seconds of RVS, followed by 2 beeps, and another period of continuous light that continued until the participant provided a response (Fig. 2). Participants were instructed to look with their eyes open at a fixation cross in the middle of a white wall in front of them, where the light was projected (Fig. 3). They were asked to indicate whether or not they perceive flicker by pressing a “yes” and “no” button on a number pad.
The trials were presented randomly in three blocks of 100 trials. Each block lasted approximately 14 minutes and was followed by a break of a variable duration (3-10 minutes). A full session had a duration of approximately one hour and fifteen minutes. The EEG was continuously recorded while the participants performed the task.

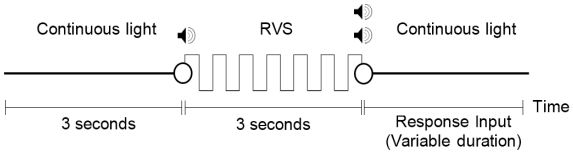

Figure 2: Structure of a trial in the flicker perception task. *Note.* RVS = Repetitive visual stimulation.

Stimuli: The RVS consisted of 30 distinct square waveforms (6 frequency x 5 MDs) that were repeated 10 times each. These conditions were created from the combination of 6 frequencies - 7, 13, 19, 37, 48 and 60 Hz - and 5 MDs selected as a proportion of the corresponding VPT of each frequency - 0.6x, 0.8x, 1.0x, 1.2x, and 1.4x. The experimental conditions are visualized in Figure 1. The light stimulation was delivered via two LEDs panels with a size of 57.5 cm x 57.5 cm suspended at a height of 2.5 m. The light stimulation was reflected on a white wall covering and area of approximately 210 cm x 360 cm (vertically x horizontally). Participants were seated at a distance of 70 cm with a visual angle of 137°. The average light luminance level was 1000 Lux and the color temperature was 4000 K.

Data acquisition: EEG data was recorded from 32 scalp sites using an elastic cap and a BioSemi^{TM} ActiveTwo signal acquisition system. Common Mode Sense Active and Driven Right Leg passive electrodes were used as ground and reference electrodes respectively. Offset values were maintained below 20 kΩ, and the sampling rate was at 2048 Hz. The onset of RVS was recorded using a photodiode placed at a distance of approximately 70 cm to the wall. The photodiode recorded the variations of the light reflected on the wall, and those variations were used to identify the start and the end of the trials in the EEG.

Data pre-processing: EEG signals were notch filtered at power-line frequency (50Hz) and then re-sampled at 256 Hz. Then, the signals were high-pass filtered at 2 Hz and blinks were removed by Independent Component Analysis [17]. After that, signals were re-referenced to a

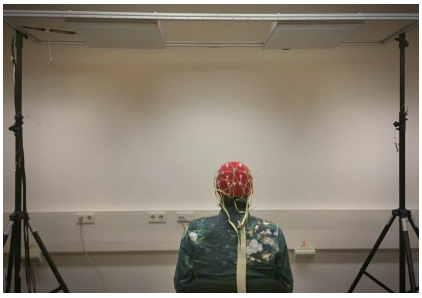

Figure 3: The experimental setup. The picture depicts a participant wearing and EEG cap and the LED panels.

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common average reference excluding T7 and T8 channels. Finally, the data was separated into non-overlapping epochs of 3 seconds, starting at stimulus onset (during stimulation epochs) and 3 seconds before stimulus onset (before stimulation epochs, baseline). The procedures were conducted using EEGLAB [18] and custom-made MATLAB scripts.

RESULTS

Behavioral responses: We calculated the rates at which people perceive RVS as discontinuous by averaging across all participants the number of "yes" responses per condition. We sought the lowest MDs at which participants perceive RVS as discontinuous in at least 50 percent of the conditions. The perception rate of 0.5 was reached in for frequencies 7 Hz and 60 Hz at MD 0.8x VPT and for frequencies 37 Hz and 48 Hz at MD 0.6x VPT. The 0.5 perception rate was not reached for frequencies 13 and 19 Hz. All the conditions had an increase in perception rates with an increase of MD.

SSVEP analysis: Power spectral density (PSD) of the EEG signal was estimated to measure the strength of the SSVEP. PSD is a measure of the power of a signal in the frequency domain and it was obtained by the use of fast Fourier transform (FFT). The FFT was applied on segments of the length of 256 samples (1 second) and an overlap of 128 samples (0.5 seconds) separately for epochs before and during stimulation (see Fig. 4). Characteristic peaks during stimulation at the frequency of stimulation were observed at 37, 48 and 60 Hz starting from MD 0.6x VPT, and were higher for higher MDs. Furthermore, during stimulation there was a decrease in power around the alpha frequency band (8-12 Hz) compared with the baseline.

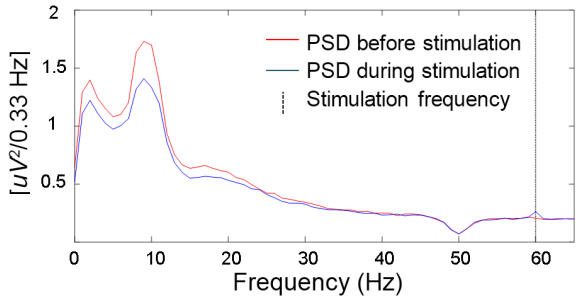

Figure 4: Power spectrum density for a condition (60 Hz and MD 1.4x VPT) at channel Pz.

To get a more objective estimation of the power change due to the RVS, PSD during stimulation was compared with PSD in the absence of flicker, before stimulus onset. To do so for each stimulation epoch we calculated a Z_{score} by subtracting the log PSD mean over all baseline epochs and dividing by the baseline log PSD standard deviation as shown in Equation 2. Positive Z_{scores} are an indication of higher power during stimulation, and they were observed for frequencies 37, 48 and 60 Hz for MDs even below 1.0x VPT (Fig. 5). Overall, Z_{scores} were larger for higher frequencies and for higher MDs.

$$Z_{score} = \frac{x - \mu}{\sigma} \tag{2}$$

where:

x = log PSD during a stimulation epoch

μ = log PSD mean baseline

σ = log PSD standard deviation baseline

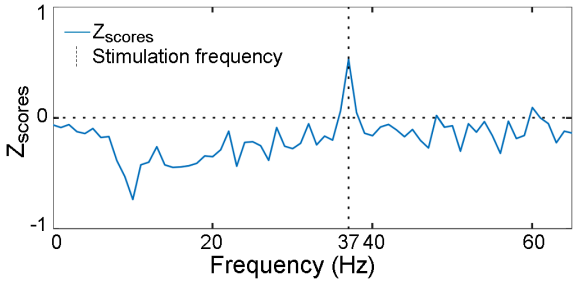

Figure 5: Z_{scores} for a condition (37 Hz and MD 1.2x VPT) at channel Pz.

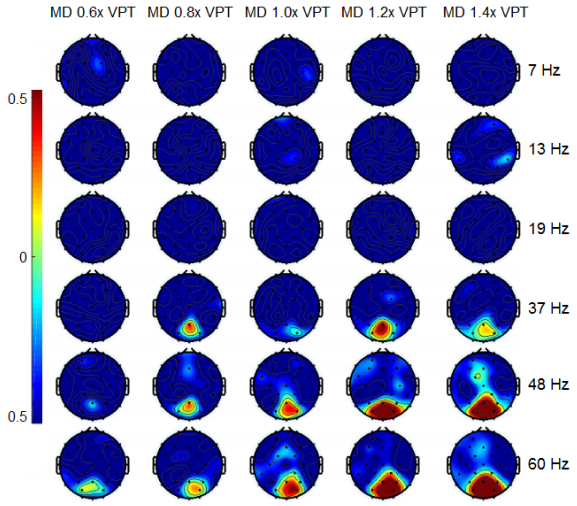

Figure 6: Spatial distribution of Z_{scores} for all the conditions. The color bar located at the left represents the Z_{scores}.

The spatial representation of the Z_{scores} can be observed in the topographic maps of the scalp in Fig. 6. The higher scores were observed in parietal (Pz) and occipital (O1, Oz, and O2) channels. The scores were higher for the higher frequencies and MDs. Frontal and temporal sites did not show significant changes associated with an increase of frequency or MD. Channel Pz displayed very consistent results across the different conditions and analyses, and we selected it for results visualization.
To better estimate the thresholds at which we can distinguish an SSVEP response from the absence of such with sufficient confidence, we selected the Z_{scores} defined by an equal probability of type I and type II errors (equal

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error rate, EER). The EER finds the point at which the probability of both types error is equal. The lower the EER the higher the accuracy of the measurement. The three lower frequencies 7, 13 and 19 Hz have EERs at chance level. An increase in MD was not associated with either an increase or decrease in the EER values for all the frequencies (Fig. 7).

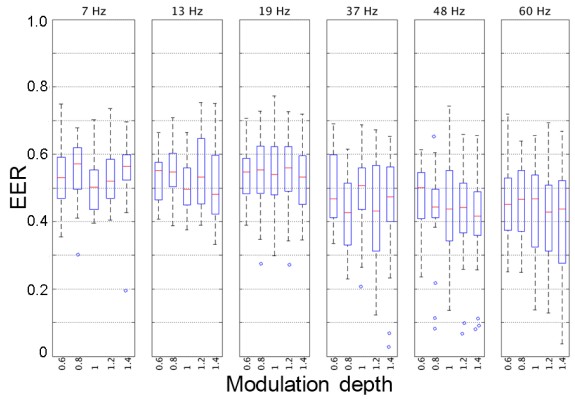

Figure 7: EER distribution at channel Pz. The box edges are the 25th and 75th percentiles. Outliers are plotted by small blue circles. Modulation depths are relative to the VPT (e.g. 0.6x VPT).

Z_{scores} and EER values were combined into a new metric ZEER: Z_{scores} at the EER. ZEER measure the strength of SSVEP, a weak SSVEP response reflected on a low Z_{scores} can be boosted by the EER in case the distribution of the samples before and during stimulation has a small overlap. On the contrary, a strong SSVEP response based on a high Z_{score} can be reduced if there is a big overlap in the distributions before and during stimulation. The ZEER were computed according to the Eq. 3.

$$\begin{aligned} if \quad EER \geq 0.5 \quad or \quad Z \leq 0 \\ then \quad Z_{EER} = 0 \end{aligned} \qquad (3)$$

$$\begin{aligned} if \quad EER \leq 0.5 \quad or \quad Z \geq 0 \\ then \quad Z_{EER} = Z * (1\text{–}EER) \end{aligned}$$

where:

EER = Equal Error Rate

Z = Z_{score}

ZEER = Z_{score} at the EER

Sensitivity curves estimation for SSVEP: We used two methods to create estimations of CSC for SSVEP, a curve containing the lowest MDs necessary to elicit SSVEP. The absolute modulation depth method (AMD) finds the lowest MD for which the ZEER is greater than zero in at least 50% of the trials . ZEER values greater than zero in at least 50 percent of the trials for a condition are an indication that SSVEP responses were elicited for that condition (see Table 1). These thresholds were found for frequencies 37, 48 and 60 Hz for MDs starting at 0.6x the VPT, and for frequency 13 Hz for MD starting at 1.0x VPT.

Table 1: Percentage (%) of ZEER scores with values greater than 0 at Pz channel.

	Frequency					
MD	7	13	19	37	48	60
0.6	37	35	36	42	48	50
0.8	33	33	38	57	52	54
1.0	45	41	37	48	51	54
1.2	37	32	31	56	55	56
1.4	36	40	37	53	53	58

Note. Gray cells indicate the lowest MD at which ZEER scores were greater than 0 in at least 50 percent of the trials.

The psychometric method (PM) makes use of a psychometric function. This method models the observed data, ZEER values, with a non-linear square regression model to estimate the coefficients of the nonlinear regression function and with that estimate the exact MD at which the SSVEP could be elicited in at least 50% of the conditions.

$$L(x;\alpha,\beta) = \frac{1}{1+e^{\frac{\alpha-x}{\beta}}} \qquad (4)$$

where:

definition range: $x \in (-\infty, +\infty)$

parameter set: $\theta = (\alpha, \beta)$

with:

$\alpha \in (-\infty, +\infty)$: position parameter

$\beta > 0$: spread parameter

AMD and PM curves together with the CSC from literature [13] can be observed in Fig. 8. Both SSVEP sensitivity curves had a similar shape and MD thresholds lower than the CSC. The MD thresholds estimated by the Psychometric method were lower than the AMD method. Furthermore, contrary to the AMD method, PM allows us to estimate the MD thresholds even for lower frequencies, e.g. 7 and 13 Hz. Those values appeared way above the MDs around the CSC. Based on our data, we could not estimate a threshold for frequency 19 Hz.

DISCUSSION

SSVEP were elicited for the highest frequencies (37, 48, and 60 Hz) for MDs below the VPT, e.g. 0.8x VPT. Consistent with visual perception research, we found out that the relationship between frequency and MD involves an increase in MD with an increase in frequency: higher MDs are required for SSVEP detection at higher frequencies. For instance, the lowest MD that elicited SSVEP at 60 Hz is more than double the lowest MD that elicited

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SSVEP at 48 Hz. In addition, the estimated contrast sensitivity curve for SSVEP has a similar shape to the CSC. Both curves show an increase of MD with an increase in frequency and this increase is particularly large for frequencies greater than 40 Hz.
SSVEP were not found for the three lowest frequencies at any MD. According to the PM, the MD thresholds for low frequencies lie much higher than the CSC. For instance, the estimated MD threshold at 7 Hz is around ten times higher than the VPT. This might be because at these frequencies the MDs covered by our choice of conditions were in general very low. This range also falls very close to the alpha band, which is known to desynchronize during visual processing [19].
The behavioral responses in our study were aligned with with existing research. The MD at which participants were able to perceive the flicker were around the CSC [13], and an increase in MD was associated with a higher perception rate. This suggests that our task was appropriate to evaluate perception of RVS.

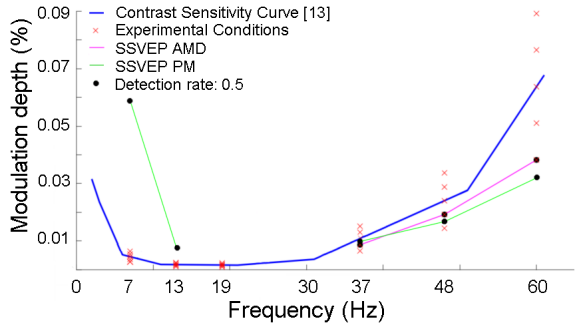

Figure 8: Contrast sensitivity curve (CSC)[13] and the SSVEP-AMD and SSVEP-PM sensitivity curves. Black dots indicate the MD at which SSVEP reaches 50% detection rate.

CONCLUSION

In this paper we studied the effect of stimulation properties, such as frequency and MD, around human visual perception thresholds on the SSVEP response. We were able to elicit SSVEP around the VPT but only for high frequencies. SSVEP were detected close or below to the behavioral CSC found in the literature, i.e by a quasi-imperceptible RVS. We estimated a contrast sensitivity curve based on SSVEP using two different methods. The shape of the estimated SSVEP contrast sensitivity curves is very similar to the behavioral CSC. Such sensitivity curve will help the development of a more diverse variety of stimuli, using more frequencies and MDs. This would increase the conditions that could be used to elicit distinct SSVEP and decrease the discomfort and the risk of photo-induced epilepsy caused by the RVS.

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