An SNR Analysis of High-Frequency Steady-State Visual Evoked Potentials from the Foveal and Extrafoveal Regions of Human Retina*

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***Abstract*—With brain-computer interaction (BCI) applications in mind, we studied the steady-state visual evoked potentials (SSVEP) from retinal fovea and extrafovea in response to a 2° circular and a 16°–18° annular white light stimuli flickering between 5Hz and 65Hz in 5Hz increments. Eight subjects (age 20–55) participated in this experiment. Their EEG signals were recorded using a 64-channel NeuroScan system. Their flickering perception and comfort levels were also noted. Spectral and canonical convolution analyses of SSVEP signals collected from nine EEG channels in the occipital area showed distinctively higher signal-to-noise ratios (SNR) in the foveal responses between 25Hz and 45Hz. Almost all the subjects also noticed less flickering and felt more comfortable with stimulation flickering between 30Hz and 45Hz. These empirical evidences suggest that lights flashing above human vision flicker fusion thresholds may be used as effective and comfortable visual stimuli in SSVEP BCI applications.**

I. Introduction

STEADY-STATE Visual Evoked Potentials (SSVEP) [1,2,16] and their P300-based counterpart, flash visual evoked potentials (FVEP) [3,4] are perhaps the most common exogenous brain computer interfacing techniques. In order to induce strong responses, these techniques often use low-frequency light signals as visual stimuli: below 2Hz for FVEP and within the alpha band (8–13Hz) for SSVEP and. These low frequency signals, however, can cause visual fatigue [5], migraine [6] and occasionally seizure [5,7] among the subjects. Efforts have therefore been made to establish high-frequency SSVEP that uses stimuli above human vision flicker fusion threshold as a viable alternative [8]. Limited success has been achieved so far due to the fact that SSVEP decreases rapidly as stimulation frequency increases. In this experiment, we investigated the possibility of exploiting the acuity of foveal vision to beat the odds against HF-SSVEP.

It is common knowledge that human fovea produces strong SSVEP responses [9,10]. Our hypothesis was that due to its high photopic visual acuity, fovea centralis should be capable of producing detectable SSVEP in response to stimuli flashing above flicker fusion thresholds. Although these responses may be weaker than those in the alpha band, they can still yield appreciable signal-to-noise ratios (SNR) since other asynchronous EEG signals also diminish in strength. With that assumption, we set out to measure the signal-to-noise ratios of human foveal SSVEP responses and compare them with those from the extrafoveal region. Eight subjects (age 20–55) participated in this experiment. Diffused *circular* (with 2° view angle) and *annular* (with 16°–18° view angles) white lights flickering between 5Hz and 65Hz in 5Hz increments were used as visual stimuli. We captured subjects' SSVEP responses using a 64-channel NeuroScan EEG recorder. We also noted subjects' perception of light flickering and their comfort levels during the experiment. The signal-to-noise ratios of SSVEP signals and their correlation with sinusoidal waveforms at different stimulation frequencies were measured using fast Fourier transform (FFT) and canonical convolution analysis (CCA). Data of each subject and their averages were analyzed in order to discover the general trends as well as individual differences. Our results show that SSVEP from the 2° *foveal avascular zone* captured at the nine occipital channels (P1, PZ, P2, PO3, POZ, PO4, O1, OZ and O2) showed distinctively higher SNR between 25Hz and 45Hz. Almost all subjects also noticed less flickering and felt more comfortable with stimulation to their foveal region between 30Hz and 45Hz. These empirical evidences suggest that light sources with 30–45Hz flickering frequencies may be used as effective and comfortable visual stimuli in high-frequency SSVEP BCI applications.

The rest of this paper is divided into four sections. A brief review of retinal physiology was included in Section II to justify the experiment. The participants, apparatus and procedures of the experiment were documented in Section III. Signal processing using fast Fourier transforms (FFT) and canonical convolution analysis (CCA) techniques were discussed in Section IV. Contribution and future work were summarized in Section V.

II. Foveal and Extrafoveal Vision

The central region of human retina can be divided into *foveola*, *foveal avascular zone*, *fovea centralis*, *parafovea* and *perifovea* [11,12]. Together, they form the 5mm wide *macula lutea* or the "yellow spot". According to Iwasaki and Inomata [13], these regions can be distinguished based on the thickness of their ganglion cell layers [Figure 1]. Foveola, approx.

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0.35mm in diameter and occupied 1° of vision field, has no ganglion cell and capillary. The foveal avascular zone, approx. 0.5mm in size and occupies 2° in vision field, has a ganglion cell layer approx. 15μm in thickness but no superficial capillary. These retinal regions produce the most acute photopic vision. The parafoveal region has the thickest layer of ganglion cells (up to 45μm) and is filled with superficial capillaries. Ganglion cells thin down to 15μm in the perifoveal region, which offers suboptimal visual acuity. The density of color photoreceptors, the "cones", also varies along with photopic vision acuity [11]. As shown in Figure 2, foveola is occupied entirely by cones. Beyond that region, cone density diminishes drastically from 50 to 12 per 100mm^2 between fovea centralis and perifovea. Almost 50% of all optical nerve fibers from each eye carry signals from the foveal regions to the visual cortex. The peripheral retinal area, known as *extrafovea*, delivers compressed visual information of significantly lower resolution. It is filled with photoreceptors, known as the "rods", for scotopic vision. The rod density peaks between 15° and 20° of the vision field, roughly coincides with the position of the "bind spot" [Figure 2].

The *flicker fusion thresholds* or *critical flicker fusion (CFF) rates* of human vision also differ notably with respect to different photoreceptors and retinal regions. The maximum fusion frequency for rod mediated vision reaches a plateau at approx. 15 Hz, whereas cones reach a plateau of approx. 60 Hz under high illumination intensity [14]. Different cone cells also have different CFF rates: green (M) cells have the highest rate of approx. 50Hz while red (L) and blue (S) cells have the lower rates in the neighborhood of 30Hz.

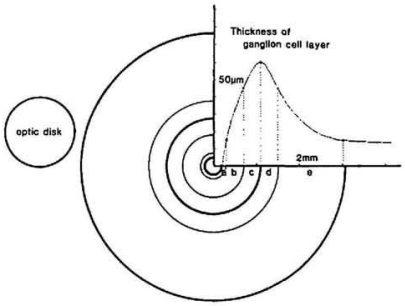


Figure 1: Distribution of ganglion cell thickness in central retina: foveola, (a) foveal avascular, (b, c) fovea centralis, (d) parafovea and (e) perifovea [13]

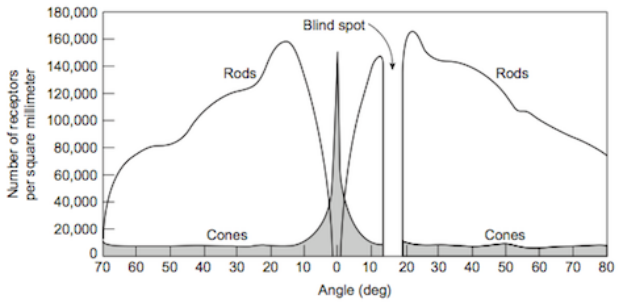


Figure 2: Distribution of cones and rods in a typical human retina [15]

III. Method

A. Participants

Eight healthy subjects (seven males and one female) with ages between 20 and 55 (mean: 27.7, standard deviation: 11.8) participated in the experiment. All subjects had normal or corrected-to-normal vision and suffered no vision impairment. To avoid complication, each subject was also confirmed to be comfortable with flashing lights and had no epileptic seizure in both personal and family medical history. All subjects were told the objectives, the potential risks and the detail procedures of the experiment and asked to sign an informed consent form before their participation.

B. Apparatus

The experiment was conducted in a radio shielded room and darkened to minimize potential contamination of visual stimulus and EEG signals. Figure 3 shows the experiment set-up with a stimulus generator and an EEG recorder.

The visual stimulus used in the experiment was diffused flickering white LED light with 170 cd/cm^2 luminance and (0.305, 0.373) CIE 1931 *xy* coordinates. The light source was an LED powered stroboscope (Monarch MVS 115/230) driven by a waveform generator (Agilent 33210A) with programmable signal frequencies and duty cycles. The light was projected onto a Mylar-covered translucent viewing screen erected 60cm in front of the subject.

Two different visual stimulation patterns were used in this experiment [Figure 4]: (a) a 2.1cm or 2° circular or centered light source for arousing the *foveal avascular zone*, and (b) a 16.9–19.0cm or 16°–18° annular or ring shaped light source for stimulating the *extrafovea* region.

EEG signals were captured using a 64-channel Quik-Cap, a NeuroScan SynAmps^2 amplifier and then recorded using a dual-core computer. The electrodes were placed according to the International 10–20 system. Moreover, the TTL-SYNC signal produced by the waveform generator was fed into the EEG recording system and used as "time ticks" to mark the firing of the light pulses.

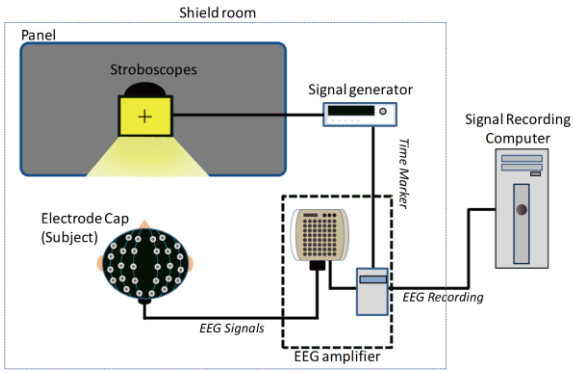
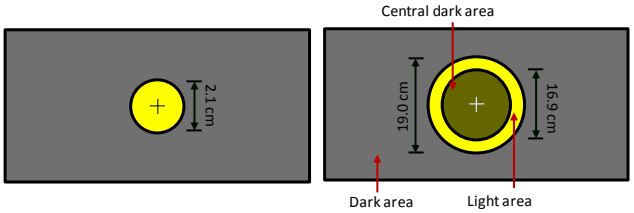


Figure 3: Block diagram of experiment set-up



(a) Circular/Centered Pattern (b) Annular/Ring Pattern

Figure 4: Two visual stimulation patterns: (A) a 2° circular/centered light pattern and (B) a 16°–18° annular/ring shaped light pattern

C. Procedures

During the experiment, each subject was asked to sit in a comfortable chair, placed his/her head on a chin-rest and stared at the diffused light patterns appeared on the viewing screen. A sequence of circular (centered) and annular (ring) shaped stimuli flickering at frequencies between 5Hz and 65Hz in 5Hz increments were shown at random on the screen. Each stimulation session lasted one minute and was separated from one another with half-minute rest periods. Each subject was also asked to repeat the experiment with two different randomized sequences on two separate days in the time of the day when they were most alert. Their responses to the same stimuli were merged together during data analysis.

Beside of recording their SSVEP signals, we also asked each subject to rate their feeling towards the flickering stimuli in each session based on the following five point scale.

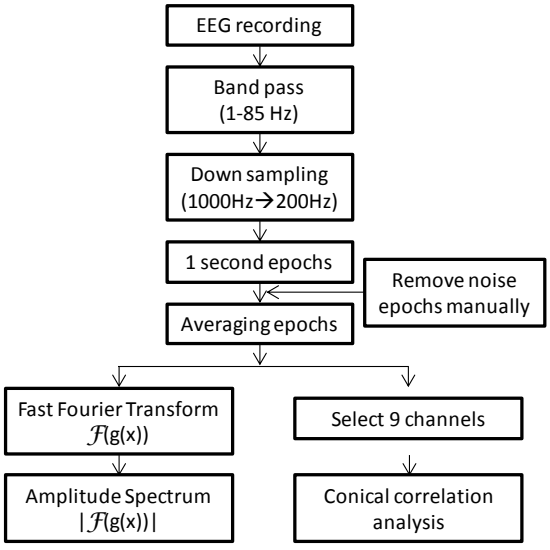
Table 1: Subjective stimulus flickering scores

1	2	3	4	5
not perceptible	perceptible / not annoying	slightly annoying	quite annoying	very annoying

D. Analyses

The SSVEP signals of each subject were analyzed using both fast Fourier transform (FFT) and conical correlation analysis (CCA) techniques. Figure 5 depicts the standard procedures for analyzing the EEG signals, which include preprocessing, signal segmentation, artifact removal and epoch averaging. Although signals captured from all sixty-four (64) channels were processed, special attention was paid to the nine occipital channels: P1, PZ, P2, PO3, POZ, PO4, O1, OZ, and O2. Only the signals from those channels were used in CCA analysis.

In order to study individual differences as well as the general trends, SSVEP of each subject and their averages have gone through both FFT and CCA analyses after they were segmented and preprocessed to remove artifacts.



(a) FFT Technique (b) CCA Technique

Figure 5: Flow chat of SSVEP signal analysis using (a) FFT and (b) CCA techniques

IV. Results

A. Flicker Perception

Figure 6 shows the distribution of subjects' flickering perception scores in a candlestick chart. The red and blue bars represent the scores of foveal (center) and extrafoveal (ring) stimulation between 5Hz and 65Hz. The two ends of the bars marked the first and the third quartile scores among the eight subjects. Average scores are marked by the squares while the entire range was marked by the thin lines.

As expected, subjects noticed less of the flickering as stimulation frequency increased and did not feel annoyed (with scores below 2) when the flickering frequencies lie above 40Hz and 45Hz for fovea and extrafovea stimulation respectively. Besides, the average scores of foveal stimulation were lower than those of extrafovea stimulation. From these data, we postulated that stimuli flickering faster than 30Hz may be suitable for most SSVEP BCI applications as they will be regarded only as slightly annoying by most subjects.

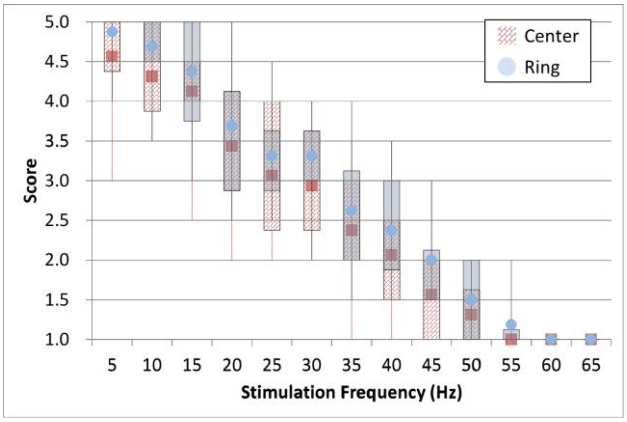


Figure 6: Evaluation of subjects' flicker perception (red and blue bars denote their responses towards center and ring stimuli respectively)

B. Spectral Analysis

The amplitude spectrum of foveal SSVEP responses between 5Hz and 65Hz are shown in Figure 7. Three scales were used to display the results: 0–3μV for 5Hz to 25Hz, 0 – 1μV for 30Hz to 45Hz and 0–0.5μV for 50Hz to 65Hz respectively. As expected, the amplitude of SSVEP spectra decreases with increase in stimulus frequency. Nonetheless, the SSVEP spectral peaks including those at fundamental and harmonic frequencies were noticeable up to 45Hz.

Figure 8 is a candlestick chart of foveal and extrafoveal SSVEP responses captured at Oz showing their maximum, third quartile, mean, first quartile, and minimum values. Obviously, the fovea SNRs were mostly higher than those of extrafovea for twelve frequencies except the stimulation frequency of 5Hz [Oz (Ring: 5.12 Center: 4.37)]. Even though, the SNR distributions of fovea and extrafovea for 5Hz were almost overlapped. The other two channels of O1, O2 also had similar tendency. Figure 8 also points out excited news for high-frequency SSVEPs, i.e., the SNRs of the fovea region in frequencies ranging from 25Hz to 50Hz were high enough to get a SSVEP signal. To confirm this exciting result, we further utilized the CCA method to analyze the SSVEPs data.

The SNR topography of foveal (center) and extrafoveal (ring) SSVEP responses at 15Hz and 45Hz were shown in

Figure 9. The SSVEP were successful evoked in occipital lobe, which contained higher SNR. A low stimulation frequency of 15Hz SSVEP signal was evoked over all head which is consistent with the results published in [8]. In contrast, 45Hz is more intensive on the occipital lobe. Generally, we can find the center responses are greater than ring's. The most interesting finding was that the SNR of 45Hz was even larger than that of 15Hz which meant high frequency SSVEPs is possible to be utilized.

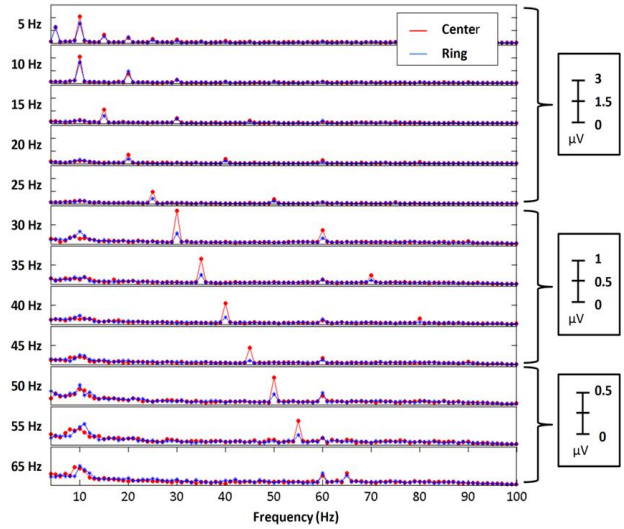


Figure 7: Average foveal SSVEP spectra between 5Hz and 65Hz in μV scale

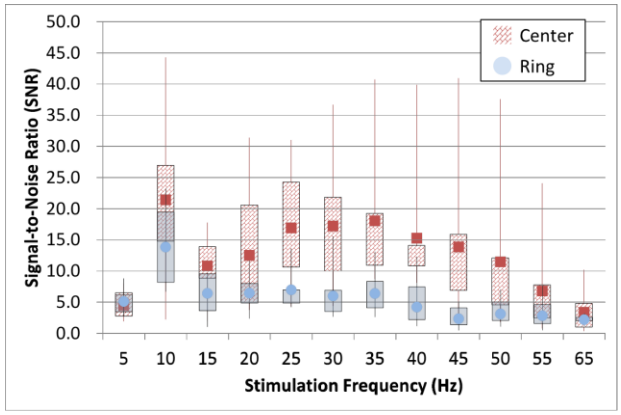


Figure 8: Distribution of SSVEP signal-to-noise ratios in response to foveal (red) and extrafoveal (blue) stimuli between 5Hz and 65Hz

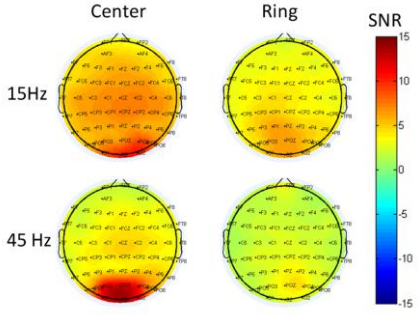


Figure 9: Topography of average SSVEP signal-to-noise ratios in response to foveal (left) and extrafoveal (right) stimuli at 15Hz and 45Hz

C. Conical Correlation Analysis

Using the CCA technique, SSVEPs of each stimulation frequency was compared to various sample frequencies and got a correlation coefficient. The averaging correlation coefficient map of various stimulation frequencies for the eight subjects using the center and ring light patterns are plotted in Figure 10.

The correlation coefficients in center stimulus light pattern were larger than those in ring stimulus light pattern. For both light patterns, a diagonal line represented that there was a highest correlation coefficient exists when a stimulation frequency was the same as a reference frequency. In the diagonal line, the correlation coefficient was decreased with an increasing stimulation frequency. For each stimulation frequency, additionally, there existed several harmonic frequencies. For example, the stimulation frequency of 15Hz has larger correlation coefficients in reference frequencies of 30Hz, 45Hz, and 60Hz. The result was consistence with those represented in Fig. 5. Besides, there were three horizontal lines (undesired lines) appeared when the reference frequencies were 5Hz, 10Hz, and 60Hz. For cases of 5Hz and 10Hz, it would be caused by α-wave of brain. The case of 60Hz, moreover, the power lines of electronic devices, such as a signal generator and the stroboscope, caused the noise even though the all power lines were shielded by grounded metal nets.

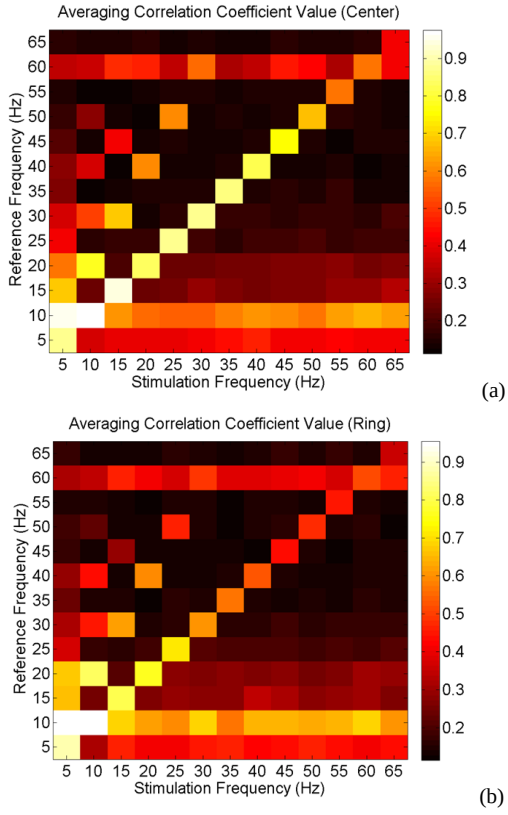


Figure 10: Averaging CCA coefficients of SSVEP responses towards (a) foveal and (b) extrafoveal stimuli between 5Hz and 65Hz

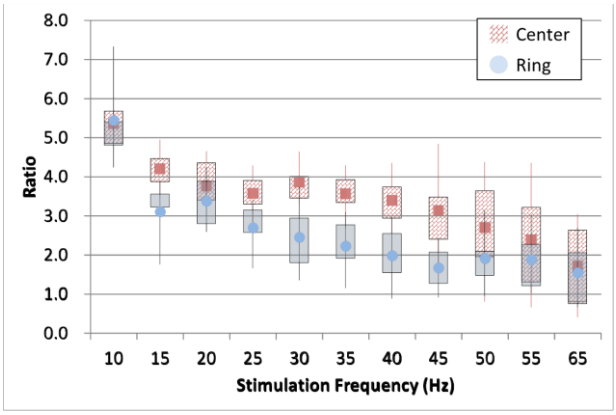


Figure 11: Distribution of CCA coefficients of SSVEP responses towards foveal (red) and extrafoveal (blue) stimuli between 5Hz and 65Hz

V. Discussions and Conclusions

This preliminary investigation confirmed our hypothesis that the SSVEP responses of fovea centralis have distinctively higher signal-to-noise ratios (SNR) in response to high frequency stimuli when compared with those from the extra-foveal region. This finding suggests that light sources flashing above the fusion thresholds may be used as effective and comfortable visual stimuli in SSVEP BCI applications. Besides, we also made the following observation based on our experiment results.

1. Although variations of signal strength among different subjects are significant, the differences among the first and the forth quartiles of SNR values remain distinct. Specifically, no overlap of mid-range values was found among stimulation with frequencies between 25Hz and 45Hz.
2. Canonical correlation analysis tends to produce more consistent results in detecting high-frequency SSVEP responses. However, only EEG signals from the occipital area should be used, including signals from the sensory-motor areas may hamper the accuracy of detection.
3. Our results showed that foveal SSVEP responses tend to have their highest SNR values around 10Hz (alpha band) and 30Hz. The other SNR peak around 45Hz reported in previous literature [16] seemed to be missing. A possible explanation was that we aimed at stimulating the foveola and the foveal avascular zone. Their SSVEP responses may differ from those of the entire foveal region.
4. Almost all subjects reported that they noticed less flickering and felt more comfortable with stimulation of their foveal region. The difference was most notable between 30Hz and 45Hz. One possible reason is that the area of the circular (foveal) stimulus was much smaller than the annular (extrafoveal) stimuli; hence, its flickering was much less irritating. Nonetheless, it was good to know that the visually acute region was not more easily irritated.

More experiments must be carried out in order to obtain the full picture of foveal vs. extrafoveal SSVEP responses. First, we shall learn more about the effects of pulse width and intensity towards the responses. Mesopic responses would be worth exploring. Finally, we shall study the high-frequency and colored SSVEP responses of parafovea and perifovea in order to map out the VEP characteristic of central retina.

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