34th Annual International Conference of the IEEE EMBS
San Diego, California USA, 28 August - 1 September, 2012

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

Fang-Cheng Lin, John K. Zao†, *Senior Member, IEEE*, Kuan-Chung Tu, Yijun Wang, Yi-Pai Huang, Che-Wei Chuang, Hen-Yuan Kuo, Yu-Yi Chien, Ching-Chi Chou, Tzyy-Ping Jung, *Senior Member, IEEE*

Abstract — **With brain-computer interface (BCI) applications in mind, we analyzed the amplitudes and the signal-to-noise ratios (SNR) of steady-state visual evoked potentials (SSVEP) induced in the foveal and extra-foveal regions of human retina. Eight subjects (age 20–55) have been exposed to 2° circular and 16°–18° annular visual stimulation produced by white LED lights flickering between 5Hz and 65Hz in 5Hz increments. Their EEG signals were recorded using a 64-channel NeuroScan system and analyzed using non-parametric spectral and canonical convolution techniques. Subjects' perception of flickering and their levels of comfort towards the visual stimulation were also noted. Almost all subjects showed distinctively higher SNR in their foveal SSVEP responses between 25Hz and 45Hz. They also noticed less flickering and felt more comfortable with the visual stimulation between 30Hz and 45Hz. These empirical evidences suggest that lights flashing above the critical flicker fusion rates (CFF) of human vision may be used as effective and comfortable stimuli in SSVEP BCI applications.**

I. Introduction

STEADY-STATE Visual Evoked Potentials (SSVEP) [1,2,15] and their P300-based counterpart, flash visual evoked potentials (FVEP) [3,4], are perhaps the most common exogenous brain computer interfacing techniques. For the purpose of inducing strong responses, these techniques often use low-frequency light signals as stimuli: below 2Hz for FVEP and within the alpha band (8–13Hz) for SSVEP. These low frequency stimuli, however, may cause visual fatigue [5], migraine [6] and occasionally seizure [5,7] among the subjects. Efforts have been made to establish high-frequency SSVEP with stimuli above the critical flicker fusion (CFF) rates of human vision as a viable alternative [8]. Only limited success has been achieved so far due to the fact that signal strength of SSVEP decreases rapidly as the 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 should be capable of producing detectable SSVEP in response to visual stimuli flashing above their critical flicker fusion (CFF) rates. Although these responses may be weaker than those in the alpha band, they still yield appreciable signal-to-noise ratios (SNR) since the asynchronous EEG signals in the background also diminish in their 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. Diffused *circular* and *annular* white LED lights flickering between 5Hz and 65Hz were used as visual stimuli. The circular stimuli were focused on the 2° *foveal avascular zone* of *macula lutea* or the "yellow spot". As shown in Figure 1, this region of human retina is populated almost entirely with color photoreceptors or the "cones" and produces the most acute photopic vision [11,12]. In contrast, the circular stimuli were focused at a 16°–18° band that lies immediately outside of human *fovea*. This peripheral retinal region, known as *extra-fovea*, is filled with the "rod" photoreceptors used for scotopic vision. It delivers compressed visual information with significantly lower resolution. Subjects' SSVEP signals from these two retinal regions were captured using a 64-channel NeuroScan EEG recorder. Their perception of flickering and their levels of comfort towards the visual stimulation were also noted. The signal-to-noise ratios of SSVEP signals and their correlation with sinusoidal waveforms at different frequencies were then computed using fast Fourier transform (FFT) and canonical correlation analysis (CCA) [13]. The EEG signals captured from each subject and their ensemble averages were both analyzed in order to discover the general trends as well as individual differences.

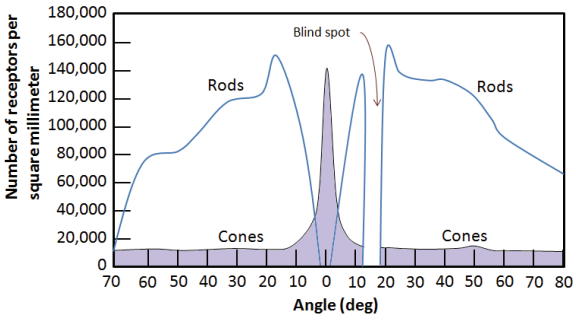


Figure 1: Distribution of cones and rods in a typical human retina [14]

This research was supported in part by the ATU Plan Phase II under Taiwan Ministry of Education II [Grant No.: 101W959] and the UST- UCSD International Center of Excellence in Advanced Bio-engineering under Taiwan National Science Council I-RiCE Program [Grant No.: NSC-100-2911-I-009-101].

Fang-Cheng Lin, Yi-Pai Huang, Yu-Yi Chien, and Ching-Chi Chou are with the Photonics Department and the Display Institute (e-mail: fclin.eo93g@nctu.edu.tw, boundshuang@mail.nctu.edu.tw, yuyichien2543.eo99g@g2.nctu.edu.tw, chingchi.di00g@g2.nctu.edu.tw).
John K. Zao, the corresponding author†, is with the Computer Science Department and Biomedical Engineering Institute (phone: +886-936-814 - 849; fax: +886-35-724-176; e-mail: jkzao@cs.nctu.edu.tw).
Kuan-Chung Tu and Hen-Yuan Kuo are with the Biomedical Engineering Institute (e-mail: tukuanchung@gmail.com, pa____pa@hotmail.com).
Che-Wei Chuang is with the Electronics Engineering Department (e-mail: p6323256@gmail.com). The above authors are affiliated with the National Chiao Tung University in Hsinchu, Taiwan, R.O.C.
Yijun Wang and Tzyy-Ping Jung are affiliated with the Schwartz Center of Computational Neuroscience, University of California at San Diego (e-mail: wangyijun97@gmail.com, jungtp@gmail.com).

Our results showed that the SSVEP responses from the *foveal avascular zone* captured at the nine occipital channels 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 three sections. The participants, apparatus and procedures of the experiment were documented in Section II. The results of fast Fourier transforms (FFT) and canonical correlation analysis (CCA) were discussed in Section III. Our contribution and future work were summarized in Section IV.

II. METHOD

A. Participants

Eight subjects (seven males and one female) with ages between 20 and 55 (mean: 27.7, standard deviation: 11.8) have 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 which was darkened to minimize potential contamination of the visual stimulus and EEG signals. Figure 2 shows the set-up of the experiment.

The visual stimulus used in the experiment was diffused flickering white LED light with 170 cd/cm^2 luminance and (0.305, 0.373) in the CIE 1931 *xy*-coordinate system. 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. As shown in Figure 3, two different kinds of visual stimulation were used in this experiment: (a) a 2.1cm or 2° circular/centered light source for arousing the *foveal avascular zone*, and (b) a 16.9cm–19.0cm or 16°–18° annular/ring shaped light source for stimulating the *extra-foveal* region.

The EEG signals of individual subject were captured and recorded using a 64-channel Quik-Cap, a NeuroScan SynAmps^2 amplifier and a dual-core computer. The electrodes were placed according to the International 10–20 system. 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.

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 displayed 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 day when they were most alert. Their responses to the same stimuli were merged together during data analysis.

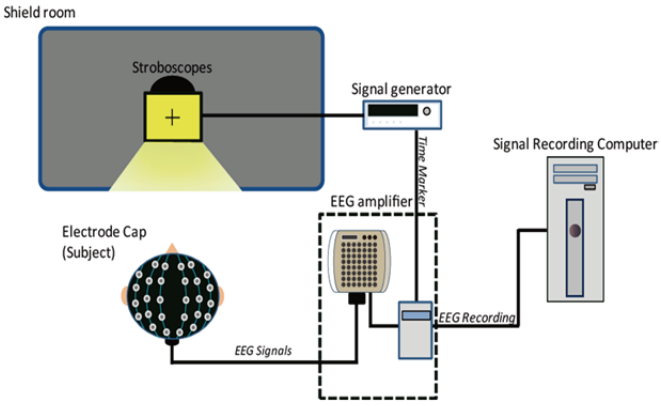
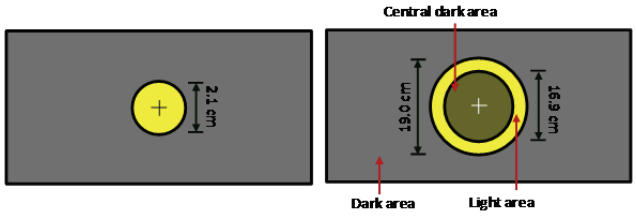


Figure 2: Block diagram of experiment set-up



(a) (b)

Figure 3: Two visual stimulation patterns: (a) a 2° circular/centered light pattern and (b) a 16°–18° annular/ring shaped light pattern

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

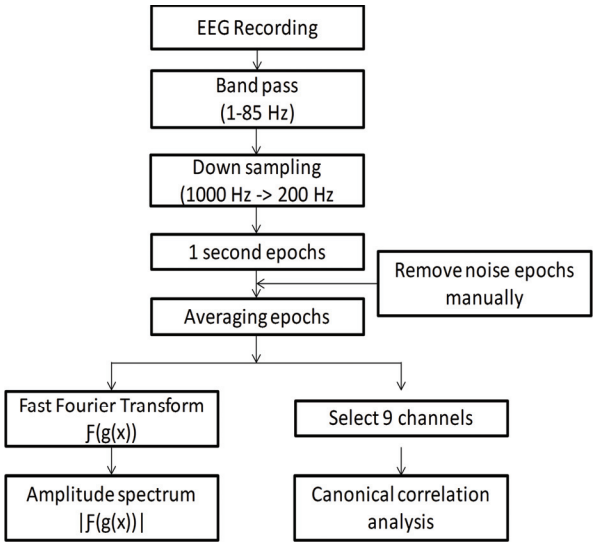
Table 1: Subjective stimulus flickering scores

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 canonical correlation analysis (CCA) techniques. Figure 4 depicts the standard analysis procedures, which include signal preprocessing, segmentation, artifact removal and epoch averaging. Signals captured from all sixty-four (64) channels were processed; however, 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 the individual differences as well as the general trends of SSVEP responses, each subject's EEG signals and their ensemble averages were subjected to both FFT and CCA analyses after they had gone through signal segmented and artifact removal.



(a) FFT Technique (b) CCA Technique

Figure 4: Flow chat of SSVEP signal analysis using (a) FFT and (b) CCA

III. Results

A. Flicker Perception

Figure 5 shows the subjects' flicker perception scores in a box plot. The red and blue bars represent the scores of foveal (center) and extra-foveal (ring) stimulation. The two ends of the boxes marked the first and the third quartile scores while the squares marked the average scores.

These scores showed that subjects were not annoyed by the flickering (and hence gave the scores below two) when the flickering frequencies lie above 40Hz and 45Hz for fovea and extra-fovea stimulation respectively. Moreover, subjects found that the flickering of foveal stimuli was less annoying than that of the extra-foveal stimuli between 25Hz and 45Hz. One possible explanation is that the annular extra-foveal stimuli occupied a much bigger area than the circular foveal stimuli. Nonetheless, we can postulate that stimuli flickering faster than 30Hz may be suitable for most SSVEP BCI applications as they are regarded only as slightly annoying by most subjects.

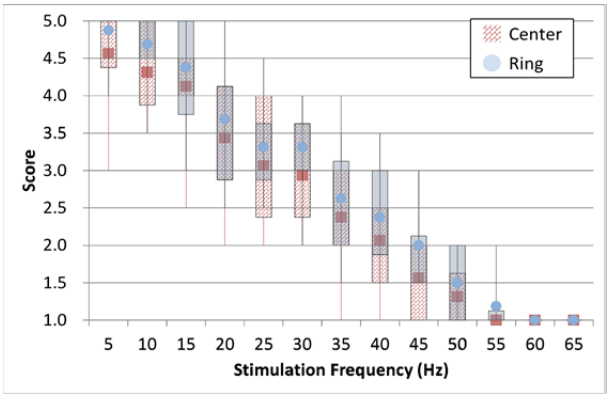


Figure 5: Evaluation of subjects' flicker perception (red and blue bars denote their responses towards center and ring stimuli respectively)

B. Spectral Analysis

Non-parametric spectral analysis of the foveal and extra-foveal SSVEP responses were performed by applying fast Fourier transform (FFT) to the average of corresponding signal samples among the ensemble of one-second epochs. Figure 6 shows the spectral amplitudes of foveal SSVEP responses between 5Hz and 65Hz. Although the amplitude of SSVEP spectra decreases as the stimulus frequency increases, the peaks of SSVEP spectra at the fundamental and harmonic frequencies remain noticeable up to 45Hz.

Figure 7 shows in a box plot, the foveal and the extra-foveal SSVEP responses captured at Oz. The foveal SNRs were higher than the extra-foveal ones at all frequencies except 5Hz (4.37 of fovea and 5.12 of extra-fovea). Moreover, the distributions of SNR values are separable between 25Hz and 50Hz. Similar tendencies were also observed amongst the signals captured at O1 and O2.

Figure 8 shows the topography of foveal and extra-foveal SSVEP SNR values at 15Hz and 45Hz. The broad spatial distribution of SSVEP SNR values at 15Hz is consistent with known results [8]. In general, foveal SSVEP tends to have higher SNR values than the extra-foveal ones. Specifically, the foveal SSVEP SNR at 45Hz was higher than the extra-foveal one at 15Hz. This high contrast implies that high-frequency foveal SSVEP can be a reliable BCI observable.

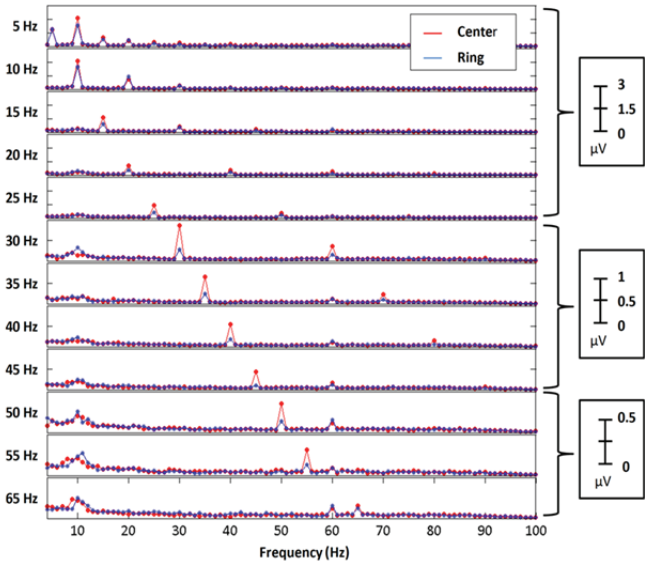


Figure 6: Average amplitude (µV) of foveal SSVEP spectra. Three different scales were used to display the spectral amplitudes: 0–3µV for 5Hz to 25Hz, 0–1µV for 30Hz to 45Hz and 0–0.5µV for 50Hz to 65Hz.

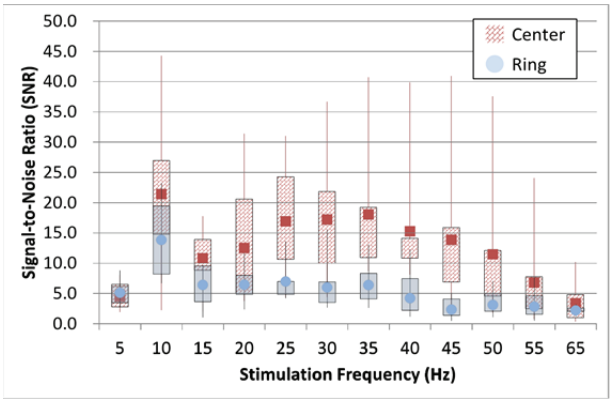


Figure 7: Box plot of SSVEP signal-to-noise ratios in response to foveal (red) and extrafoveal (blue) stimuli between 5Hz and 65Hz

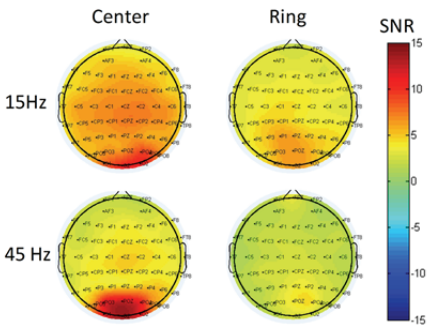


Figure 8: Topography of average SSVEP SNR values in response to foveal (left) and extrafoveal (right) stimuli at 15Hz (upper) and 45Hz (lower).

C. *Canonical Correlation Analysis*

To confirm our findings, we also estimated the cross correlation between the foveal/extra-foveal SSVEP signals and the sinusoidal waveforms using canonical correlation analysis (CCA) technique [13]. Figure 9 shows again in a box plot, the distribution of the CCA coefficient ratios of foveal and extra-foveal SSVEP responses of the eight subjects between 5Hz and 65Hz. Figure 10 then shows in graphic colors, the differences between the averages of these ratios in the same frequency range. A remark must be made on the way we computed these CCA coefficient ratios. A *CCA coefficient ratio* was defined as the ratio between the CCA coefficient of the SSVEP signal and the sinusoid at the stimulation frequency vs. the average of the CCA coefficients at the other frequencies. In order to eliminate the influences of harmonic frequencies, we excluded those CCA coefficients between the SSVEP signals and its harmonics of their stimuli from the calculation. These ratios of CCA coefficients are the close analogues to the SNR values of SSVEP responses.

Like Figure 7, Figure 9 shows a clear separation between the CCA coefficient ratios of foveal and extra-foveal SSVEP responses. The ratios have notably high values between 25Hz and 50Hz. Furthermore, the spread of these ratios is much narrower than that of the SNR values. This implies that CCA may be a more robust technique for quantifying SSVEP responses.

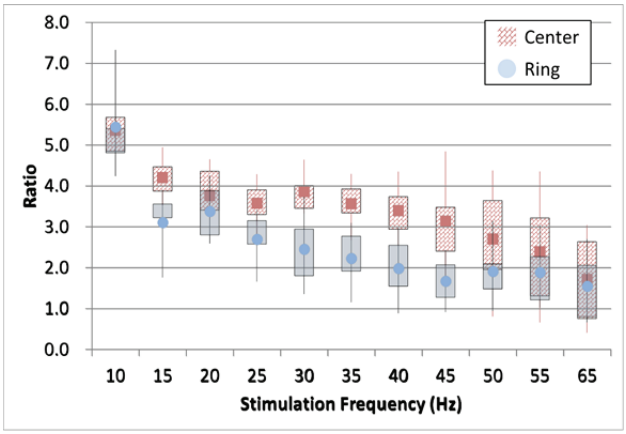


Figure 9: Box plot of CCA coefficient ratios of foveal (red) and extra-foveal (blue) SSVEP responses between 5Hz and 65Hz.

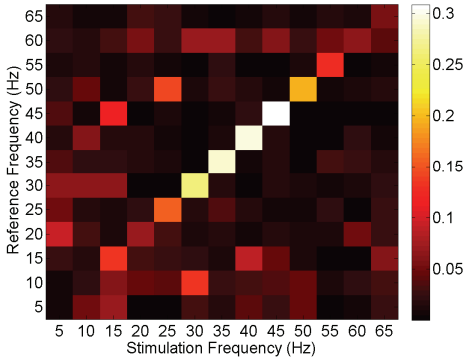


Figure 10: Differences between the averaged CCA coefficient ratios of foveal and extra-foveal SSVEP responses between 5Hz and 65Hz.

In the above figure, we can clearly see that the averaged CCA coefficient ratios of the foveal SSVEP responses are significantly higher than those of the extra-foveal SSVEP responses. The out-lying bright patches suggest that the harmonics of foveal SSVEP responses may also be used to boost robust SSVEP detection using CCA.

IV. Discussion and Conclusion

This preliminary investigation confirmed our hypothesis that the SSVEP responses of human foveal have distinctively higher signal-to-noise ratios (SNR) than those from the extra-fovea in response to the stimuli between 25Hz and 45Hz. These empirical results suggest that lights flashing above the critical flicker fusion rates (CFF) of human vision may be used as effective and comfortable stimuli in SSVEP BCI applications.

We can also make a few more observation based on our experiment results.

1. Canonical correlation analysis tends to produce more consistent results in quantifying high-frequency SSVEP responses. Nonetheless, only EEG signals from the occipital area should be used in CCA, adding EEG signals collected from the sensory-motor areas may hamper the accuracy of the results.
2. Our results revealed a twin-peak profile of foveal SSVEP responses. The SNR tends to attain its highest values in the neighborhood of 10Hz and 30Hz. The other peak around 45Hz that was reported in the previous literature [15] seemed to be missing. It is possible that the SSVEP responses from the foveola and foveal avascular zone may be different from the response of the entire fovea.
3. 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.

Many more experiments will need to be performed in order to construct a 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 the parafovea and the perifovea in order to map out the VEP characteristic of the central retina.

REFERENCES

[1] Middendorf, M., et al., "Brain-computer interfaces based on the steady-state visual-evoked response". *IEEE Transactions on Rehabilitation Engineering*, **8**(2): pp. 211-214, 2000.

[2] Cheng, M. et al., "Design and implementation of a brain-computer interface with high transfer rates". IEEE Transactions on Biomedical Engineering. **49**(10): pp. 1181-1186, 2002.

[3] Beverina, F., et al., "User adaptive BCIs: SSVEP and P300 based interfaces". *PsychNology Journal*, **1**(4): pp. 331-354, 2003.

[4] Lee, P.L., et al., "Visual evoked potential actuated brain computer interface: a brain-actuated cursor system". *Electronics letters*, **41**(15): pp. 832-834, 2005.

[5] Jeavons, P.M. and Harding, G.F.A., "Photosensitive epilepsy: a review of the literature and a study of 460 patients". *Heinemann [for] Spastics International Medical Publications*, 1975.

[6] de Tommaso M, Sciruicchio V, Guido M, Sasanelli G, Puca F. "Steady-state visual evoked potentials in headache: diagnostic value in migraine and tension-type headache patients". *Cephalalgia*, **19**(1):23-6, Jan. 1999.

[7] Wilkins, A.J. "Photosensitive epilepsy and visual display units". In E. Ross, D. Chadwick and R. Crawford (ed.), *Epilepsy in Young People*. pp. 147-155, Chichester: John Wiley, 1987.

[8] Wang, Yijun, et al. "Brain-computer interface based on the high-frequency steady-state visual evoked potential". *IEEE 1st Int'l Conference on Neural Interfaces and Control*, Wehan, China, May 26–28, 2005.

[9] Regan, D. "Some characteristics of average steady-state and transient responses evoked by modulated light." *Electroencephalography and Clinical Neurophysiology* 20(3): 238-248, 1966.

[10] Regan, D. *Human brain electrophysiology: Evoked potentials and evoked magnetic fields in science and medicine*, Elsevier, 1989.

[11] Hecht, Optics, Addison Wesley, 3rd Ed., p. 206, 1998.

[12] Millodot: *Dictionary of Optometry and Visual Science, 7th edition*, 7th Ed., Butterworth-Heinemann, 2009.

[13] Thompson, B., *Canonical Correlation Analysis*, Wiley Online Library, 2005.

[14] Lindsay, P. H. and Norman, D. A. *Human Information Processing*, 1977.

[15] Wang, Y., X. Gao, et al. "Brain-computer interfaces based on visual evoked potentials." *IEEE Engineering in Medicine and Biology Magazine*, 27(5): 64-71, 2008.