33rd Annual International Conference of the IEEE EMBS
Boston, Massachusetts USA, August 30 - September 3, 2011

Effect of competing stimuli on SSVEP-based BCI

Kian B. Ng, *Student Member*, Andrew P. Bradley, *Senior Member, IEEE,* and Ross Cunnington

Abstract— **Steady-state visual evoked potential (SSVEP)-based Brain-Computer Interface (BCI) works on the basis that an attended stimulus shows an enhanced visual evoked response. By examining EEG power at the frequency of the dominant evoked response, we are able to determine which stimulus the subject is attending. However, due to the limited processing capability of human visual system, when presented with multiple stimuli in the same visual field, the stimuli will compete for neural representations in the cortices. This study elucidates the effect of competing stimuli on SSVEP amplitudes by exploring the relationship between the number of stimuli and their inter-distance on the power spectra of attended stimuli. Results show that competing stimuli, when placed less than five degrees from the centre of the fovea, create a significant suppressive effect on the dominant frequency response. This result should guide how visual stimuli of SSVEP-based BCIs are spatially designed.**

I. Introduction

In a steady-state visual evoked potential (SSVEP)-based Brain-Computer Interface (BCI), multiple visual stimuli of constant frequencies are presented to the subject. As the subject fixates on one stimulus, light information is received at the photoreceptors of the retina, which eventually arrives at the ganglion cells. The ganglion cells are neurons that, in response to light stimulation, fire action potentials that propagate through the optic nerves to the visual cortex of the brain. By placing electrodes at the occipital region of the scalp, we are able to capture the evoked potentials that register at the visual cortex. Fig. 1 depicts the various parts involved in the visual processing of an SSVEP-based BCI.

Evidence suggests that when the subject focuses their attention selectively on a particular stimulus, elevated neuronal activities are observed that lead to an enhanced response in the steady-state visual evoked potential [1]. By measuring the frequency and phase of the dominant response, we are able to decipher which stimulus the subject is attending [2]. While research has also shown that visual evoked potentials are enhanced with higher perceived luminance [3], it is this selective attention-enhanced response model that forms the basis of SSVEP-based BCI.

In SSVEP, although the subject attends to one selected stimulus, the brain needs to process all stimuli within the visual field. However, there is a limit to the visual processing capacity of the human brain [4]. Studies indicate that when multiple visual stimuli are simultaneously displayed in the visual field, they are observed to compete for neural representation in the brain [5][6][7]. Based on the Stiles-Crawford effect [8], which states that light entering the pupil through the centre is perceived to be brighter than light entering near the edge of the pupil, the competing effect of the stimuli would follow to be more intense when multiple stimuli are located spatially close to each other. Given that most SSVEP-based BCIs require the user to view centrally at the stimulus field, the relationship between the spatial positions of the stimuli and the SSVEP response of the attended stimulus needs to be carefully studied.

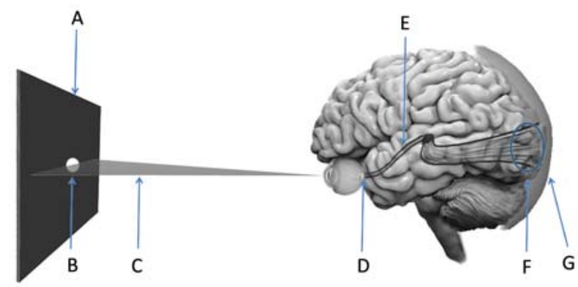

Fig. 1. The various parts involved in the visual processing of a SSVEP-based BCI - (A) display screen for stimuli (not shown), (B) centre of attention, (C) field of view, (D) retina, (E) optics nerves, (F) primary visual cortex, (G) scalp where electrodes (not shown) are attached to capture the response.

The aim of this study, therefore, is to examine the relationship between the number of stimuli and their inter-stimulus distance on the power spectral density (PSD) of the evoked potentials elicited by the central stimulus. Here, the PSD was implemented using a short-time Fourier transform.

II. Materials and Methods

A. Participants

A total of seven healthy subjects, one male and six females, participated in the experiment. All were right handed and between the ages of 21 and 28. All had normal or corrected-to-normal vision. None of them had any history of neurological disorder. Written informed consent was obtained from each participant prior to the beginning of the experiment.

Manuscript received 13 April 2011.

K. B. Ng and R. Cunnington are with The University of Queensland, Queensland Brain Institute, St. Lucia, QLD 4072, Australia (p: +61-7-3346-6300; f: +61-7-3346-6301; e-mail: k.ng1@ uq.edu.au).

A. P. Bradley is with the University of Queensland, School of Information Technology and Electrical Engineering, St. Lucia QLD 4072, Australia. (e-mail: bradley@itee.uq.edu.au).

B. EEG Acquisition

The experiment was conducted in a Faraday-caged room to reduce any electromagnetic interference from external sources. Continuous EEG was acquired using a 64-channel Biosemi ActiveTwo system. Two additional electrodes, CMS (Common Mode Sense; active electrode) and DRL (Driven Right Leg; passive electrode) were used to compose a feedback loop for amplifier reference. The electrodes used were placed according to the international 10-20 system using an appropriate EEG cap that fitted the head size of the individual subject. The EEG data were sampled at a rate of 2048 Hz to 24 bit precision.

C. Stimuli

The stimuli were hexagons flashing in black and white displayed on a mid gray background using a LED monitor (Samsung 23" XL2370) with a response time of 2 milliseconds. The luminance of the white hexagon was 165 cd/m^2 whereas luminance of the black hexagon was 0.70 cd/m^2. The primary advantage of hexagonal stimuli over traditional square shaped stimuli is that the distance between the centre of each hexagon and centres of all adjacent hexagons can be made constant. This ensures a consistent measurement of inter-stimulus distance across all stimuli.

As there is a constrain on the hardware timer of the stimulus computer and the screen refresh rate, the stimulus tagging frequencies were set to: 11.25, 13.58, 16.08, 18.33, 21.42 and 23.3 Hz. These frequencies were also chosen to fall between the high alpha and beta band of EEG signals and are the typical frequencies used in SSVEP-based BCI. Studies have previously demonstrated that the highest gain of SSVEPs is found in the range of 10–20 Hz [9]. An *in-house* presentation software was written to create and display the stimuli. This allowed us to control and measure the exact timing of the tagging frequencies.

The stimuli were each set to a constant size that subtended a visual angle of 2° from edge to edge. There were two main factors examined. One varied the distance between the outer stimuli and the attended central stimulus (at 2° , 3° , 5° and 7° of visual angle), while the other varied the number of simultaneous "competing" stimuli (at 0, 2, 3, and 4 outer stimuli). Table I summaries all the possible combinations of conditions. The condition with no competing stimuli, and hence no inter-distance to measure, was used as a reference to compare against those with competing stimuli.

TABLE I
COMBINATION OF INTER-DISTANCE AND NUMBER OF STIMULI

		INTER-DISTANCE			
		2°	3°	5°	7°
NO. OF COMPETING STIMULI	0	-	-	-	-
	2	(2°, 2)	(3°, 2)	(5°, 2)	(7°, 2)
	3	(2°, 3)	(3°, 3)	(5°, 3)	(7°, 3)
	4	(2°, 4)	(3°, 4)	(5°, 4)	(7°, 4)

D. Experiment Paradigm

Throughout the experiment, subjects were seated 70cm in front of the monitor. They were instructed to fixate on a central crosshair and focus their attention only on the flashing hexagon that appeared in the centre; ignoring all other stimuli. The crosshair always appeared in the centre, therefore the attended stimulus was always centrally viewed.

For each trial, the flashing stimuli appeared for 8 s duration followed by 8 s with just the fixation crosshair. The subjects were asked to maintain their central fixation for 8 s while the central stimulus was present. While VEPs can be captured in a much shorter time span, the 8 s epoch gives enough data samples to perform a high temporal resolution PSD analysis using the short-time Fourier transform. Across trials, the number of competing stimuli (0, 2, 3, or 4) and the spatial separation of stimuli (2° , 3° , 5° and 7°) were varied. The tagged frequency of the central stimulus was also varied and tested once with each of the six different tagging frequencies. Fig. 2 shows an example of the experiment sequence using three competing stimuli.

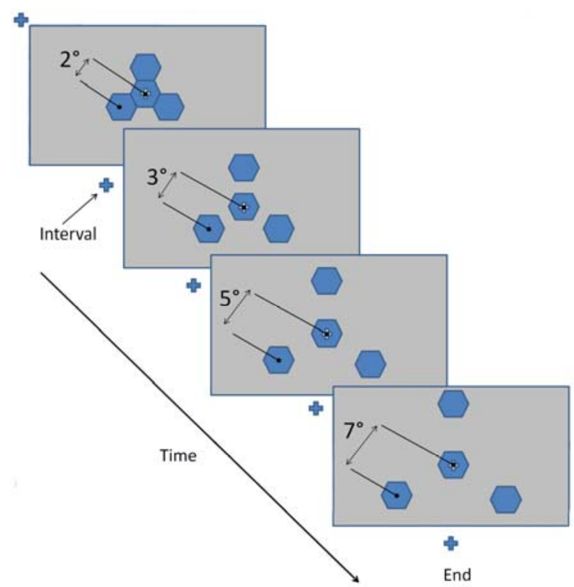

Fig. 2. The visual evoked potential response was explored by varying the distance between the centrally attended stimulus and surrounding competing stimuli. Shown here is the case for 3 competing stimuli (not to scale).

To ensure that the subjects maintained fixation and attention to the central stimulus, they were told to note the frequency difference between each successive central stimulus. If the frequency was perceived as faster than the previous, the subject would press the 'z' key, if slower, press the 'enter' key. In addition, to avoid frequency adaptation, the frequency of the central stimulus was randomly selected from the six designated frequencies at each epoch.

III. Analysis and Results

All EEG signals were processed digitally offline. The data were initially filtered with a 50Hz notch filter and a 4^{th} order Butterworth band-pass filter with cut-off frequencies at 10 and 25 Hz. The common average reference (CAR) procedure was used to re-reference all electrodes. This re-referencing procedure removes background activity.

Time-frequency analysis was carried out using Short-time Fourier transform (STFT). The STFT is defined as

$$STFT_x^g(f,\tau) = \int_{-\infty}^{\infty} x(t) g^*(t-\tau) e^{-j2\pi ft} dt \quad (1)$$

Here, t and τ are time variables, $x(t)$ represents the signal to analyze, $g(t)$ represents a window function, f is the frequency variable and * denotes complex conjugate. The STFT is preferred over wavelet transform as our frequencies were narrow-band limited between high alpha to beta with a range of approximately 12 Hz. Keeping in mind the time-frequency uncertainty principle [10], a relatively long observation time of 8 s was used for each epoch in the experiment. A hamming window was used as the sliding window function with length of 8192 samples and 50% overlap. This leaves us with frequency resolution of 0.25 Hz and time resolution of 2 s for our analysis. The spectrogram was obtained by squaring the magnitude of STFT.

The spectrogram obtained for subject 1, Channel O1 is shown in Fig. 3 and Fig. 4(a)-(c). Fig. 3 shows the spectrogram obtained when there were no competing stimuli present. Four consecutive bars across time at the same frequency indicate a steady-state response observed during that epoch. It is clear that we are able to obtain dominant evoked potential responses at the 6 different frequencies tagged to the central stimulus (Fig. 3). In Fig. 4(a)-(c), the power for each response appears to strengthen as the inter-distance between stimuli increases.

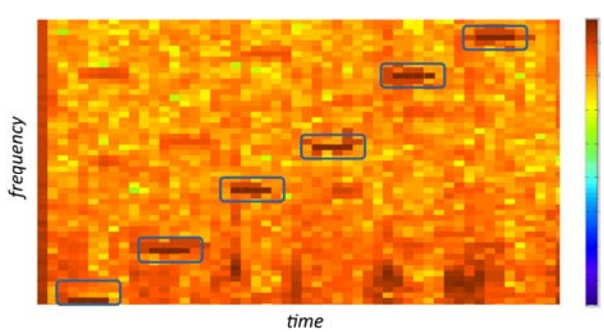

Fig. 3. Shown here is the spectrogram without any competing stimuli for subject 1 at Channel O1. Four consecutive blocks across the time (8 s duration) indicates a steady state response during that epoch. It is clear that the six frequencies used in the experiment are able to evoke a steady state potential.

To compare results across trials for each subject, we calculated the average power across frequency for each time bin and calculated the ratio of the power at each designated tagged frequency to this average. This gives us an estimate of signal-to-noise ratio (SNR) for each subject. Dominant responses were observed with SNR values greater than 3dB. They were also observed to correspond to electrodes at the occipital region (O1, O2, Lz, Oz, POz, PO3, PO4).

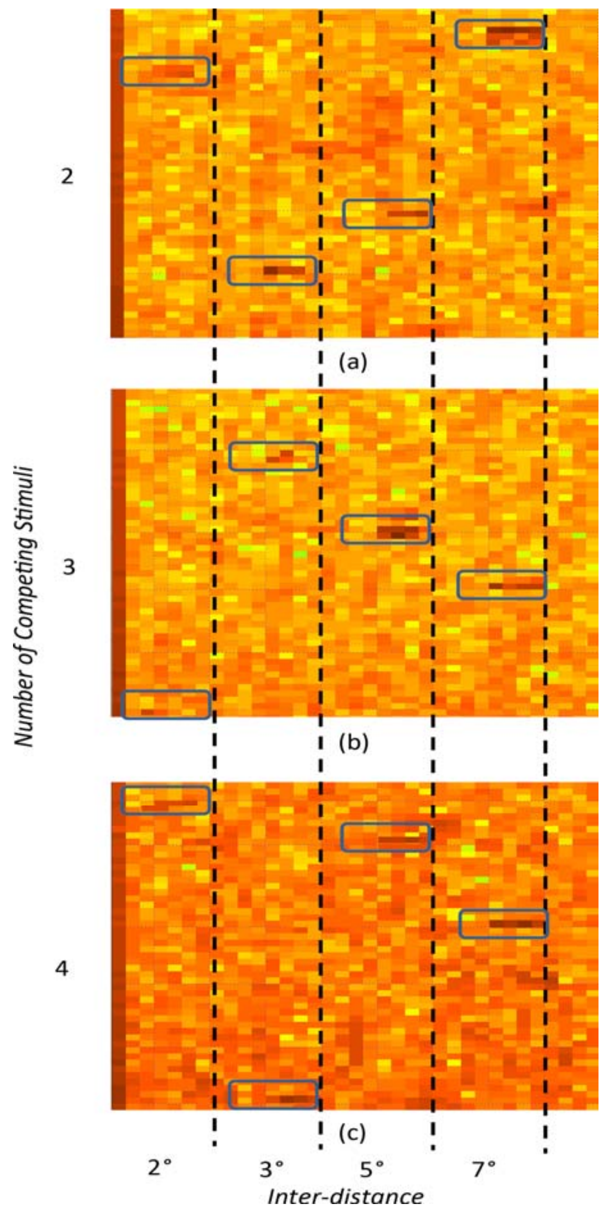

Fig. 4. Shown here is the spectrograms obtained for subject 1, at Channel O1. From (a) to (c), the number of competing stimuli increases from 2 to 4, respectively. Across the horizontal axis, inter-stimuli distance increases from 2° to 7° according to Table I. Evidently, the power for each response appears to strengthen as the inter-distance between stimuli increases. The frequency of the attended stimulus was randomly assigned from the 6 designated frequencies at the beginning of each epoch.

Next, for each subject, we *normalized* their SNR using SNR estimated for the case where there were no competing stimuli. Fig. 5 illustrates the plot of the mean normalized SNR against inter-stimulus distance and the number of competing stimuli. The error bars represent standard errors of these means.

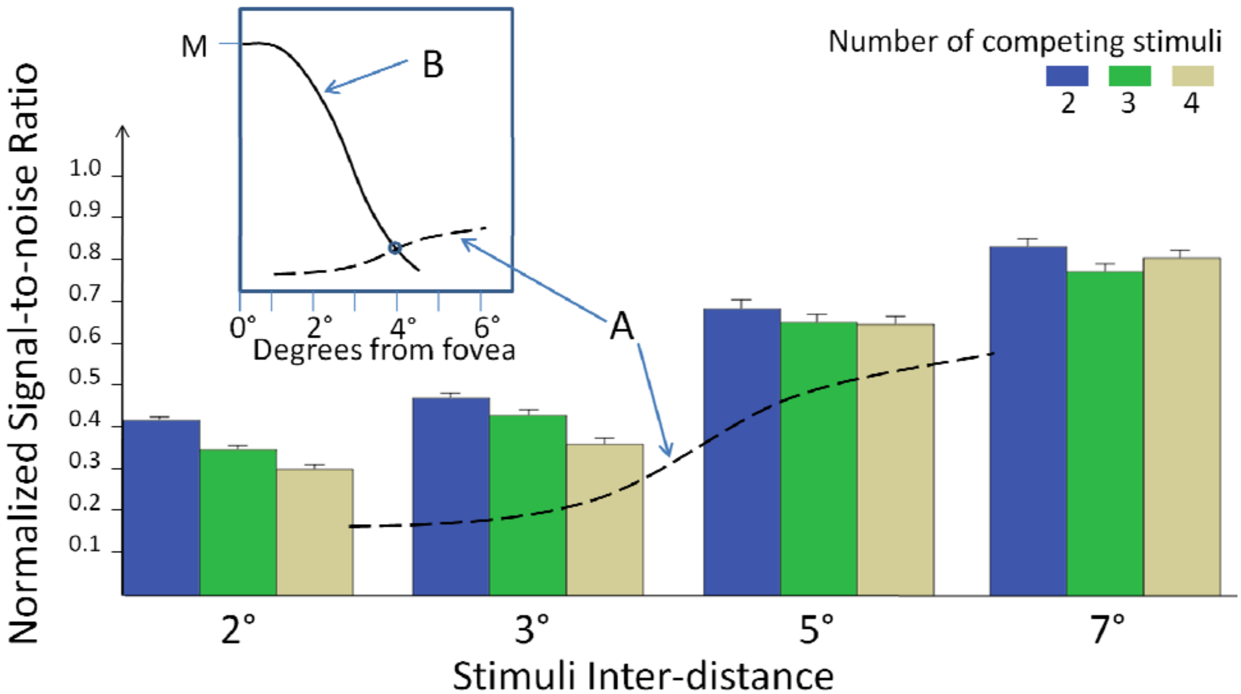

Fig. 5. Normalized mean SNR across subjects, as a ratio of spectra power with no competing stimuli, plotted against inter-stimulus distance and the number of competing stimuli. A trend line A is obtained by measuring the moving averages of all observations (2, 3, and 4 competing stimuli) against the distance (2°, 3°, 5°, and 7° visual angle). Shown in the inset is the plot of the luminance against the foveal distance according to the

IV. Discussion and Conclusion

As is evident in Fig. 5, the evoked potentials clearly increase as the distance between the competing stimuli increase. Curve A shows the trend of this increase with a point of inflection at about 4°. Curve B, in the inset, is a plot of the luminance against the foveal distance according to the Stiles-Crawford effect [8][11], with M being the maximum. By generally matching curves A and B using their visual angles and the point of inflection of curve A, it is clear that the increase in the evoked potentials coincides with the diminished effect of the Stiles-Crawford. Thus we can deduce that the competing stimuli, when placed at less than 5° of visual angle from the central stimulus, will have a suppressive effect on the steady state visual evoked potential response. Also, when competing stimuli are within 5° of visual angle, the power of the evoked potential response to the central stimulus is reduced further with increasing numbers of competing stimuli. This effect is not evident when competing stimuli are separated by more than 5° of visual angle.

Translating this into an SSVEP-based BCI design, results imply that the spatial separation of visual stimuli should be at least 5° visual angle. With a typical viewing distance of about 70 cm, this translates to a physical distance of approximately 6 cm between the centres of competing stimuli. Therefore, any inter-distances less than this may result in a suppressed SSVEP response that would reduce the performance of the SSVEP-based BCI system.

V. References

[1] Y. Joon Kim, M. Grabowecky, K. A. Paller, K. Muthu, and S. Suzuki, “Attention induces synchronization-based response gain in steady-state visual evoked potentials,” *Nat Neurosci*, vol. 10, no. 1, pp. 117-125, Jan. 2007.

[2] D. Regan, *Human Brain Electrophysiology: Evoked Potentials and Evoked Magnetic Fields in Science and Medicine*. Elsevier Science Ltd, 1989.

[3] J. C. Armington, “The electroretinogram, the visual evoked potential, and the area-luminance relation,” *Vision Research*, vol. 8, no. 3, pp. 263-276, Mar. 1968.

[4] D. E. Broadbent, *Perception and Communication.* Elsevier Science Ltd, 1958.

[5] R. Desimone and J. Duncan, “Neural mechanisms of selective visual attention,” *Annual Review of Neuroscience*, vol. 18, pp. 193-222, 1995.

[6] J. Duncan, “Converging levels of analysis in the cognitive neuroscience of visual attention.,” *Philosophical Transactions of the Royal Society B: Biological Sciences*, vol. 353, no. 1373, pp. 1307-1317, Aug. 1998.

[7] C. Bundesen, “A theory of visual attention,” *Psychological Review*, vol. 97, no. 4, pp. 523-547, Oct. 1990.

[8] W. S. Stiles and B. H. Crawford, “Luminous Efficiency of Rays entering the Eye Pupil at Different Points,” *Nature*, vol. 139, no. 3510, pp. 246-246, 1937.

[9] Y. Wang, R. Wang, X. Gao, B. Hong, and S. Gao, “A practical VEP-based brain-computer interface,” *IEEE Transactions on Neural Systems and Rehabilitation Engineering: A Publication of the IEEE Engineering in Medicine and Biology Society*, vol. 14, no. 2, pp. 234-239, Jun. 2006.

[10] P. M. Oliveira and V. Barroso, “Uncertainty in the time-frequency plane,” in *Statistical Signal and Array Processing, 2000. Proceedings of the Tenth IEEE Workshop on*, 2000, p. 607–611.

[11] N. W. P. & D. G. Childers, *The human visual evoked response. Method and theory*. Charles C. Thomas, 1969.