Objective detection of Steady State Visual Evoked Responses for different lighting conditions

A M Tannus¹, C J Tierra-Criollo¹², D B Melges¹
¹Graduate Program in Electrical Engineering - Federal University of Minas Gerais - Av. Antônio Carlos 6627, 31270-901, Belo Horizonte, MG, Brazil
²Biomedical Engineering Program - Federal University of Rio de Janeiro – Av. Horácio de Macedo 2030, 21941-914, Rio de Janeiro, RJ, Brazil

E-mail: alexandretannus@gmail.com; carjuliot@gmail.com; danilomelges@gmail.com

Abstract: This work aims at evaluating the performance of two Objective Response Detection (ORD) techniques: the Magnitude-Squared Coherence (MSC) and the Multiple Coherence (MC) for detecting Steady State Visual Evoked Response (SSVEP) for two different lighting conditions (scotopic and photopic). EEG signals were collected (using a wireless headset) from ten volunteers without history of neurological diseases during stimulation with white LED flickering at frequencies of 6, 7, 8, 9, 10 and 11 Hz. The experimental protocol was composed by 13 sessions in a dark room and 13 in a bright one. The frequency order was randomized. The MSC was applied to derivations [P7], [P8], [O1] and [O2], and MC to the combinations of leads [O1-O2], [O1-O2-P7], [O1-O2-P8] and [O1-O2-P7-P8]. Both estimates were calculated using $M = 11$ epochs. The detection rates for MSC presented an important decrease at photopic condition compared to the scotopic one for all derivations and all frequencies. The employment of MC to [O1-O2-P7-P8] allowed overcoming this limitation, leading to detection percentages of at least 80% for all frequencies (except 9 Hz). These results show that MC is a promising technique for building SSVEP Brain Computer Interfaces (BCI).

1. Introduction

Assistive technology development has grown in the last years, and it is mainly directed to people with severe motor impairment, caused by spinal cord injury, cranial trauma and degenerative neurological diseases such as multiple sclerosis [1], amyotrophic lateral sclerosis (ALS) [2] and primary lateral sclerosis [3]. In Brazil, according to IBGE (Geography and Statistics Brazilian Institute), there are around 13 million people who declare to have a motor disability [4]. From these people, 4.5 million present severe disabilities.

In this context, the brain-computer interface (BCI) is a class of assistive technology that allows these individuals to control devices or assess cognitive functions [5] employing the brain electrical activities (electroencephalogram – EEG), usually during some kind of stimulation (evoked potential - EP) [6]. Generally, the EP is commonly categorized in transient or steady-state. The EP is classified as transient when the response to a stimulus finishes before another stimulus is presented, and as steady-state, on the contrary.

The signals employed in a BCI can be obtained by invasive or non-invasive techniques. The invasive methods can require the use of needle or even surgically implanted electrodes [7]. These
techniques include electrocorticogram (ECoG) and methods for recording action potentials (AP) and local field potentials (LFP) [7]. Among the non-invasive methods there are: the EEG, the magnetoencephalogram (MEG), and the functional magnetic resonance imaging (fMRI). However, the most used non-invasive techniques are the EEG and evoked potentials that have low-cost and simple-execution [8].

Particularly, the visual evoked potential (VEP) produces cortical response in the same frequency of the stimulation and, therefore, has been used for many different BCI applications, such as controlling a computer mouse [9], a car [10] and a robotic hand [11]. The VEP can be elicited by different types of stimuli, such as checkerboards, flashing images and flashing LEDs [12,13]. The latter is known to produce cortical response with high signal-to-noise ratio [14].

Statistics based techniques, known as Objective Response Detection (ORD), have been used for identify cortical responses to sensory stimulation, including auditory [15], somatosensory [16,17] and visual [18]. Among these techniques, the Magnitude-Squared Coherence (MSC) has presented promising results, as well as its multivariate version, the Multiple Coherence (MC).

Hence, this work aims at evaluating the performance of MSC and MC for detecting response to visual stimulation for two different lighting conditions (scotopic and photopic) and investigating whether there is habituation to the stimulus.

2. Material and methods

2.1. Magnitude Squared Coherence (MSC)

The MSC is the square module of the coherence function and represents the parcel of the squared mean value of the measured EEG signal \( y[k] \) caused by stimulation \( x[k] \) for a frequency \( f \). A coherence estimator can be calculated based on the discrete windowed signal by [19]:

\[
\hat{\kappa}^2(f) = \frac{M}{\sum_{m=1}^{M} Y_m(f)^2 - \left( \frac{\sum_{m=1}^{M} Y_m(f) \bar{Y}_m(f)}{M} \right)^2}
\]

where \( Y_m(f) \) is the Discrete Fourier Transform of the \( i^{th} \) epoch of the EEG signal and \( M \) is the number of EEG epochs. When there is no response to stimulation, \( \hat{\kappa}^2(f) \) tends to zero and, when there is consistent response, \( \hat{\kappa}^2(f) \) tends to 1.

In order to infer about the presence/absence of the response, the critical value, which consists of a detection threshold for the MSC, can be calculated for \( M \) EEG epochs and the significance level \( \alpha \) (false positive rate) by [20]:

\[
\hat{\kappa}_{crit}^2 = 1 - \alpha^{M-1}
\]

When the estimate value exceeds the critical one (\( \hat{\kappa}^2(f) > \hat{\kappa}_{crit}^2 \)), there is detection for such a frequency \( f \).

2.2. Multiple Coherence (MC)

The multiple coherence estimate between a stimulus \( x/k \) and a set of \( N \) signals \( y[k] \) is given by [21]

\[
\hat{\kappa}_{X,Y}^2(f) = \frac{\bar{V}^H( f ) \hat{S}^{-1}_{XY} \bar{V}( f )}{M}
\]
Where \( M \) is the number of epochs, \( H \) is the Hermitian operator and \( V(f) \) and \( \hat{S}_{xy}^{-1} \) are, respectively

\[
V(f) = \left[ \sum_{i=1}^{M} Y_{1i}(f) \sum_{i=1}^{M} Y_{2i}(f) \ldots \sum_{i=1}^{M} Y_{Ni}(f) \right]^{T}
\]

and

\[
\hat{S}_{xy}^{-1} = \begin{bmatrix}
\hat{S}_{y_{1y_{1}}}(f) & \hat{S}_{y_{1y_{2}}}(f) & \ldots & \hat{S}_{y_{1y_{N}}}(f) \\
\hat{S}_{y_{2y_{1}}}(f) & \hat{S}_{y_{2y_{2}}}(f) & \ldots & \hat{S}_{y_{2y_{N}}}(f) \\
\vdots & \vdots & \ddots & \vdots \\
\hat{S}_{y_{Ny_{1}}}(f) & \hat{S}_{y_{Ny_{2}}}(f) & \ldots & \hat{S}_{y_{Ny_{N}}}(f)
\end{bmatrix}
\]

where \( Y_{i}(f) \) is the Fourier Transform of the \( i \)th epoch of the signal \( y[k] \), * denotes the complex conjugate and \( \hat{S}_{y_{p}y_{q}}(f) \) is the cross-spectrum of derivations \( p \) and \( q \).

The critical value of MC for a significance level \( \alpha \), \( M \) EEG epochs and \( N \) derivations, can be calculated as:

\[
\hat{k}_{N \text{crit}}^{2} = \frac{F_{\text{crit.}2M,2(M-N)}}{F_{\text{crit.}2M,2(M-N)} + (M-N)N^{-1}}
\]

The detection for a frequency \( f \) is based on the same principle used for MSC, that is, when the estimated value is higher than the critical value \( (\hat{k}_{N}^{2}(f) > \hat{k}_{N \text{crit}}^{2}) \).

### 2.3. EEG Data Acquisition

EEG signals were collected from 14 derivations, AF3, F7, F3, FC5, T7, P7, O1, O2, P8, T8, FC6, F4, F8, AF4, using the Emotiv Epoc™ wireless headset (Emotiv). The derivations were filtered from 0.2 to 45 Hz, sampled at 128 Hz (14-bit resolution). EEG was acquired from 10 adult volunteers (7 men and 3 women, aged from 20 to 35 years old), without history of neurological diseases. This research was approved by the Ethics Committee of Federal University of Minas Gerais (UFMG) - protocol n. 11525613.4.0000.5149 - and all volunteer signed written informed consent.

### 2.4. Experimental Protocol

The volunteers were stimulated by white LEDs with the following frequencies: 6 Hz, 7 Hz, 8 Hz, 9 Hz, 10 Hz and 11 Hz. The order of the stimulation frequency was randomized. All frequencies were presented in two lighting conditions: in a dark room (luminance lower than 2 lux) and in a controlled - luminance room (around 80 lux). The stimulation was applied using equipment developed in the Biomedical Engineering Laboratory of UFMG [13].

The experimental protocol was composed by 26 sessions of two-minutes duration, 13 in a dark room and 13 in bright one, alternating spontaneous EEG and EEG during visual stimulation, as illustrated in Figure 1. The first 13 sessions were performed in scotopic condition while the other 13 were performed in a photopic situation.

Figure 1. Experimental Protocol
2.5. Pre-processing

The EEG signals were digitally band-filtered from 2 to 40 Hz (Butterworth 6th order, zero-phase) and windowed in 4-second epochs with 50% overlapping. Then, an artefact rejection technique was applied to each window. This technique consists in calculating the standard deviation (SD) of a noisy-free EEG segment and remove EEG windows where 10% of any samples or 5% of consecutive samples exceeds ± 3 SD [17].

2.6. MSC and MC performance evaluation

The MSC and MC were employed to identify the stimulation response. $\hat{k}^2(f)$ and $\hat{k}^2_M(f)$ were estimated for $M = 11$ epochs. The critical values $\hat{k}^2_{\text{crit}}$ and $\hat{k}^2_{\text{M,crit}}$ were calculated with $\alpha = 0.05$. The MSC was obtained for derivations [O1], [O2], [P7] and [P8], and the MC for the combinations: [O1-O2], [O1-O2-P7], [O1-O2-P8] and [O1-O2-P7-P8]. Based on the response identification for each frequency and all casuistry, the detection rates were obtained.

3. Results

The percentages of detection for derivations [O1], [O2], [P7] and [P8], in the scotopic condition, using MSC, are presented to 4 different sets of $M = 11$ EEG epochs in order to identify habituation effects (Figure 2). As it can be seen, no adaptation to the stimulation was evidenced for a specific frequency, i.e., there was no important decreasing in the detection rates along the experiment.

In the same figure, it is possible to note that the best detection rates occurred at 7 and 8 Hz, which achieved more than 80% for all sets in derivation [O2]. A 100% detection rate was reached in 8 Hz at [P8]. On the other hand, responses to 6 and 11 Hz presented the worst detection rate, presenting no more than 70% for all sets and all leads, except for the second set at [O2]. Frequencies of 9 and 10 Hz presented higher fluctuations in the percentages, achieving more than 80% in some sets and less than 60% in other for [O2], [P7] and [P8].

In the photopic condition, detection rates were lower than 60% for the majority of frequencies, independently of the derivation or the set considered (Figure 3). Detection rate of 100% was achieved only for 11 Hz at derivation [O2] and 10 Hz at [P7].

Detection rates for the MSC applied to the first set of 11-epochs are presented in Figure 4 for both scotopic and photopic conditions. As it can be seen, the percentages of detection decreased for the majority of frequencies in all leads, except for 10 Hz at [P7] and 11 Hz for [P8], [O1] and [O2]. However, the proportion test indicated significant difference only for [P7] at 7 and 9 Hz, and at [P8] from 6 to 9 Hz.

Figure 5 shows the percentages of detection for the Multiple Coherence applied to four different combinations of derivations, [O1-O2], [O1-O2-P7], [O1-O2-P8] and [O1-O2-P7-P8]. The 2-leads combination [O1-O2] presented rates of at least 80% at 7, 10 and 11 Hz for both conditions. For 3-leads combinations ([O1-O2-P7] and [O1-O2-P8]), higher rates than 90% were achieved at scotopic and photopic situations for 7, 8 and 10 Hz. Finally, [O1-O2-P7-P8] showed a detection rate of 100% at 8 and 10 Hz for both conditions. Moreover, only for 9 Hz, lower detection than 80% was observed in the photopic situation. However, the proportion test showed no significant difference between any detection rates, when the conditions are compared.
Figure 2. MSC detection rates at occipital and parietal derivations for $M = 11$ at scotopic condition.

Figure 3. MSC detection rates at occipital and parietal derivations for $M = 11$ at photopic condition.
Figure 4. Comparison between detection rates (MSC) at scotopic and photopic conditions for the first set of $M = 11$ epochs at all derivations. * indicates significant difference between detection rates.

Figure 5. Comparison between detection rates (MC) at scotopic and photopic conditions for the first set of $M = 11$ epochs at all combinations of leads.

Figure 4. Comparison between detection rates (MSC) at scotopic and photopic conditions for the first set of $M = 11$ epochs at all derivations. * indicates significant difference between detection rates.

Figure 5. Comparison between detection rates (MC) at scotopic and photopic conditions for the first set of $M = 11$ epochs at all combinations of leads.
4. Discussion

In this work, the MSC and MC were applied to verify the best frequencies for a BCI based steady-state visual evoked potential for two different lighting conditions (scotopic and photopic). The first technique showed a very poor performance at photopic situation for all used frequencies. At scotopic condition, better detection rates were achieved, reaching 80% in [O2] for 7 and 8 Hz. These frequencies were already studied by Pinto [18], who reported a detection rate of at least 74% with MSC at them and also at 9 Hz. However, in that work, the author employed a clinical EEG amplifier, which has a better signal-to-noise ratio.

In order to improve the detection rates, a multiple coherence (MC) analysis was performed. Four combinations of leads were investigated, all including the occipital derivations [O1] and [O2]. Using this technique the results were better than for MSC, in both conditions, and the detection rates increased with the addition of new leads. A four leads combination led to the best detection rate, with percentages higher than 80% at all frequencies, except 9 Hz. The increase in the performance with new leads addition was also reported by Miranda de Sá et al. [19], who compared MSC and MC in the detection of 10 Hz SSVEP, by Zanotelli et al. [22] in the evaluation of auditory evoked responses and by Melges et al. [16] in an experiment with somatosensory stimulation and the same techniques.

For SSVEP BCI, other signal processing methods had been employed for feature extraction. The Wavelet Packet Transform (WPT) was used by Bian et al. [23] to develop a four-command BCI with stimulation frequencies of 7, 10, 15 and 20 Hz. This BCI showed an accuracy of 83%. Another technique studied was the Continuous Wavelet Transform (CWT), which was applied by Zhang et al. [24] to detect responses at 8.57, 10, 12 and 15 Hz. In this work, the authors compared CWT with six different mother-wavelet and a FFT based technique, reporting that the highest performance was achieved with a Complex Morlet CWT, which presented more than 90% accuracy. Wang [10] and Muller-Putz et al. [25] studied the SSVEP employing the power spectrum analysis. The first developed an electrical car control using 9, 11, 13, 15 and 17 Hz stimulation frequencies, obtaining an average accuracy higher than 85%. The latter implemented a hand orthesis control with commands associated with 6, 7, 8 and 13 Hz. The accuracy of this system varied between 44% and 88%.

Similar to our study, Braga et al. [26] applied Objective Response Detection technique, the Spectral F-Test (SFT), to identify response to stimulation at 6, 7 and 8 Hz, with average hit rate higher than 90%, calculated based on the time evolution analysis of SFT. On the other hand, in this study, some of the above mentioned frequencies were employed. However, the detection rates were used, instead of the accuracy rate, to compare the detection probability for two different lighting conditions.

Finally, the percentages of detection for different sets of EEG epochs revealed no habituation effect, since no important decrease in the rates was observed for each derivation.

5. Conclusion

Based on the results of detection rates for the MSC, 7 and 8 Hz were considered the best frequencies for obtaining SSVEP. Thus, these frequencies should be assigned to commands in a BCI that need fast and reliable response. As second choice, the frequency of 10 Hz, with slight lower rates, could be also used. However, for natural illumination environment, which presents luminance compatible with the photopic condition employed in this work, the use of MSC is not recommended since an important decrease in the detection percentages was observed.

The use of a multivariate ORD technique, Multiple Coherence (MC), allowed overcoming the MSC limitation, leading to better detection rates for scotopic and photopic situations. MC presented high detection probability for all frequencies, when parietal and occipital derivations were employed.

Finally, the time evolution analysis of the MC and the calculation of BCI accuracy have to be investigated in order to build a SSVEP BCI.
Acknowledgments
To CAPES, CNPq, FAPEMIG and PRPq/UFMG for the financial support.

References
[1] Ziemssen T 2009 Multiple sclerosis beyond EDSS: depression and fatigue. J Neurol Sci 277 Suppl S37–41
[2] Gupta P K, Prabhakar S, Sharma S and Anand A 2012 A predictive model for amyotrophic lateral sclerosis (ALS) diagnosis. J Neurol Sci 312 68–72
[3] Le Forestier N, Maisinobe T, Spelle L, Lesort A, Salachas F, Lacomblez L, Samson Y, Bouche P and Meininger V 2001 Primary lateral sclerosis: further clarification. J Neurol Sci 185 95–100
[4] IBGE 2010 Tabelas de resultados Censo Demográfico 2010 Características gerais da população, religião e pessoas com deficiência 2010 Available on ftp://ftp.ibge.gov.br/Censos/Censo_Demografico_2010/Caracteristicas_Gerais_Religiao_Deficiencia/tab1_3.pdf Accessed on 18/05/2013
[5] Iversen I H, Ghanayim N, Kübler A, Neumann N, Birbaumer N and Kaiser J 2008 A brain-computer interface tool to assess cognitive functions in completely paralyzed patients with amyotrophic lateral sclerosis. Clin Neurophysiol 119 2214–23
[6] Misulis K E 1994 Spehlmann’s Evoked Potential Primer (Newton, MA: Butterworth-Heinemann)
[7] Moran D 2010 Evolution of brain-computer interface: action potentials, local field potentials and electrocorticograms. Curr Opin Neurobiol 20 741–5
[8] Leuthardt E C, Schalk G, Roland J, Rouse A and Moran D W 2009 Evolution of brain-computer interfaces: going beyond classic motor physiology. Neurosurg Focus 27 E4
[9] Ming C M C, Xiaorong G X G, Shangkai G S G and Boliang W B W 2005 Stimulation frequency extraction in SSVEP-based brain-computer interface First International Conference on Neural Interface and Control (Wuhan: IEEE) pp 64–7
[10] Wang H 2010 Remote control of an electrical car with SSVEP-Based BCI 2010 IEEE International Conference on Information Theory and Information Security (Beijing: IEEE) pp 837–40
[11] Ortner R, Allison B Z, Korisek G, Gaggl H and Pfurtscheller G 2011 An SSVEP BCI to control a hand orthosis for persons with tetraplegia. IEEE Trans Neural Syst Rehabil Eng 19 1–5
[12] Vialatte F-B, Maurice M, Davuvels J and Cichocki A 2010 Steady-state visually evoked potentials: focus on essential paradigms and future perspectives. Prog Neurobiol 90 418–38
[13] Pinto M A S, Souza J K S, Baron J and Tierra-Criollo C J 2011 A low-cost, portable, micro-controlled device for multi-channel LED visual stimulation. J Neurosci Methods 197 82–91
[14] Wu Z, Lai Y, Xia Y, Wu D and Yao D 2008 Stimulator selection in SSVEP-based BCI. Med Eng Phys 30 1079–88
[15] Cagy M, Infantosi A F C and Gemal A E 2000 Monitorização do Plano Anestésico por Técnicas Estatísticas no Domínio da Freqüência Rev Bras Eng Biomed 16 95–107
[16] Melges D B, Miranda de Sá A M F L and Infantosi A F C 2012 Tibial nerve somatosensory evoked response detection using uni and multivariate coherence Biomed Signal Process Control 7 215–20
[17] Simpson D M, Tierra-Criollo C J, Leite R T, Zayen E J and Infantosi a F 2000 Objective response detection in an electroencephalogram during somatosensory stimulation. Ann Biomed Eng 28 691–8
[18] Pinto M A S 2011 Estudo do potencial evocado visual em regime permanente baseado em LED para interface cérebro máquina (UFMG)
[19] Miranda de Sá A M F L and Felix L B 2001 On the Detection of Visual Evoked Potential Responses by Using Multiple Coherence 23rd Annual EMBS International Conference (Istanbul: IEEE) pp 2002–5
[20] Miranda de Sá A M F L and Infantosi A F C 2007 Evaluating the relationship of non-phase locked activities in the electroencephalogram during intermittent stimulation: a partial coherence-based approach. Med Biol Eng Comput 45 635–42
[21] Miranda de Sá A M F L, Felix L B and Infantosi A F C 2004 A matrix-based algorithm for estimating multiple coherence of a periodic signal and its application to the multichannel EEG during sensory stimulation. IEEE Trans Biomed Eng 51 1140–6
[22] Zanotelli T, Santos T S, Felix L B and Tierra-Criollo C J 2010 Deteção do potencial evocado auditivo em regime permanente utilizando coerência e coerência múltipla XXII Congr Bras Eng Biomed (Tiradentes) pp 1162–5
[23] Bian Y, Li H, Zhao L, Yang G and Geng L 2011 Research on Steady State Visual Evoked Potentials based on Wavelet Packet Technology for Brain-Computer Interface Procedia Eng 15 2629–33
[24] Zhang Z, Li X and Deng Z 2010 A CWT-based SSVEP classification method for brain-computer interface system Int Conf Intell Control Info Process (Dalian: Ieee) pp 43–8
[25] Muller-Putz G and Pfurtscheller G 2008 Control of an electrical prosthesis with an SSVEP-based BCI IEEE Trans Biomed Eng 55 361–4
[26] Braga V C C, Cerqueira F G G and Criollo C J T 2012 Interface Cérebro Máquina por Potencial Evocado Visual em Regime Permanente Wireless com Coleta Online XXIII Congr Bras Eng Biomed (Porto de Galinhas) pp 1–5