Biomedical Signal Processing and Control 40 (2018) 234–239

Contents lists available at ScienceDirect

Biomedical Signal Processing and Control

journal homepage: www.elsevier.com/locate/bspc

Research Paper

Comparison of univariate and multivariate magnitude-squared coherences in the detection of human 40-Hz auditory steady-state evoked responses

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ARTICLE INFO

Article history:
Received 29 March 2017
Received in revised form 4 September 2017
Accepted 30 September 2017

Keywords:
Auditory steady-state responses
Magnitude-squared coherence
Multiple magnitude-squared coherence
Electroencephalogram

ABSTRACT

Objective response detection (ORD) techniques for evaluating bioelectrical evoked responses in the electroencephalogram (EEG) are based on statistical criteria rather than on visual inspection. Hence, they do not depend on human evaluation, which is often a subjective approach. Furthermore, since such techniques do not involve heuristic approaches, they may be more easily implemented and used in automatic systems. The Magnitude-Squared Coherence (MSC), together with its recently developed multivariate extension (the multiple magnitude-squared coherence – MMSC), have been pointed out as one of the most efficient ORD techniques for detecting steady-state responses in the EEG. In this work, both MSC and MMSC were applied to EEG signals collected during auditory stimulation in order to allow comparison in the detection of auditory steady-state responses (ASSRs). The stimuli consisted of 40 Hz amplitude-modulated tones delivered binaurally in the intensity of 50 dB SPL (*sound pressure level*). The best result was obtained by using MMSC in the two-electrode set C4 and Fz. This configuration led to a 0.92-detection ratio, within 111.55 s in average to detect each response and kept the false alarm ratio under 0.05. The average improvement in performance was about 11% when compared to the MSC. These results allow concluding that the detection protocol of 40 Hz ASSRs can be improved by using MMSC in multichannel EEG analysis when compared to the traditional univariate MSC approach.

1. Introduction

The evoked potential (EP) corresponds to an electrical manifestation of the brain response to an external stimulus [1]. They may be either transitory, whenever the response to a given stimulus vanishes completely before the next one is applied, or a steady-state one, whenever the following stimulus is applied before the response to the previous one vanishes.

The EP may be recorded on the scalp, together with the ongoing electroencephalogram (EEG). However, due to its reduced amplitude in comparison with this latter, the EP is not easily noticeable in the EEG. This occurs due to the fact that the EEG reflects other rhythmic activities from the brain, face muscles and the neck [2]. Therefore, signal processing techniques are often necessary for revealing the EP.

For the case of auditory stimulation, amplitude modulated (AM) tones lead to auditory steady-state responses (ASSRs). The most used AM tones in studies with human beings have modulating frequency within a range close to 40 Hz [3]. Such kind of stimulation results in an energy increase at the modulation frequency in the signal power spectrum [4]. Thus, ASSRs are more easily detected by means of frequency domain techniques. Assessing the presence of ASSRs in the EEG is an important task in monitoring surgeries [5], newborn auditory screening [6], as well as in brain-computer interfaces [7,8].

In this scenario, objective response detection (ORD) techniques have arisen as a way of turning the EP detection less dependent on visual inspection of averaging signals or their corresponding spectra. In such techniques, the sampling distribution of a detector is obtained under the null hypothesis of no EP in the EEG in order to establish a critical value that corresponds to a threshold for the

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https://doi.org/10.1016/j.bspc.2017.09.024
1746-8094/

detection [9]. The magnitude-squared coherence (MSC) estimate between the stimulating signal and the EEG has been suggested as an efficient ORD technique [10]. The MSC is analogous to the coefficient of determination (the square of the correlation coefficient), but in the frequency domain. Since the signal-to-noise ratio (SNR) is known to be greater in the stimulating frequency and the harmonics [11], coherence between both signals is expected to be greater in such frequencies. Furthermore, the sampling distribution of the coherence estimate is well established for Gaussian signals [12] and, for the particular case of coherence equal to zero, the statistics remain the same in spite of the sampling distribution of the second signal, provided the first one is Gaussian [13]. This leads to a very robust detector, since the false positive detection ratio will not depend on the shape of the evoked response. Furthermore, in this particular case of one periodic, deterministic signal, coherence may be estimated using only the EEG signal, which simplifies the experimental setup, since the stimulating signal need not be recorded [14].

However, for a given SNR-value, the detection ratio can only be increased at the expense of using longer stretches of EEG signals [15], which may constitute an issue in monitoring surgeries, when detection should occur as fast as possible in order to avoid injuries to the patient. With the purpose of increasing the detection ratio with coherence without augmenting the record length, the use of signals from different electrodes has been suggested to allow multiple coherence estimation [15,16]. This multivariate, spectral detector, named as multiple magnitude-squared coherence (MMSC), has been further investigated in [17] in the EEG during photic stimulation and compared to its univariate counterpart. It is worth mentioning the inexistence of published works investigating the efficiency of MMSC in the detection of ASSRs.

Thus, this work aims at evaluating the MMSC in the detection of ASSR and at establishing the more suitable electrode set that should be used. Thus, EEG signals during AM tones stimulation were collected and the detection protocol was applied based on such multivariate objective response detection (MORD) technique.

2. Mathematical background

2.1. Magnitude-squared coherence

The coherence estimated for finite-length, discrete-time signals $x[k]$ and $y[k]$, divided into M windows, is given as [18]

$$\hat{\gamma}^2_{xy}(f) = \frac{\left|\sum_{i=1}^{M} X_i^*(f)\, Y_i(f)\right|^2}{\sum_{i=1}^{M} |X_i(f)|^2 \sum_{i=1}^{M} |Y_i(f)|^2}, \tag{1}$$

where * is the complex conjugate, M is the number of windows, $X_i(f)$ and $Y_i(f)$ are the $i^{-\text{th}}$ window, Fourier Transforms of the signals. In cases where stimulation ($x[k]$) is deterministic, periodic and synchronized in each window ($X_i(f) = X(f), \forall i$), the Eq. (1) can be simplified and called Magnitude-Squared Coherence [10]:

$$M\hat{S}C(f) = \frac{\left|\sum_{i=1}^{M} Y_i(f)\right|^2}{M \sum_{i=1}^{M} |Y_i(f)|^2}. \tag{2}$$

In case of absent response to stimulation, the numerator value tends to zero (for M tending to infinity), thus, MSC tends to 0. On the other hand, in case of presence of an equal response in all windows, the value of MSC tends to 1.

For the Null Hypothesis (H0) of Absent Response, $M\hat{S}C(f)$ is distributed as a beta distribution, and the critical value for H0 is obtained with the following equation [19]:

$$MSC_{crit} = 1 - \alpha^{\frac{1}{M-1}}, \tag{3}$$

where α is the significance level. The signal is detected by rejecting H0, i.e., $MSC(f) > MSC_{crit}$.

2.2. Multiple magnitude-squared coherence

According to [16], the MMSC estimate between one periodic stimulus and the EEG of N electrodes ($y_j[k]$, $j = 1, 2, \ldots, N$) is given as

$$M\hat{M}SC(f) = \frac{V^H(f)\, S_{yy}^{-1}(f)\, V(f)}{M}, \tag{4}$$

where "H" denotes the Hermitian operator, M is the number of data windows, $S_{yy}(f)$ is the estimate of the cross-spectral matrix of N signals and

$$V(f) = \begin{bmatrix} \sum_{i=1}^{M} Y_{1i}^*(f) \\ \sum_{i=1}^{M} Y_{2i}^*(f) \\ \vdots \\ \sum_{i=1}^{M} Y_{Ni}^*(f) \end{bmatrix}, \tag{5}$$

where $Y_{ji}(f)$ – ($j = 1, 2, \ldots, N$) – is the discrete Fourier Transform of the i^{-th} signal segment in channel j.

Critical values with significance level α that constitute a threshold for detecting evoked responses may be obtained according to [19]:

$$MMSC_{crit} = \beta_{crit\alpha,N,M-N} \tag{6}$$

Where $\beta_{crit\alpha,N,M-N}$ is the inverse of the beta probability density function with shape parameters a and b, evaluated for a significance level α. The detection of the presence of a response can be obtained by comparing the values of the $MMSC$ with the critical value ($MMSC(f_0) > MMSC_{crit}$).

3. Materials and methods

3.1. Experimental design

The experiments were performed in an acoustically isolated cabin in the Interdisciplinary Center for Signal Analysis (NIAS), Federal University of Viçosa. Total eight healthy subjects (2 female and 6 male) ages in between 20 and 43 years were included in the study. The subjects gave written consent to participate and the experiment was conducted according to a protocol approved by the local ethics committee (CEP/UFV No. 2.105.334). The volunteers were instructed to sit comfortably, keeping eyes closed and to not sleep. Each volunteer underwent 4 stimulation sessions (one for each carrier), each one lasting about 4.5 min.

The EEG was collected at electrodes FP1, FP2, Fz, F3, F4, F7, F8, Cz, C3, C4, T3, T4, Pz, P3, P4, T5, T6, O1 and O2 (10–20 International System) using the biological signal amplifier BrainNET BNT-36 (EMSA, Brazil) and Ag-AgCl electrodes. The reference electrode was Oz and the ground was the forehead (Fpz). The sampling frequency was set to 600 Hz, with the notch filter set to 60 Hz and band-pass filtering at 0.1–70 Hz.

A third-order Butterworth band-pass digital filter was offline applied with bandpass range from 30 to 50 Hz.