Objective Response Detection of Multiple Auditory Steady-State Responses: Rice Detector vs Component Synchrony Measure

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Abstract. Multiple auditory steady state responses (MASSR) is used to assess the integrity auditory pathways for different frequencies applied simultaneously without significant increases in exam time. Objective Response Detection (ORD) techniques have been employed for hearing screening since it conducts to response identification with statistical basis. This work aims at comparing time and detection rate of two ORD, Rice detector (RD) and Component Synchrony Measure (CSM). The binaural auditory stimulation was applied to 21 normal hearing infants and consisted of four amplitude-modulated (AM) tones presented simultaneously on each ear with the carriers 500, 1000, 2000 and 4000 Hz, and at 50 and 40 dB_{SPL} intensity levels. The CSM presented higher detection rates than RD for all carriers, both intensities and ears (statistical difference, assessed by proportion test with significance level of alfa=0.05, only for 500 Hz in both ears and for 1000 Hz in the left ear). Moreover, detection times were lower for CSM compared to RD (unpaired Wilcoxon rank-sum test with alfa=0.05 indicated statistical difference for 1000 Hz at 50 dB_{SPL} and 2000 Hz at 50 dB_{SPL} both for the left ear). Hence, the CSM could be considered more effective for hearing screening purposes.

1. Introduction

The detection of congenital hearing losses followed by the appropriate diagnosis and intervention allows the child development without impairment in their linguistic skills [1]. In this context, the improvement of hearing assessment techniques has been the motivation of several studies [2,3,4,5], which aimed to achieve more effective universal hearing screening programs. The employed techniques for the auditory system evaluation includes otoacoustics emission test [6], the Brainstem Evoked Response Audiometry (BERA) and, recently, the auditory response to amplitude-modulated sinusoidal stimulation [2,3,4].

The otoacoustics emission is a quick test performed to detect hearing loss for intensities higher than 30 dB_{HL} (HL - Hearing Level) [7]. However, it only evaluates the external ciliated cells, hence, it is not suitable to determine hearing threshold or identify whether the hearing loss is conductive or sensorineural [7]. On the other hand, BERA is able to determine the hearing threshold, although it becomes very time-consuming for evaluating specific frequencies hearing loss [2]. Moreover, BERA allows inferring about the hearing pathways integrity only until the inferior colliculus on the brainstem [8]. The assessment of cortical auditory information processing is possible through the Auditory Steady State Response (ASSR), which can be obtained by applying auditory clicks at high stimulation rates or modulated tones, leading to time overlapping evoked responses [9].

For the amplitude-modulated stimuli, the basilar membrane, located within the cochlea, vibrates in the specific region related with the carrier frequency. The basilar membrane vibration produces deflection on the ciliated cells that are in contact with the tectorial membrane. Since the ciliated cells depolarize for deflections in only one direction, a rectified stimulation response is obtained [2]. The spectrum of the ASSR presents a component in the modulation frequency, which is related to the hearing sensitivity to the corresponding carrier [2]. Therefore, employing several modulated tones at different frequencies simultaneously can result in a faster exam for hearing sensitivity evaluation [2]. This method is known as multiple auditory steady-state responses (MASSR) and employ objective response detection (ORD) techniques, which are based on statistical tests, for identifying the stimuli response with a maximum false positive rate, previously established.

Particularly, the frequency-domain ORD techniques have been studied in order to minimize the response detection time. These techniques may use only the magnitude of the Fourier Transformed EEG such as the Spectral F Test –SFT [6], only the phase as in the Component Synchrony Measure – CSM [10], or both such as in the Magnitude-Squared Coherence – MSC [11]. The SFT, CSM and MSC have been used to MASSR in order to minimize the detection time and maximize the detection probability [4,5]

Recently, FARINA et al. [12] introduced a frequency-domain ORD technique based on the Rice distribution (Rice Detector – RD), for somatosensory evoked potential detection, obtaining promising results. Therefore, this paper proposes comparing the performance of RD and CSM for MASSR detection.

2. Materials and methods

2.1. Component Synchrony Measure (CSM)

The CSM measures the degree of synchronism of each spectral component considering only the phase of Fourier Transform and can be estimated by [10]:

$$\hat{\rho}^2(f) = \left(\frac{1}{M}\sum_{i=1}^{M}\cos\theta_i(f)\right)^2 + \left(\frac{1}{M}\sum_{i=1}^{M}\operatorname{sen}\theta_i(f)\right)^2 \qquad (1)$$

where $\theta_i(f)$ is the phase of the i[th] EEG epoch of the spectral component f. If no response to the stimulation is expected (null hypothesis of response absence), the phase of EEG Fourier Transformed epochs is assumed to be randomly distributed between 0 and 2π and it can be showed that the CSM probability density function tends asymptotically to a chi-squared distribution with 2 degrees of freedom (χ_2^2) [10].

Hence, the critical value for the CSM estimates can be calculated by [10]:

$$\hat{\rho}^2_{crit} = \frac{\chi^2_{2,\alpha}}{2M} \qquad (2)$$

Where M is the number of EEG epochs and α is the significance level of the statistical test.

The detection is obtained when the estimate exceeds the critical value ($\hat{\rho}^2(f) > \hat{\rho}^2_{crit}$).

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2.2. Rice Detector (RD)

The Rice Detector (RD) evaluates the presence of stimuli response based on the EEG Fourier Transformed epoch $X_i(f)$ and calculated as [12]:

$$\hat{r}_m = \frac{1}{M}\left[\left(\sum_{i=1}^{M} Re\left(X_i(f)\right)\right)^2 + \left(\sum_{i=1}^{M} Im\left(X_i(f)\right)\right)^2\right]^{1/2} \tag{3}$$

where M is the number of epochs used in the average calculation.
The $\hat{r}_m$ analytical critical value for a given significance level α can be calculated as [12]:

$$\hat{r}_{m_{crit}} = \left(\frac{2\sigma^2 \ln\left(\frac{1}{\alpha}\right)}{M}\right)^{1/2} \tag{4}$$

Since this value depends on the signal variance σ, and as this parameter is not known a priori, the statistics of interest can be redefined as suggested by [12]:

$$\hat{\xi} = \frac{\hat{r}_m}{\sigma} \tag{5}$$

Thus the critical value for the new metrics depends only on the significance level α and the number of epochs M [12]:

$$\hat{\xi}_{crit} = \left(\frac{2\ln\left(\frac{1}{\alpha}\right)}{M}\right)^{1/2} \tag{6}$$

Similarly, the detection is obtained when the estimate exceeds the critical value ($\hat{\xi}(f) > \hat{\xi}_{crit}$).

2.3. EEG acquisition

The electroencephalographic signals were collected from 21 individuals, aged between 9 and 11 years old, without history of neuropathies and normal hearing verified by tonal threshold audiometry. The signals were recorded, in a background noise controlled environment, by means of electrodes positioned in derivation [Cz] of the 10-20 International System. The ground electrode was located at [Fpz] and the signal reference about 3 cm below the inion.

The stimulus consisted of four AM tones presented simultaneously on each ear (binaural stimulation), at the intensities of 50 and 40 dB_{SPL} (SPL - Sound Pressure Level) by insert earphones 5A model (Aearo-Technologies). The modulation frequencies used for right ear were 77.15, 86.91, 98.63 and 104.49 Hz, respectively, for the carriers 500, 1000, 2000 and 4000 Hz. For the left ear, the modulation frequencies were 81.05 (carrier of 500 Hz), 94.73 (1000 Hz), 100.59 (2000 Hz) and 106.45 Hz (4000 Hz) [4].

The *AudioStim System* [13], developed in the Biomedical Engineering Laboratory of the Federal University of Minas Gerais (UFMG), was employed for both EEG acquisition and stimulation.

This research was approved by the Ethics Committee of UFMG (protocol n. 0369020300010) and the children legal sponsors signed written informed consent.

2.4. Pre-processing

The EEG signal was analogically band-filtered in the range from 30 to 300 Hz. Moreover, a notch filter at 60 Hz was also employed in order to minimize net noise influence. The signal was sampled at 1000 Hz, and then segmented into 1024-samples epochs. The epochs with more than 1% of samples exceeding 10 mV were discarded.

2.5. Objective Response Detection

The critical values for both techniques, $\hat{\rho}^2_{crit}$ and $\hat{\xi}_{crit}$, were calculated for the significance level $\alpha = 0.05$, using expression (2) and (6). Both the estimates and critical values were calculated by successively increasing the M number of EEG epochs. The detection time was based on five consecutive estimates exceeding the corresponding critical value.

2.6. Statistical analyses

The nonparametric unpaired Wilcoxon rank-sum test was applied for comparing the detection time between CSM and RD. The detection percentages were compared employing the proportion test. The significance level of 0.05 was used for both statistical tests.

3. Results

Figure 1 compares the detection performance of CSM and RD for each carrier frequency and the 21 individuals evaluated at intensity of 50 dB_{SPL}. The detection percentages were lower than 75% for CSM and RD at the carrier of 500 Hz in both ears. Detection response occurred for, 95.2% at 1000 and 4000 Hz, and 100% at 2000 Hz for right ear in CSM (Figure 1, top chart), while RD presented response only for 85.7% at 1000 and 2000 Hz, and 81.0% at 4000 Hz. For the left ear, CSM presented detection percentage equal to 85.7, 100 and 90.5%, for 1000, 2000 and 4000 Hz, respectively; while RD showed rates of 76.2, 90.5 and 76.2%. Hence, CSM showed superior performance for all cases, but without significant statistical difference.

The results for 40 dB_{SPL} are presented in Figure 2 for both ears. The detection rates for CSM and the right ear were of 85.7, 95.4 and 100%, respectively for the carriers 1000, 2000 and 4000 Hz. The RD showed 66.7% (1000 Hz), 90.5% (2000 Hz) and 81.0% (4000 Hz) for the same ear (Fig. 2, top chart). In the left ear, lower rates were found such as 66.7% (1000 and 4000 Hz) and 90.5% (2000 Hz) for CSM and 28.6% (1000 Hz), 85.7% (2000 Hz) and 57.1% (4000 Hz) for RD. The proportion test showed significant difference only for the carriers 500 Hz ($p<0.07$ for both ears) and 1000 Hz ($p<0.0005$ for the left ear), which presented detection rates lower than 77%.

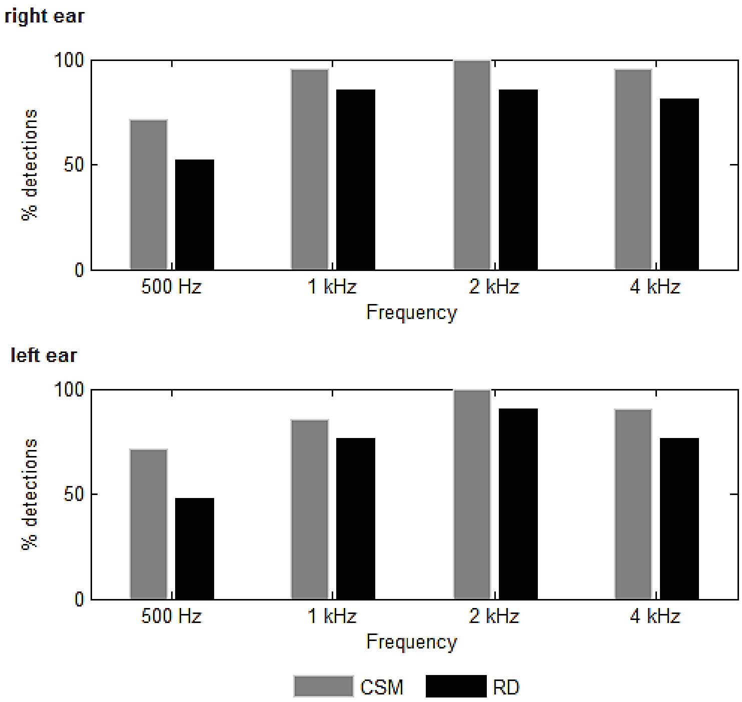

Figure 1. Detection rates for CSM and RD and each carrier at 40 $dB_{SPL.}$

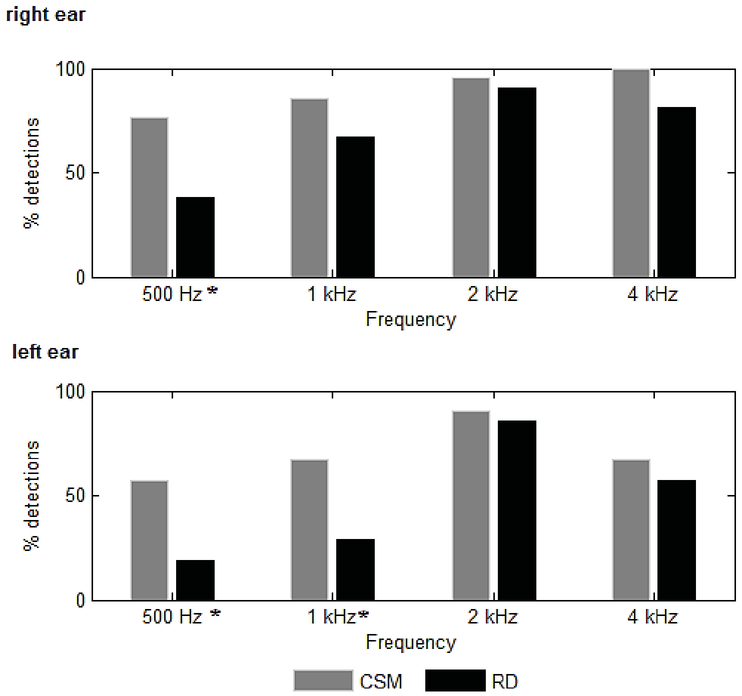

Figure 2. Detection rates for CSM and RD and each carrier at 50 dB_{SPL} (* indicates statistical difference).

The detection times for both techniques are presented in Fig. 3 for stimulation at 50 dB_{SPL} by means of boxplot. Table 1 summarizes the time medians for each carrier and both techniques and ears. It also presents the p-values for comparison of the medians by applying the unpaired Wilcoxon rank-sum test. Statistical significant difference was found only for 1000 Hz, left ear.

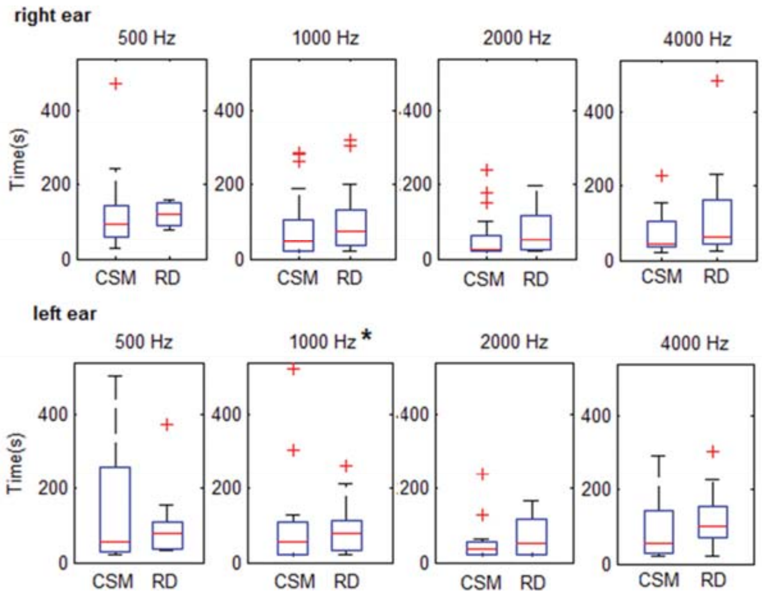

Figure 3. Boxplot of detection times for CSM and RD at 50 dB_{SPL} (* indicates statistical difference).

Table 1. Results of the unpaired Wilcoxon rank-sum test and medians of detection times (in seconds) for each carrier and both techniques and ears – stimulation at 50 dB_{SPL}.

	Carrier	CSM	RD	p-value
Right ear	500 Hz	95.2	119.3	0.3456
	1000 Hz	49.2	73.7	0.1596
	2000 Hz	26.6	50.2	0.1130
	4000 Hz	45.1	61.4	0.1749
Left ear	500 Hz	56.3	77.8	0.6024
	1000 Hz	56.8	80.4	0.0176
	2000 Hz	35.8	51.2	0.1181
	4000 Hz	57.3	102.4	0.1162

Finally, Fig 4 shows the detection times for CSM and RD and stimulation at 40 dB_{SPL}. The time medians are presented in Table 2 together with the result of the Wilcoxon test. Statistical significant difference was found only for 2000 Hz, left ear.

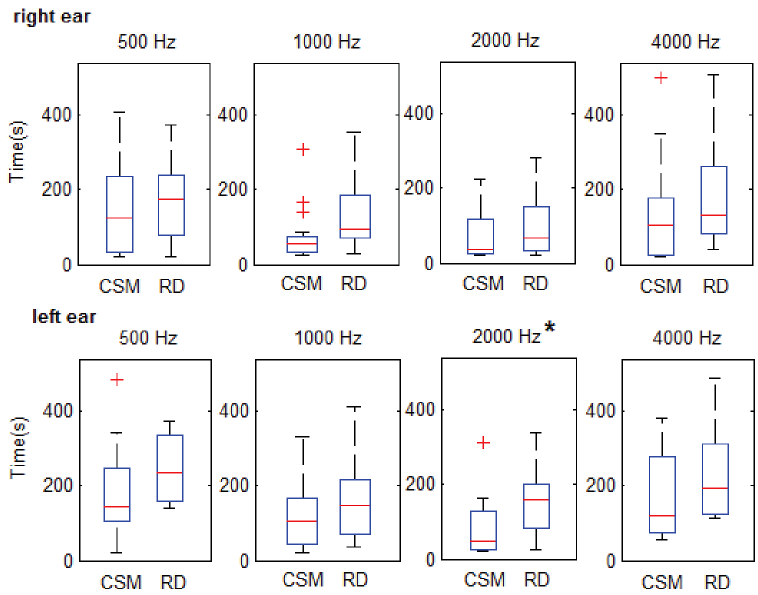

Figure 4. Boxplot of detection times for CSM and RD at 40 dB_{SPL} (* indicates statistical difference).

Table 2. Results of the unpaired Wilcoxon rank-sum test and medians of detection times (in seconds) for each carrier and both techniques and ears – stimulation at 40 dB_{SPL}.

	Carrier	CSM	RD	p-value
Right ear	500 Hz	123.9	172.5	0.7602
	1000 Hz	55.3	94.7	0.3596
	2000 Hz	36.4	68.6	0.0927
	4000 Hz	103.4	132.1	0.2602
Left ear	500 Hz	143.9	236.0	0.2615
	1000 Hz	106.0	146.9	0.3427
	2000 Hz	49.2	160.3	0.0121
	4000 Hz	119.3	193.0	0.1166

4. Discussion

This paper aimed at comparing the performance of CSM and RD for MASSR identification. To our known, this is the first study to employ RD in order to identify MASSR.

FARINA *et al.* [12] have introduced the use of RD applying to somatosensory evoked response detection, and this ORD technique presented performance equivalent to the Magnitude-Squared Coherence (MSC) [12]. The MSC uses magnitude and phase information of the Fourier Transformed EEG epochs, whilst the RD uses only magnitude information and the CSM only phase.

In our study RD showed detection rates lower than the CSM, regardless the frequency or intensity tested, leading to the interpretation that the phase is predominantly essential for ASSR detection. In fact, other studies reported the phase to be more important than magnitude in auditory evoked potential, particularly, for low signal-to-noise ratio [14,15]. Thus, using only magnitude information can lead to a relevant reduction in the detection performance, whilst there is a slight effect when only phase is employed [10,14]. The phase importance for response identification was also corroborated by [16], which reported the phase synchronism with the modulation frequency, even at threshold intensities, especially for amplitude-modulated stimuli, in experiments conducted with mammals.

Despite the low performance of RD, detection percentages difference between the ORD techniques was only significant for 500 Hz (both ears) and 1000 Hz (left ear). For the carrier of 500 Hz, the response identification was poor for both techniques, which agree with other authors results [3,17].

For audiology, both speed and consistency of response detection are important, respectively, as efficiency and stop criteria [1]. For this reason, in this work, the detection time was determined based on positive response identification in five consecutive ORD (CSM or RD) estimates. RD presented higher median detection times than CSM for all frequencies and both ears, although significant difference was only found for 1000 Hz at 50 dB_{SPL} and 2000 Hz at 40 dB_{SPL} on the left ear. This result agrees with other works, since the phase spectrum is important not only for achieving higher detection rates, but also for fastening the exam [10,14].

5. Conclusions

The CSM presented better performance than RD for both studied criteria: detection rate and detection time, with statistical significance for some of the employed carriers. These results point to the predominance of phase synchronism in the auditory response and indicate the CSM as preferable for hearing screening programs

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