Analysis of reproducibility in auditory evoked responses to amplitude modulation

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Introduction

Electroencephalographic analysis revealed an oscillating electrical activity in the auditory brain areas in response to amplitude modulated noise [1]. This activity reproduces almost perfectly the modulation frequency f_m but shows an amplitude varying with the precise place where it is recorded. In this paper, we extract the three characteristic parameters of oscillation that are the amplitude, phase and frequency and we study their variability to repeated stimuli. Then, we examine the sequential variability of the response amplitude.

Materials

We use responses recorded on stereoelectroencephalographic (SEEG) electrodes implanted in auditory areas of twenty epileptic patients suffering from partial refractory epilepsy (114 leads in the right auditory cortex and 94 in the left one). The anatomical positions of the leads were determined in a parallel study [2].

Stimuli were 1-second long white noises with a sinusoidal amplitude modulation at frequencies 4, 8, 16, 32, 64, and 128 Hz and a modulation depth of 100 %. Sounds were presented binaurally via headphones to the listener by series of 50 to 100 stimuli of two randomly alternated frequencies f_m (4/32 Hz ; 8/64 Hz ; 16/128 Hz). In this study, only intervals presenting some clear oscillation and free of transient response were considered. Their length was around 800 ms.

Model

For a given lead, the j-th response is named an epoch and may be modeled on the considered interval as a noisy sinusoidal activity

$$x^{(j)}(t) = a^{(j)}.\sin\left(2\pi\frac{f_0^{(j)}}{f_e}t + \phi^{(j)}\right) + n^{(j)}(t) \quad (1)$$

$$= s^{(j)}(t) + n^{(j)}(t) \quad (2)$$

at time t, where $a^{(j)}$, $f_0^{(j)}$ and $\phi^{(j)}$ are respectively samples of three random variables A (amplitude), F_0 (observed oscillation frequency) and Φ (phase), and f_e is the sampling rate. The quantity $n^{(j)}(t)$ is a sample of the brain activity, N, seen as a noise and $s^{(j)}(t)$ is a sample of the useful signal S, seen as a function of t, A, F_0 and Φ.

Parameters estimation

Frequency and amplitude estimation

On each epoch, we compute FFT spectrum (2048 points). We take the frequency $f_0^{(j)}$ and the amplitude $a^{(j)}$ of the nearest spectral peak to f_m (4, 8, 16, 32, 64, 128 Hz).

Phase estimation

We estimate the phase by using the DFT at f_m:

$$\widehat{\phi^{(j)}} = \arg\left(\frac{1}{q}\sum_{t=1}^{q} x^{(j)}(t)e^{-2i\pi\frac{f_m}{f_e}t}\right) \quad (3)$$

where q is the number of samples of the epoch $x^{(j)}$.

SNR estimation

To estimate the noise PSD, we consider that a first estimation of the signal may be given by $\overline{x}(t) = \frac{1}{q}\sum_{t=1}^{q} x^{(j)}(t)$. In this way, the noise PSD is given by

$$\widehat{\gamma}_n(f) = \overline{\gamma_{x^{(j)}-\overline{x}}(f)}. \quad (4)$$

We slightly improved the noise PSD estimation by carrying out spline interpolation around f_m to take into account the residual oscillation present in $x^{(j)} - \overline{x}$. Then, we estimate the signal PSD using cross-products of epochs spectra, so that

$$\widehat{\gamma}_s(f) = \Re eal\left(\frac{1}{p(p-1)}\sum_{k=1}^{p}\sum_{j=1,j\neq k}^{p} X^{(k)*}(f)X^{(j)}(f)\right). \quad (5)$$

Finally, if f_0 is the frequency of the nearest spectral peak to f_m in $\widehat{\gamma}_s$, we estimate the SNR for the SEEG oscillating activity for each lead by

$$SNR = 10\log_{10}\left(\frac{\widehat{\gamma}_s(f_0)}{\widehat{\gamma}_n(f_0)}\right). \quad (6)$$

Reproducibility of the response

Considering the model in eq. 1, we compare now the standard deviation (STD) on the parameters A, F_0, and Φ observed on the epochs for each lead to simulated data.

On simulated data using eq. 1 where $a^{(j)} = 10$, $\phi^{(j)} = 0$, $f_0^{(j)} = 4, 8, 16, 32, 64, 128$ Hz, $f_e = 1000$ Hz, and $n^{(j)}$ is an AR model learned on 40 leads, we evaluate the STD

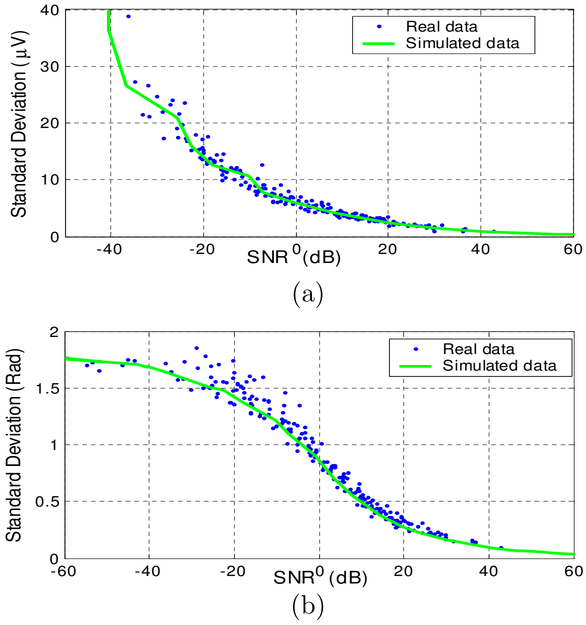

Figure 1: STD of (a) amplitude and (b) phase estimation obtained on real data and simulated data for f_m equal to 16 Hz.

on 1000 epochs of 800 ms length (in figure 1 are displayed the results only for phase and amplitude).

The STD observed on real data may be explained entirely by the SNR level, for each parameter.

Trends in amplitudes of records

For each lead, we study trends in the sequence of amplitudes in repeated stimuli.

Tests

To detect monotonic trends, we use the Mann-Kendall test, whose power is equivalent to Spearman's ρ test ([3]). For other trends, for each lead, we project the sequence of amplitudes $\left(a^{(j)}\right)_{j=1..p}$ on the d first components of Fourier basis

$$a^{(j)} = \Re eal\left(\sum_{k:-d\leq j\leq d} \beta_k e^{2i\pi k\frac{j}{p}}\right) + u_j. \qquad (7)$$

We compare the quality of models for $d \in \{1, ..., p-1\}$ by minimizing BIC criterion [4] close to the AIC criterion but derived from a Bayesian approach:

$$BIC = p\log\left(\widehat{\sigma_u}^2\right) + (2d+1)\log(p). \qquad (8)$$

This is equivalent to compare the successive low-frequency filterings of the $\left(a^{(j)}\right)_{j=1..p}$ sequency. If the best value of d is 0, the model is constant, otherwise we test significance of the coefficients β_k found with a Student test. If coefficients are not-null and if the Mann-Kendall test fails, we find a non-monotonic trend.

Simulations show that this method is slightly less efficient than the Mann-Kendall test on linear trends, but it is efficient on quadratic or sinusoidal trends where the Mann-Kendall test fails.

Experimental results

Only leads with $SNR > 0$ (eq. 6) are kept. Trends are constant for all modulation frequencies in the majority (figure 2). Non-constant trends are unexplained but are almost all monotonic.

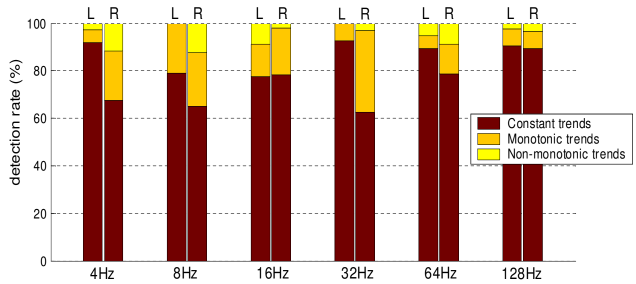

Figure 2: Trends in amplitudes of oscillations in response to repeated amplitude modulated noises versus the modulation frequency f_m (hemispheres : R = right, L = left).

Concluding remarks

The STD of amplitude, phase and frequency of the oscillation is very linked to the SNR level in SEEG activity and sequences of amplitudes are most often constant. So, we may consider that a, f_0, and ϕ are constant in eq. 1 and the theoretical model really observed for the oscillations is

$$x^{(j)}(t) = a.\sin\left(2\pi\frac{f_0}{f_e}t + \phi\right) + n^{(j)}(t). \qquad (9)$$

Hence the hypothesis of reproducibility of the physiological response (amplitude, frequency, phase) is acceptable.

ACKNOWLEDGMENTS

The authors wish to thank the Laboratory of Neurophysiology and Neuropsychology of the University of Aix-Marseille (France) for recording the database.

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