Neural Potentials Disorder during Differential Psychoacoustic Experiment evaluated by Discrete Wavelet Analysis

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***Abstract*— The aim of the paper is the assessment of neural potentials disorder during a differential sensitivity psychoacoustic procedure. Ten volunteers were asked to compare the duration of two acoustic pulses: one reference with stable duration of *500ms* and one trial which varied from *420ms* to *620ms*. During the discrimination task, *Electroencephalogram* (*EEG*) and *Event Related Potential* (*ERP*) signals were recorded. The *mean Relative Wavelet Energy* (*mRWE*) and the *normalized Shannon Wavelet Entropy* (*nSWE*) are computed based on the Discrete Wavelet analysis. The results are correlated to the data derived by the psychoacoustic analysis on the volunteers responses. In most of the electrodes, when the duration of the trial pulse is *460ms* and *560ms*, there is an increase and a decrease in nSWE value, respectively, which is determined mostly by the mRWE in *delta* rhythm. These extrema are correlated to the *Just Noticeable Difference* (*JND*) in pulses duration, calculated by psychoacoustic analysis. The dominance of *delta* rhythm during the whole auditory experiment is noteworthy. The lowest values of nSWE are noted in *temporal* lobe.**

I. INTRODUCTION

Psychoacoustics is the branch of psychophysics which deals with the human perception of the acoustic stimuli (sound), making a sharp distinction between the physical stimulus and psychological response to it. During the last decade, researchers (e.g [1]) have started combining results from the Psychoacoustic Analysis of subjects responses to predefined questions during psychoacoustic tasks, with corresponding results obtained from the recorded Electroencephalogram (EEG) and Event Related Potential (ERP) signals. Their scope is to understand the different mechanisms participating in the reception and processing of the acoustic information. However in most of the publications, the recorded EEG-ERP signals are just observed or partially processed. The literature study triggered the idea to combine the application of a strict and powerful mathematical tool on the recorded EEG-ERP signals with the results derived from the Psychoacoustic Analysis. In order to analyze effectively nonlinear and nonstationary signals, such as EEG-ERP signals, a localization both in time and frequency is required. For this reason, the *Discrete Wavelet Transform* (*DWT*) is selected in order to compute selected metric indexes which combined with the psychoacoustic data can lead to a complete delineation of the auditory stimuli processing.

II. TIME DISCIMINATION TASK

During EEG-ERP signal recording, the volunteer participates in a psychoacoustic time discrimination procedure (under the principles outlined in the Helsinki Declaration of 1975, as revised in 2000), designed according to the method of *constant stimuli* ([2]). In total, ten volunteers (5 men and 5 women, age: 31.1 ± 4.2 years) investigate the differential sensitivity of duration. An acoustic pulse sequence, developed in LabView 8.5 (National Instruments), is driven to the volunteer headphones. It consists of four pulses: a) Reference (t_{ref}: $500ms/1000Hz$), b) Trial (11 levels t_{trial}: from $420ms$ to $620ms$ with $\Delta t = 20ms$ step/$1000Hz$), c) Trigger ($100ms/500Hz$), d) Post-trigger ($100ms/500Hz$). The EEG-ERP recording lasts in total 5700ms. Variable duration of EEG recording before reference pulse assures that the total duration of each iteration is stable. The pulse sequence characteristics are illustrated in Fig. 1. Each level of the trial is applied 10 times, resulting to 110 iterations, reassuring that the data under analysis is statistically safe. The determination of the range of the trial levels was made based on preliminary tests where it was concluded that the subjects could discriminate a shorter trial pulse more easily than a longer one. During the psychoacoustic procedure, the EEG-ERP signal is recorded through 32 electrodes, attached according to international 10/20 system. The reference electrode is placed on the subject ear lobe. A 50 Hz notch filter has been used in order to eliminate power supply related noise. During EEG-ERP measurement, the subject is requested to keep his/her eyes closed. The sampling frequency is $1000Hz$ leading to a signal of 5700 samples.

III. MATHEMATICAL TOOL

A. Wavelet transform

The wavelet representation provides information about which frequencies exist in a signal and when in time these frequency components exist. The wavelet is an oscillating function which, unlike sine and cosine of Fourier analysis, is relatively localized in both time and frequency and is band-limited. A wavelet family $\psi_{s,\tau}(t)$ is the set of elemental functions generated by scaling and translation of a basic wavelet which is called mother wavelet $\psi(t)$ as it is shown

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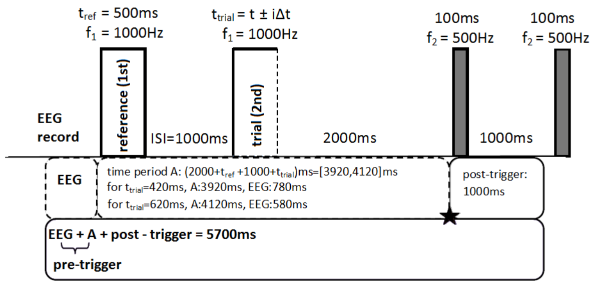

Fig. 1. Acoustic pulse sequence for one iteration, used in the psychoacoustic time discrimination procedure. Variable duration of EEG recording before reference pulse assures that the total duration of each iteration is stable. At the interval after the first post-trigger pulse the EEG-ERP recording, which lasts in total 5700ms, stops and after the second post-trigger pulse the subject responses YES/NO to the question: ”Is the trial longer than the reference?”.

in the following equation ([3]):

$$\psi_{s,\tau}(t) = \frac{1}{\sqrt{(s)}}\psi(\frac{t-\tau}{s}) \tag{1}$$

B. Discrete Wavelet Transform

The discrete wavelet transform (DWT) provides a highly efficient wavelet representation that can be implemented with a simple recursive filter scheme. The wavelet representation is modified to the piecewise continuous function ([3]):

$$\psi_{j,k}(t) = \frac{1}{\sqrt{(s_0^j)}}\psi(\frac{t-ks_0^j}{s_0^j}) \tag{2}$$

The correlated DWT provides a non-redundant representation of the initial signal and its values constitute the wavelet coefficients. The DWT produces only as many coefficients as there are samples within the signal under analysis without the loss of any information. These wavelet coefficients provide a direct estimation of local energies at the different relevant scales, meaning at the different frequencies.

C. Relative Wavelet Energy

Let $\gamma_j(k)$ be the wavelet coefficients in every level j of the wavelet analysis. The energy of the wavelet in every level is given by ([4])

$$E_j = \sum_k |\gamma_j(k)|^2 \tag{3}$$

So the total energy is

$$E_{total} = \sum_j \sum_k |\gamma_j(k)|^2 = \sum_j E_j \tag{4}$$

The Relative Wavelet Energy (RWE) in every level j is given by

$$E_{rel,j} = \frac{E_j}{E_{total}} \tag{5}$$

The E_{rel} yields, at different scales, the probability distribution for the energy. Clearly,

$$\sum_j E_{rel,j} = 1 \tag{6}$$

D. Shannon Wavelet Entropy

The Shannon Wavelet Entropy (SWE) is defined as ([5])

$$S = -\sum_j E_{rel,j} ln[E_{rel,j}] \tag{7}$$

SWE appears as a measure of the degree of disorder of the signal, giving information about the underlying dynamical process associated with it. A very ordered process can be represented by a signal with a narrow band spectrum. A wavelet representation of such a signal will be resolved at one unique wavelet resolution level, so all RWE will be almost zero except at the wavelet resolution level which includes the representative signal frequency at which RWE will almost equal unity. As a consequence, the SWE will acquire a very small value. A signal generated by a totally random process can be taken as representative of a very disordered behaviour. This kind of signal will have a wavelet representation with contributions coming from all frequency bands and all contributions will be of the same order. Consequently, the RWE will be almost equal at all resolution levels, and the SWE will acquire its maximum possible value.

IV. EEG DATA PROCESSING PROCEDURE

A mathematical tool was developed in MATLAB 2013 in order to process the recorded EEG signals and calculate the DWT metric indexes. As mother wavelet, the reverse bio orthogonal rbio3.3 was used. This choice was made after systematic search, aiming at maximizing the discrimination ability of the different EEG frequency bands. For each iteration, DWT is applied in seven levels of analysis for frequencies corresponding to physiological EEG activity i.e *gamma*, *beta*, *alpha*, *theta* and *delta*. The input signal is the raw EEG minus its mean value. The mean value constitutes a dc-offset which is baseline noise and needs to be removed. Firstly, Wavelet coefficients are computed resulting in a single value of RWE in each rhythm, for each iteration, for each electrode, for each subject and a single value of nSWE for each iteration, for each electrode, for each subject. The first and the last 500 wavelet coefficients are excluded from the mean calculation, in order to avoid coefficients affected by the boundary effects. Then, the mRWE is computed across the 10 iterations of the same level of trial pulse and across the 10 subjects for each electrode in each rhythm. Respectively, nSWE is computed across the 10 iterations of the same level of trial pulse and across the 10 subjects for each electrode.

V. RESULTS

A. Psychoacoustic Data

The psychoacoustic procedure aims at the determination of the *Just Noticeable Difference (JND)* in the duration of reference and trial pulses, providing information about the *Differential Limen (DL)*[2]. The subject is aware of the task and after the post-trigger pulse he/she has to response YES/NO to the question: ”Is the trial longer than the reference?”. For each subject, the percentage of YES responses (y axis) is plotted versus the duration of each level of the trial pulse (x axis) (*psychometric function*).

Then, the DL is calculated as the difference that corresponds to 75% and 50% (PSE - Point of Subjective Equality) of positives responses. Based on the subjects responses, the mean *DL* was calculated $40.47ms$ with Standard Deviation (SD:31.79), while the *Weber fraction* $\frac{DL}{t_{ref}}$ reached 0.08[2]. The high value of standard deviation is correlated to high variation in the percentage of positive responses (subjects: 3, 5, 8). Literature calculations of DL ($32.2ms$)([6]) and Weber fraction (0.1)([7]) for time discrimination tasks verify the present results.

B. EEG-ERP Data

The bar graph for nSWE versus the 11 levels of the trial pulse, for different anatomical regions of the human brain is illustrated in Fig. 2. It is observed that the lowest values

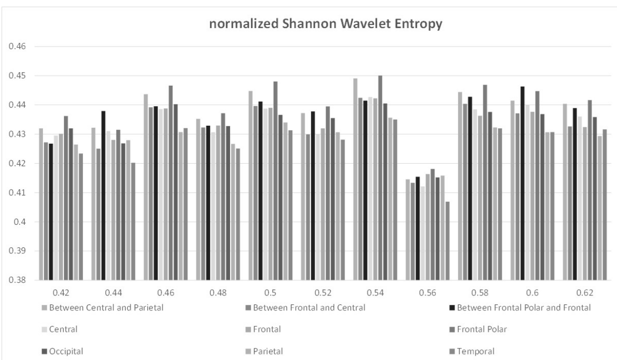

Fig. 2. Normalized Shannon Wavelet Entropy (nSWE) bar graph versus the 11 levels of the trial pulse, for different anatomical regions of the human brain.

of nSWE are noted in *temporal* lobe except for the points which correspond to duration of trial pulse of $460ms$ and $620ms$.

Fig. 3 shows the nSWE for each of the 32 electrodes versus the 11 different levels of the trial pulse, whereas in Fig. 4 the computed mRWE, for each of the 32 electrodes, for each rhythm, plotted versus the 11 different levels of the trial pulse is illustrated.

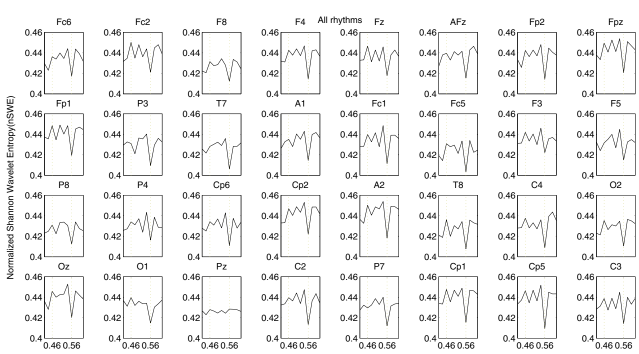

Fig. 3. Normalized Shannon Wavelet Entropy (nSWE) versus the 11 levels of the trial pulse, for each electrode.

It is observed that:

- The points at which the duration of the second pulse is equal to *460ms* and *560ms* are indicated as points of high importance. At these points a local or global minimum or maximum is presented in most of the electrodes.
- The mRWE of *delta* rhythm takes much higher values than in the other rhythms and dominates during the psychoacoustic experiment. So it is this rhythm which determines the values of nSWE.

VI. DISCUSSION

Brain potential synchrony is regarded as the leading mechanism for neuronal communication (e.g [8], [9]). EEG is regarded as reflecting the activity of ensembles of generators producing oscillations in several frequency ranges. Upon stimulation, they begin to act together in a coherent way. This transition from a disordered to an ordered state is accompanied by a resonance phenomenon and results in frequency stabilization and synchronization of the ongoing EEG activity [10]. Entropy is a thermodynamic quantity describing the amount of disorder in a system. Research has shown that decrease of entropy is correlated with response to a target stimulus (e.g [11],[12]) so that the transition between the EEG and ERP has been suggested to correspond to transition from a disordered to an ordered state.

Looking at the obtained results of the present study, an important observation concerns the points at which the duration of the second pulse is equal to *560ms* and *460ms* at which a local or a global minimum or maximum is presented in all metric indexes in most of the electrodes. Specifically, it is observed that for all electrodes nSWE has a global minimum at the level of *560ms* except for P_z. In all electrodes except for P_3, P_7, F_5, T_7 nSWE has a global or local maximum at the level of *460ms*. Thus, it is presumed that, at these points, there is a different standard of order and the acoustic information is processed and transferred by the brain in a different way. It is observed that there is an asymmetry at the distance of the position of the extrema from the reference pulse, in relation with high and low levels in trial pulse. This is in accordance with the preliminary research which showed that the subjects had higher facility comparing the two pulses when the trial pulse was shorter than the reference. Given the psychoacoustic data according to which the mean DL is $40.47ms$ with a S.D $31.79ms$ the time intervals of $40ms$ and $60ms$ are directly connected to *DL* and *DL+SD*, respectively.

Furthermore, it is observed that the mRWE of *delta* rhythm acquires much higher values than in other rhythms and dominates during the psychoacoustic experiment. This phenomenon was observed in psychophysical experiments conducted by other researchers as well (e.g [13],[14]) who suggested that this rhythm is connected with high attention and concentration, and its values increase during difficult mental work. Till recently, *delta* oscillations were supposed to dominate only in waking reptiles. However, recent evidence indicates that *delta* oscillations are also associated with evolutionary old basic processes, which in waking adults are connected with advanced processes ([15]). The role of *delta* rhythm on adults constitutes a state of the art challenge.

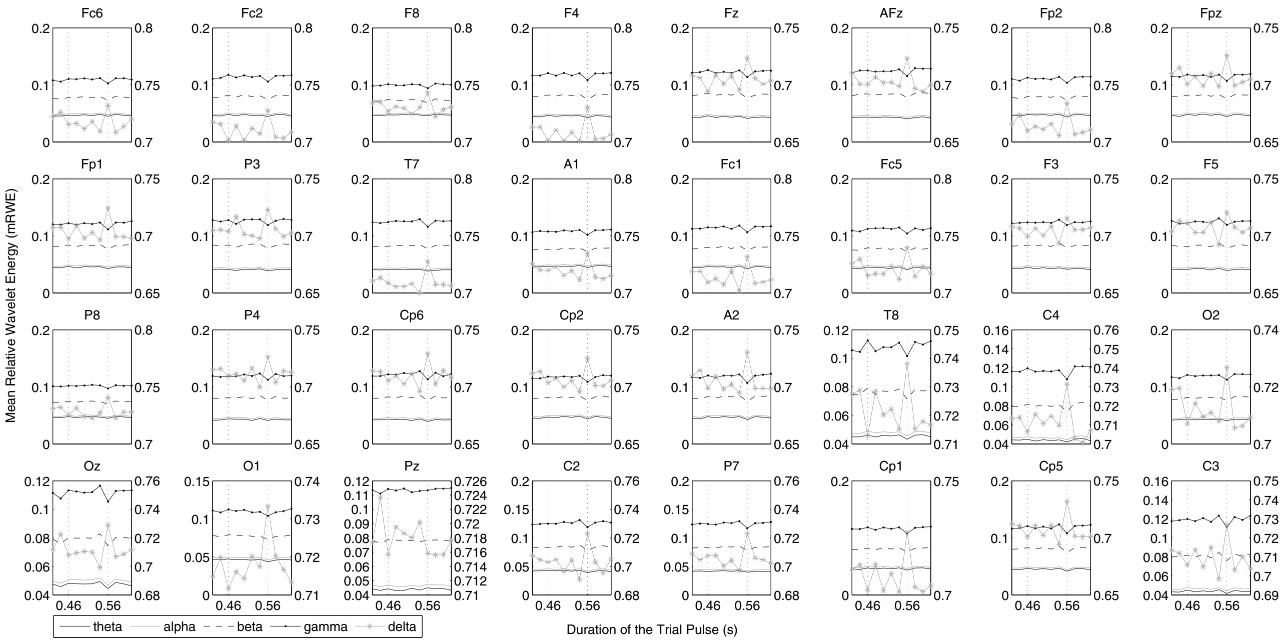

Fig. 4. Mean Relative Wavelet Energy (mRWE) versus the 11 levels of the trial pulse, for each electrode. Left y-axis scaling: γ, β, α, θ rhythms, Right y-axis scaling: δ rhythm

Finally, it is observed that the lowest values of nSWE are noted in *temporal* lobe except for two points $(460ms, 620ms)$ where the values of nSWE are still low. This indicates that this area obtains higher order due to the stimulus. Recent research (e.g[16]) supports that temporal lobe is associated with receiving and processing of the acoustic information and attention.

VII. CONCLUSIONS

The scope of the paper was the assessment of neural potentials disorder during a differential sensitivity psychoacoustic procedure. The correlation of psychoacoustic data and data obtained from the Discrete Wavelet Analysis of EEG-ERP signals, lead to the following conclusions. It is observed that local or global extrema of the *nSWE* and *mRWE* are presented at the points in which the trial pulse is *60ms* longer and *40ms* shorter than the reference. Given the mean DL (*40.47ms*) and its S.D (*31.79ms*), the mRWE and nSWE variations are highly correlated to the time Differential Limen between reference and trial pulses. Moreover, it is notable that *delta* rhythm oscillations dominate during the whole psychoacoustic procedure and the lowest values of nSWE are detected in *temporal* lobe, indicating that in this anatomical region many neurons get activated as a reaction to the auditory stimulus.

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