Continuous Wavelet Application for the Assessment of Neural Potential Interaction during Time Discrimination Task

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Abstract— **The aim of the paper is to assess the interaction of the neural potentials during a time discrimination psychoacoustic task. Ten subjects participated in the experiment and were asked about the equality of two acoustic pulses: one *reference* of 500*ms* and one *trial* that varied from 420*ms* to 620*ms*. During the experimental procedure, *Electroencephalogram* (*EEG*) and *Event Related Potential* (*ERP*) signals were recorded. The analysis combines results from Continuous Wavelet signal processing and subjects responses which were analyzed based on psychoacoustic theory. The Wavelet Coherence metric index is employed to assess the interaction of neural potentials. The results indicate the points at which the duration of the trial pulse is equal to 560*ms* and 460*ms* as the minimum and maximum of the Wavelet Coherence metric index, respectively. This observation is valid in most electrodes, for all basic EEG rhythms, revealing in parallel the differentiation of the *gamma* rhythm, in relation to the others. These maximum and minimum values are correlated to the *Just Noticeable Difference* (*JND*) in pulses duration, calculated by the psychoacoustic analysis.**

I. INTRODUCTION

Understanding the human brain is one of the greatest challenges facing the 21^{th} century science. In order to describe the assimilation of acoustic information, many studies combine *Electroencephalogram* (*EEG*) and *Event Related Potential* (*ERP*) data, recorded during psychoacoustic experiments, with corresponding results from psychoacoustic analysis of the subjects response (e.g.[1], [2], [3], [4], [5]). In these studies, the results of the psychoacoustic analysis were in some cases the criterion to confirm or reject the results obtained from the EEG-ERP signals and in some others the tool to conceptualize a specific characteristic of the brain which was analyzed in the next stage, using the recorded EEG-ERP data. However, until now, in most of the studies the results which were related to the recorded signals were obtained using observations and/or signal subtractions. The motivation behind the present study is the need of using a powerful mathematical tool, such as the wavelet transform, to mine information from the EEG-ERP signals, to compute specific parameters and then to correlate them with the corresponding parameters which are extracted using psychoacoustic analysis of the subjects responses to a predefined acoustic stimulus.

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II. METHODS

A. Experimental Procedure

During EEG-ERP signal recording, the subject participates in a psychoacoustic (i.e. the scientific study of sound perception) experimental procedure. In the experimental protocol, the method of constant stimuli ([6]) is applied to investigate the differential sensitivity of duration. The subject wears headphones to which the acoustic stimulus, developed in LabView 8.5 (National Instruments), is driven. Each subject listens to 110 iterations of a pulse sequence of stable duration (5700*ms*) which consists in four pulses: 1) *Reference* (t_{ref}: 500*ms*/1000*Hz*), 2) *Trial* (11 levels from t_{trial}: 420*ms* to 620*ms* with 20*ms* step/1000*Hz*), 3)*Trigger* (100*ms*/500*Hz*), 4)*Post-trigger* (100*ms*/500*Hz*). Between the pulses, there are intermediate intervals of silence, which vary in duration in order to maintain stable the total duration of each iteration. Each level of the trial pulse is applied 10 times, resulting to 110 iterations, in total. It is notable that the range of the trial levels is unbalanced, 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 sampling frequency is 1000*Hz*. Ten subjects participated in the experiment (5 men and 5 women, age: 31.1±4.2 years). The experimental procedure has been conducted under the principles outlined in the Helsinki Declaration of 1975, as revised in 2000. Despite the low number of subjects, the large number of iterations reassure that the data under analysis are statistically safe.

B. Psychoacoustic Data

The scope of the psychoacoustic procedure is the determination of the *Just Noticeable Difference* (*JND*) in the duration of reference and trial pulses, providing information about the *Differential Limen* (*DL*)[6]. 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?", providing a percentage of confidence. For each subject, the percentage of YES responses (y axis) is plotted versus the duration of each level of the trial pulse (x axis), resulting to the psychometric function. Then, the DL is defined as the difference in duration values that correspond to 75% and 50% (*Point of Subjective Equality-PSE*) of

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positives responses. Based on the subjects responses, the mean *DL* is calculated $40.47ms$ ($\sigma = 31.79ms$), while the *Weber fraction*= $\frac{DL}{t_{ref}}$ reaches 0.08[6]. Due to ripples of the response data, another methodology can be proposed (e.g. [8]), according to which the logistic function

$$\Psi(x) = \frac{1}{1 + exp[-(x-a)/b]} \tag{1}$$

is fitted to data, where x corresponds to t_{trial}. DL is then calculated by $b \cdot log(\frac{0.75}{0.25})$([7]), while a equals to PSE. However, this method has as prerequisite the large number of iterations for each level of trial pulse, which is usually avoided in human studies. The high standard deviation is correlated to high variation in data mainly in subjects 3, 5, 8 that makes the exponential fitting difficult. Literature calculations of DL ($32.2ms$)([8]) and Weber fraction (0.1)([9]) for time discrimination tasks verify the present findings. Indicatively, Fig. 1 shows the psychometric function and the corresponding logistic function for the subjects 3 and 7, where the (a,b) are calculated $(510, 73.36)ms$ and $(472, 27.25)ms$, respectively.

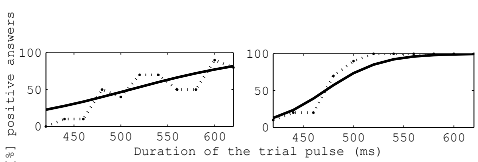

Fig. 1. Psychometric functions (dotted line) and corresponding fitted logistic functions (continuous line) for subjects 3 (high variation of experimental data, left) and 7 (smooth alternation of experimental data, right).

III. Mathematical Tool

A. Continuous Wavelet Transform

Let $x(t)$ be a continuous time signal, the *Continuous Wavelet Transform* (*CWT*) can decompose the signal into a set of finite basis functions and is defined by the integral

$$W_x(\tau, s) = \frac{1}{\sqrt{|s|}} \int x(t) \cdot \psi^*(\frac{t-\tau}{s}) \mathrm{d}t \tag{2}$$

where $\psi(t)$ is called the *mother wavelet function* and the star symbol denotes the complex conjugation. In the above definition, it is clear that the CWT of a time signal, is a function of two variables, the *scale s* and the *translation* τ, which means that it is actually the projection of the signal in a two dimensional-space. From a computational point of view, the wavelet coefficients (W_x) are obtained by the convolution of the analyzed signal with the scaled and translated version of mother wavelet function and the factor $\frac{1}{\sqrt{|s|}}$ is for energy normalization across the different scales. The *mother wavelet* which was selected for this study is the *Complex Morlet Wavelet* with $f_b = 1$ and $f_c = 1$.

B. Wavelet Coherence

Let $x(t)$, $y(t)$ be two continuous time signals with corresponding wavelet coefficients W_x and W_y. To refine the relationship between these two signals the *Wavelet Coherence* (*WCOH*) is proposed to quantify the *first-order relationship* which characterizes these signals. The Wavelet Coherence is defined as([10]):

$$WCOH(s, \tau) = \frac{S(W_{xy}(s,\tau))}{\sqrt{S(W_{xx}(s,\tau))S(W_{yy}(s,\tau))}} \tag{3}$$

where $W_{xx} = W_x \cdot W_x^*$, $W_{yy} = W_y \cdot W_y^*$ and $W_{xy} = W_x \cdot W_y^*$. This metric index ranges from 0 to 1, which means no or strong relationship, correspondingly. The analyzed signals are usually characterized by high deviation due to the presence of noise and as a result the computed wavelet coefficients also exhibit high fluctuations. The operator $S()$, is used as a smoothing operator in order to increase their stability. In this approach, a *21-point moving average time filter* has been selected to perform the required smoothing of the computed coefficients. In addition, dyadic scales were used and those corresponding to the range of physiological EEG rhythms ($0.5 - 100Hz$) were chosen for the analysis.

IV. Data Processing Procedure

In order to analyze the EEG data, a mathematical tool has been developed in MATLAB 2013a. For each iteration WCOH is computed for the range of frequencies corresponding to physiological EEG activity i.e *gamma*, *beta*, *alpha*, *theta* and *delta*. Each one of the 32 electrodes, creates 31 pairs with every other and as result a total of 31 pairs are computed from a given electrode, for each EEG rhythm. The mean WCOH was computed across the 31 pairs of each electrode, for each EEG rhythm. The analysis consists of the following steps:

- Wavelet coefficients were computed resulting in a single value of the metric index in each rhythm, for each iteration, for each electrode, for each subject. Note that the first and the last 500 wavelet coefficients are excluded from the mean calculation, in order to avoid coefficients affected by the boundary effects.
- The mean WCOH was computed across the 10 iterations of the same level of the trial pulse and the 10 subjects, for each electrode, in each rhythm.

V. Results

Fig. 2 shows the computed mean WCOH (mWCOH), for each of the 32 electrodes, for each rhythm, plotted versus the 11 different levels of the trial pulse.

- It is clear that the *gamma* rhythm has relatively the *lowest* values in the mWCOH for all the different levels of the trial pulse in all electrodes, when the *delta* rhythm has, for the same levels, the *highest* ones. It is also overt that there is a gap between the values of the *gamma* and the four other rhythms.
- The point at which the level of the *trial pulse is equal to* $560ms$, is indicated as an interesting point. In the *beta*, *alpha*, *theta* and *delta* rhythms the mWCOH, in each electrode, has a *global minimum* there. On the contrary, the pattern is not present in the graph of the *gamma* rhythm in all electrodes. In some of them, this point is only a *local minimum* while in some others it is not a minimum at all.

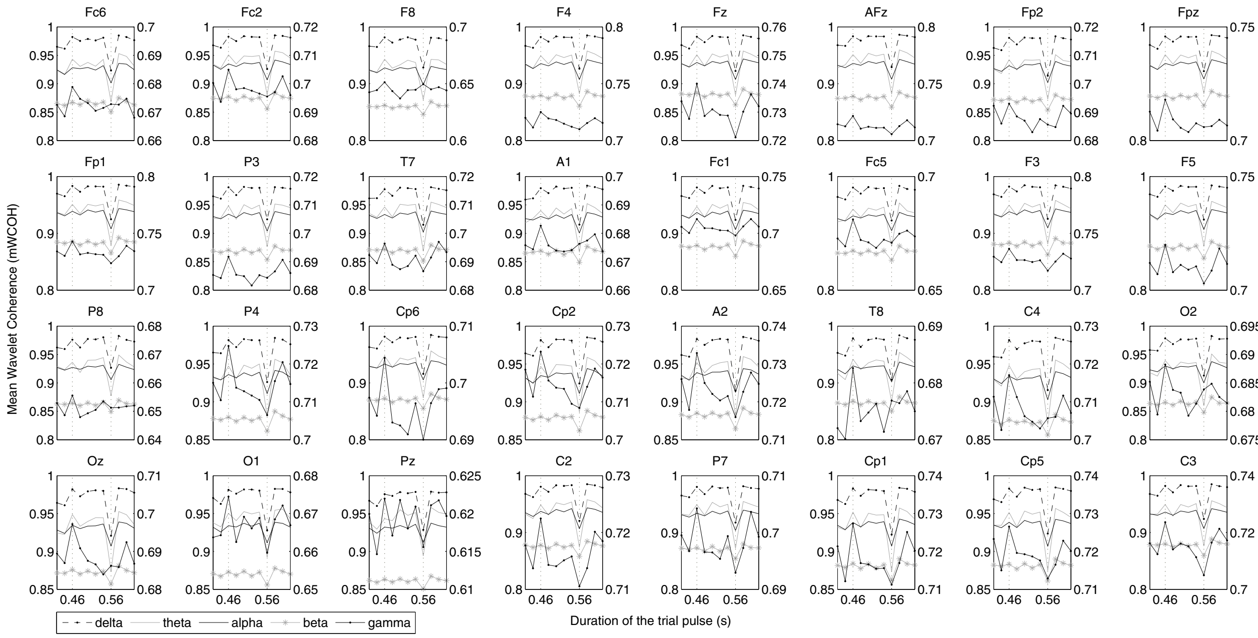

Fig. 2. Mean Wavelet Coherence (mWCOH) plot for each of the 32 electrodes. Every plot shows the mWCOH computed across the 31 pairs which the given electrode creates. Left y-axis scaling: β, α, θ, δ rhythms, Right y-axis scaling: γ rhythm.

- The point at which the *trial pulse is equal to* 460*ms*, is also an important point. At this point, in each electrode and in each rhythm the mWCOH has a *maximum*. This maximum is sharper in *delta*, *theta* and *gamma* rhythms, when in *alpha* and *beta* rhythms is not so overt and smoother. In many electrodes and in many rhythms it is actually a *global maximum* of the metric index.

Fig. 3 shows a bar graph of the mWCOH in *gamma* rhythm versus the 11 levels of the trial pulse, for different anatomical regions of the human brain. This graph is obtained after the categorization of the 32 electrodes in different anatomical regions (main lobes and regions between the main lobes) and the computation of the mWCOH across the electrodes in the same region. The graphs for the *beta*, *alpha*, *theta* and *delta* rhythm are almost the same and the illustration of all of them does not provide additional information. Indicatively, the bar graph for the *delta* rhythm is illustrated in Fig. 4.

- In the graph of the *gamma* rhythm, the values of the mWCOH are characterized by high variations which correspond to different anatomical regions. Although there are small differences in the mWCOH of the other four rhythms too, only in the *gamma* rhythm can someone draw the conclusion that there is a dependence between the anatomical region of the head where the electrode is placed and the corresponding values of the mWCOH in this region. The highest values of the mWCOH in *gamma* rhythm are observed between the Frontal Polar and the Frontal lobe, between the Central and the Parietal lobe and in the Central lobe while the lowest ones, in the Parietal lobe.

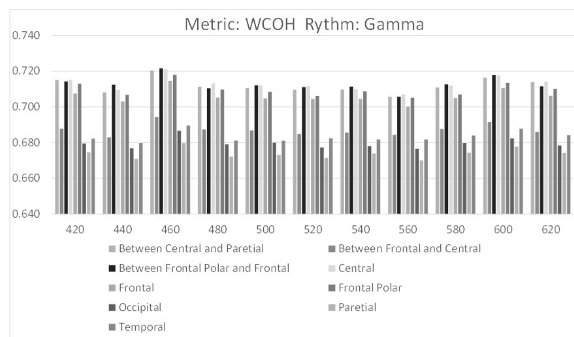

Fig. 3. Mean Wavelet Coherence (mWCOH) bar graph in *gamma* rhythm, for the different anatomical regions.

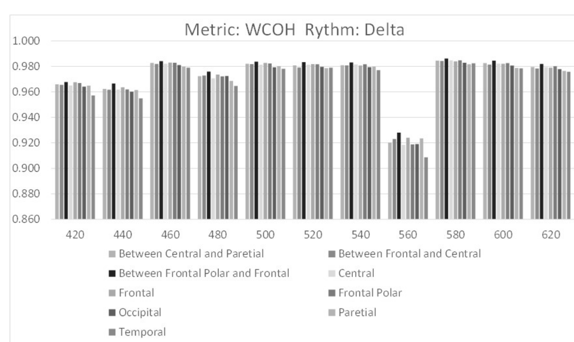

Fig. 4. Mean Wavelet Coherence (mWCOH) bar graph in *delta* rhythm, for the different anatomical regions.

VI. Discussion

In this study, the Wavelet Coherence has been used, to assess the first order time-frequency correlation of the EEG-ERP signals during a time discrimination psychoacoustic task. Neuronal activity is believed to act in a coherent way upon stimulation and wavelet transform is an efficient algorithm suitable for the trial analysis of non-stationary signals, such as EEG and ERP. Its use can reveal several stages of brain synchrony. The idea of brain potential synchrony as a leading mechanism for neuronal communications descends from some basic ideas of N.E. Vvedensky and A.A. Ukhtomsky ([11]). A.A. Ukhtomsky proposed that the EEG synchronization can reflect the functional connectivity between two or more cortical areas. The reason is that in this case signals from one neuronal oscillator repeatedly reach the other oscillator in one and the same phase of its excitation cycle. When this phase is the exaltatory one, the excitation threshold of the second oscillator is lowered, facilitating its neurons response and their recruitment in a concerted activity with the first oscillator neurons. Usually in EEG recordings the coherence is high between close electrodes and falls dramatically with the growth of interelectrode distance. If rhythmic activities dominate in EEG, the degree of cooperativity increases in a very significant way, such that coherent activity can occur over larger extents of the cortical surface ([12]) and in some cases the dependence of coherence on distance may not be gradual([13], [14]). This evidences the fact that the EEG rhythms synchronization is related to interaction of distant areas that participate in mutual functioning.

Based on the results of this study, the points at which the level of the trial pulse is equal to 560*ms* and 460*ms* are of great interest. The sharp drop (rise) of the mWOCH, indicates, a decrease (increase) in the interaction of the different neural regions. As a result, these duration levels can be considered as key drivers where the acoustic information is processed and transferred. Additionally, if the EEG and psychoacoustic data are correlated, interesting conclusions can be derived. Based on the subjects responses, the mean DL is 40.47*ms* with a standard deviation (σ) 31.79*ms*, value which is involved into the variation of the mWCOH. Given the unbalanced perception of the discrimination task between short and long durations of trial pulse, the maximum (460*ms*) and minimum (560*ms*) reference points in mWCOH variation are also unbalanced positioned (time difference compared to t_{ref} (500*ms*): 40*ms* and 60*ms*, respectively). Both time intervals are directly connected to DL and $DL+\sigma$, respectively.

The relatively low values of the Wavelet Coherence in *gamma* rhythm and the absence of the sharp and global minimum at 560*ms* in some electrodes (Fc6, F8, Fpz, P3, A1, P8, T8, C4, O2, Oz), clearly show the differentiation of this rhythm in relation to the others. All these, in conjunction with the fluctuation of mWCOH values with respect to the spatial position of the neural regions, may indicate the *gamma* rhythm as a rhythm of high importance in psychoacoustic experiments and also highlight a need for a deeper understanding of the role which this rhythm plays in the assimilation of the acoustic information.

VII. Conclusions

The aim of this paper is to assess the interaction of neural potentials during a time discrimination task, using the Continuous Wavelet Transform and then to correlate the results with the corresponding ones from the psychoacoustic analysis of the subjects response. The different way that the acoustic information is being processed and transferred in the *gamma* rhythm is reflected to the relatively low values of the Wavelet Coherence in this rhythm, to the absence of a sharp minimum at 560*ms* in some electrodes (Fc6, F8, Fpz, P3, A1, P8, T8, C4, O2, Oz) when the level of the trial pulse is 560*ms* and finally to the high fluctuation of metric index values with respect to the spatial position of the neural region. The minimum and maximum values of mWCOH can be indicative to the time Differential Limen between reference and trial pulses.

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