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A wavelet Methodology for EEG Time-frequency Analysis in a Time Discrimination Task

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Abstract. EEG signals recorded by surface electrodes placed on the scalp can be thought as non-stationary stochastic processes in both time and space, especially in response to external stimuli. Cognitive tasks, in particular, are reflected by changes in EEG dynamics concerning both rhythms energy and connectivity across different brain regions. In the frequency-domain, EEG analysis is complicated and time-frequency methodologies are needed. The Wavelet Transform, in particular, represents a powerful tool for analysing, within a time-frequency embedding, the EEG. In this study we applied a wavelet-based methodology to extract quantitative time-frequency parameters from EEG signals recorded during a time discrimination task in 12 subjects. We used a continous wavelet transform with a complex Morlet as mother function. In order to improve the time-frequency resolution and to make it satisfactory, each of the four standard EEG rhythms (i.e. theta, alpha, beta, gamma) was studied with Morlet wavelet parameters tuned ad hoc on the basis of both the width of the specific frequency band and the particular type of activity under examination. The numerical values of the estimated time-frequency indexes were then compared, evidencing statistically significant differences in the brain response between experimental conditions.

Keywords: Wavelet Transform, ERPs, time discrimination

1. Introduction

Electroencephalogram (EEG) maps the activity of brain neurons by measuring electrical potentials through the use of (several) surface electrodes (e.g. 32) suitably placed on the scalp. It is well known that EEG has a large intra-individual and inter-individual variability. In particular, the EEG spectral content, conventionally split in its five main frequency bands (i.e. delta, theta, alpha, beta, gamma), is a function of time which reflects subject condition. EEG also exhibits a high spatial variability, i.e. signal features change according to the observed brain region and, hence, to the monitored electrode [Pfurtscheller and Lopes da Silva, 1999]. As a consequence, EEG can be thought as a non-stationary stochastic process in both time and space, especially in response to external stimuli. Cognitive tasks, in particular, are reflected by changes in EEG dynamics concerning both rhythms energy and connectivity across different brain regions.

An important field of EEG research is devoted to the study of brain activities that are transient and "localized" in space and time. In particular, event-related potentials (ERPs), which represent brain responses in phase with external stimuli, are widely exploited for such a scope. Conventionally, ERP analysis is performed into the time-domain. In the frequency-domain, given signal non stationarity, the analysis is more difficult and time-frequency methodologies are needed [Brémaud, 2002]. The Wavelet Transform, in particular, represents a powerful tool for analyzing, within a time-frequency embedding, the EEG [Tallon-Baudry et al., 1996] and it is used for different purposes, such as separation of the noise from signal [Quian Quiroga and Garcia, 2003], identification of spikes and high frequency oscillations activities [Sitnikova et el., 2009; Schiff et al., 1994], compression of neuroelectric waveforms [Bertrand et al., 1994], study of brain oscillations in different type of tasks [Fründ et al., 2007]. In particular, the Continuous Wavelet Transform permits to analyze a signal at arbitrary scales, while the Discrete Wavelet Transform utilizes orthogonal wavelets at fixed frequencies, allowing the reduction of the redundancy of the so-obtained coefficients.

The aim of this work is to study EEG signals recorded in 12 participants during a time discrimination task. To our knowledge, few studies have conducted time-frequency analysis of EEG in timing tasks [Praamstra et al., 2006, Babiloni et al., 2004]. These studies have employed implicit timing paradigms, where temporally predictable and unpredictable stimuli were presented to participants, who were not aware of such a temporal mismatch. The main findings of these studies showed that alpha activity modulation was adjusted to the timing requirements of the task. In the present study an explicit time task was examined, in which participants were explicitly instructed to pay attention to stimulus duration. By using the continuous wavelet transform, we study the possible spectral changes in EEG rhythms during such a timing task. The Morlet mother function is selected. In order to improve the time-frequency resolution, each of the four standard EEG rhythms (i.e. theta, alpha, beta, gamma) was studied with wavelet parameters tuned ad hoc. The numerical values of the estimated time-frequency indexes were then compared, evidencing statistically significant differences in the brain response between different experimental conditions.

2. Material and Methods

2.1. Experimental task

The time discrimination consisted on two identical visual stimuli (a picture of 70x160 pixels) successively presented to the studied volunteers (age ranging from 21 to 27 years, 6 male) at the center of a screen. The first stimulus (hereafter the “standard stimulus”) lasted either 500, 1000 or 2000 ms; the second stimulus (hereafter the “comparison” stimulus) could have duration of the 30% shorter or longer than the standard one. Participants were required to compare the duration of the two stimuli and to determine, by pressing a button, whether the comparison one was shorter or longer than the standard. Participants performed a total of 40 trials per condition. EEG data were recorded from 32 electrodes with a sampling rate of 512 Hz.

2.2. Wavelet analysis

The chosen mother function was the continuous complex Morlet wavelet. This is a complex exponential modulated by a Gaussian function which depends on a parameter, the so-called (total) “number of oscillations”, which has to be chosen by the user. This tuneable parameter is related to the time and frequency resolutions, determined by the “standard deviations” σ_t and σ_f, respectively (Tallon-Baudry et al, 1996). In this contribution, this tuneable parameter was fixed ad hoc, for each of the four considered EEG rhythms, in order to improve the time-frequency resolution. In particular, the values of σ_t (expressed in ms) and σ_f (expressed in Hz) which resulted suited to describe temporal spectral changes related to external stimuli were: for theta band, at f=5Hz, σ_t=80 and σ_f=2; for alpha band, at f=10Hz, σ_t=72 and σ_f=2; for beta band, at f=25Hz, σ_t=48 and σ_f=3; for gamma band, at f=50Hz, σ_t=38 and σ_f=4. The wavelet coefficient at time τ and at scale a, denoted by $C(a,\tau)$, is obtained through the inner product between the signal $x(t)$ and a shifted and scaled version $\psi_{a,\tau}(t)$ of the mother wavelet $\psi(t)$. Mathematically:

$$C(a,\tau) = \left\langle x, \psi_{a,\tau} \right\rangle = \int_{\Re} x(t)\psi^{*}_{a,\tau}(t)dt \qquad (1)$$

where * represents the conjugate complex operator. Therefore, the higher is $C(a,\tau)$, the more significant is the match between the signal and the wavelet. The wavelet coefficient can be expressed as $|C(f,\tau)|$, where the frequency f is obtained from the scale variable a ($f=f_0/a$, where f_0 is the central frequency of the mother wavelet).

We considered the wavelet coefficients obtained by analyzing the evoked potential calculated via conventional averaging in each subject. The percentage change of $|C(f,\tau)|$, relative to its pre-stimulus value, was calculated. We considered as pre-stimulus interval the 500 ms immediately before the second stimulus onset and the pre-stimulus value of $|C(f,\tau)|$ was calculated, at a given frequency f, as the mean of $|C(f,\tau)|$ with τ varying in the pre-stimulus interval. These percentage values were compared by the Wilcoxon test in order to identify the time-frequency ranges in which there are significant differences ($p<0.05$) between the three stimulus durations (standard stimulus equal to 500, 1000 or

2000 ms). Average values on time-frequency intervals, whose size varied according to the EEG rhythm considered, were calculated.

3. Results and discussion

The electrodes on the median line (Cz, Fz, Fpz, Pz) and the occipital O1 and O2 were analyzed. Several variations in EEG activity were found near the second stimulus offset. Evoked EEG activity at the fronto-central electrode Cz site before the offset of the stimulus was especially examined, in this site the highest modulation in mean ERP amplitudes according to stimulus duration was found. Changes in oscillatory activity were noticed, in particular, in the beta band. Fig.1 shows the grand-average of the percentage change of $|C(f,\tau)|$ in the three stimulus durations. In the top panel the "500 ms" condition is shown, in the central panel the "1000 ms" and in the bottom panel the "2000 ms" condition. Colors toward "red" indicate an increase in the activity compared to pre-stimulus values.

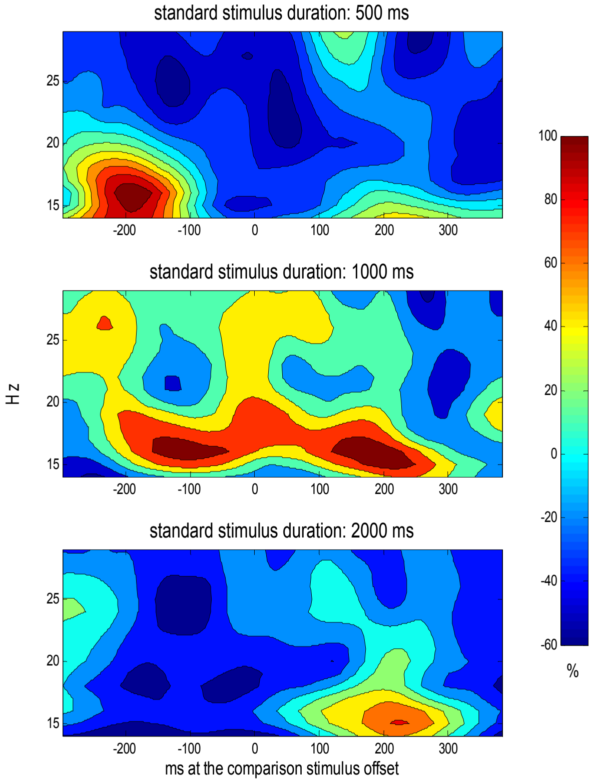

Figure 1. *Grand-average of the percentage change of $|C(f,\tau)|$ in beta band for the representative channel Cz and the standard stimulus equal to 500 ms (top panel), 1000 ms (central panel), 2000 ms (bottom panel). The zerotime is the offset of the comparison stimulus.*

Colors toward "blue" indicate a decrease in the activity. In order to make it easier, here only durations shorter than the standard are taken into account.

As one can see, the beta activity is different in the three experimental conditions, both before and after the offset of the comparison duration. In particular, the shorter is the stimulus duration, the stronger is the beta synchronization before the offset, whereas the longer is the stimulus duration the stronger is the beta synchronization after the offset. In order to have more quantitative indexes, average values of percentage change of $|C(f,\tau)|$, on time-frequency intervals varying according to the considered EEG rhythm, were computed. A maximum in beta activity is observed in the window from -200 to 0 ms relative to the offset of the comparison stimulus in 500 and 1000 ms conditions compared to 2000 ms. The Wilcoxon test revealed statistically meaningful differences in this time window between 14-20 Hz ($p<0.05$).

These results are in line with previous evidence on gamma band activity during a time discrimination task, in which durations shorter than 300 ms were used (Busch et al., 2004). In addition, we demonstrated that the adjustment in time course of beta activity starts before the end of the duration to be judged.

Variations in EEG activity were found near the second stimulus offset in other frequency bands. Interestingly, statistically significant differences were found in theta band in the electrodes Fz and Fpz after the second stimulus offset. In the 200-400 ms time interval, the “500 ms” and the “1000 ms” conditions show an increase of synchronization compared to the “2000 ms” condition. Theta responses have been associated with focused attention and working memory processes. Moreover, theta EEG frequency has been more frequently related with activations of frontal lobe networks (Jordanova et al., 2006).

4. Conclusions

In this study we applied a wavelet-based methodology to extract quantitative time-frequency parameters from EEG signals recorded during a time discrimination task. In order to improve the time-frequency resolution, each of the four standard EEG rhythms (i.e. theta, alpha, beta, gamma) was studied with wavelet parameters determined ad hoc. The numerical values of the estimated time-frequency indexes were then compared, evidencing statistically significant differences in the brain response between experimental conditions. The results suggest that by using a suitably-designed technique based on wavelet EEG analysis, it is possible to quantify differences in brain during the execution of a cognitive task that ERPs only can not provide.

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