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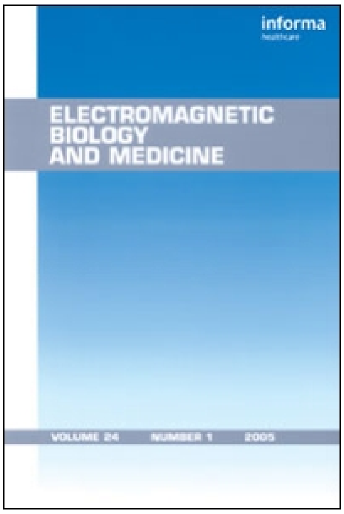

Electromagnetic Biology and Medicine
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713597249

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Online Publication Date: 01 January 2009

To cite this Article Teplan, M., Šušmakova, K., Paluš, M. and Vejmlka, M.(2009)'Phase Synchronization in Human EEG During Audio-Visual Stimulation',Electromagnetic Biology and Medicine,28:1,80 — 84

To link to this Article: DOI: 10.1080/15368370802714148

URL: http://dx.doi.org/10.1080/15368370802714148

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Electromagnetic Biology and Medicine, 28: 80–84, 2009
Copyright © Informa Healthcare USA, Inc.
ISSN 1536-8378 print/1536-8386 online
DOI: 10.1080/15368370802714148

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Phase Synchronization in Human EEG During Audio-Visual Stimulation

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Synchrony of EEG data recorded under influence of audio-visual stimulation was investigated. Instantaneous phases were derived from Wavelet transform method. Phase synchronization is assessed quantitatively via measure derived from uniformity of phase difference distribution. EEG data came from 6 healthy volunteers repeatedly exposed to 20 min AVS program with intervals with stable stimulation at 4 and 17 Hz. Phase synchronization during AVS significantly increased in comparison to non stimulation conditions in all examined cortex locations. The lowest increases in synchronization occurred in the frontal areas. In central region no dumping in synchronization was recognizable in comparison to backward locations where visual processing centers are situated.

Keywords Synchronization; EEG; Wavelet; Audio-visual stimulation.

Introduction

Synchronization phenomena play a key role in organization of biological structures. Phase synchronization is one type of cooperative behavior recently discovered between two coupled nonlinear dynamical systems (Rosenblum et al., 1996). According to coupling conditions, subsystems can be in desynchronized state, state with phase locking, or in the state of general synchronization when also amplitudes are locked. Even a very weak coupling between two chaotic systems can result in phase synchronization, while amplitudes remain uncorrelated. However, in such cases synchronization may be quite masked. Moreover, in the case of experimental data contaminated by noise it can be difficult to distinguish phase synchronized regime from asynchronous one.

Phase synchronization can be expected to occur in real biosystems at different organizational levels due to nonlinear nature of complex processes and feedback ties. State of synchronization is often advantageous for energetically optimal regime and for functioning of dynamical system it may provide stability and characteristics of integrity.

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A number of linear and nonlinear techniques for estimation of synchronization in real complex data were introduced (Paluš, 1997; Pereda et al., 2005). Successful application of related methods were in areas of epilepsy[1]onset and predictions, characteristics of cardio-respiratory data, questioning dependence of atmosphere CO2 concentration, and sun spot cycles (Quyen et al., 2001; Bartsch et al., 2007). Here we introduce one of the methods that is able to quantify a degree of phase synchrony.

The method was applied on audio-visual stimulation (AVS) data. AVS is a way of external influence of the brain by rhythmic light and sound stimuli. A rapid change in a sensory stimulus initiates a transient evoked potential. When such stimulus occurs repetitively at a rate high enough to prevent the evoked potentials from returning to a baseline state, the elicited response is developed in a form of steady-state evoked potential (EP). A distinctive feature of the visual steady-state evoked potential is occurrence of sinusoidal components at stimulus frequency and its harmonics. Mechanisms governing neuronal activity are sensitive enough to be entrained by repetitive low-amplitude EPs. Under entrainment of the brain waves this kind of resonant effect is understood. AVS primarily activates brain centers for visual and sound processing. Stimulation technique has been reported to influence sleep and learning disorders, neurological disorders, tension, anxiety, migraine headaches, etc. (Russell, 1997).

In our previous studies, we identified direct, transient, as well as long-term changes under impact of AVS. Cortex reacted by expressive increase of overall electrical activity in parieto-occipital areas during the stimulation. Intense brain wave entrainment as a direct reaction to AVS was significant through increase of spectral powers and coherences around the stimulating frequency bands in occipital areas, spreading also to central and frontal regions (Teplan et al., 2008). Long-term influence of AVS on electro-cortical activity was examined in (Teplan et al., 2006), where we have introduced several significant changes in EEG, commonly reported to be features specific to relaxation or altered states of consciousness. For example, as a result of 25 repetition of AVS training, significant power increase has been detected in the range from 4–10 Hz.

Methods

The research question was whether phase synchrony between different pairs of cortex locations during AVS changed in comparison to non stimulation conditions. Thus, we were focused on identification of synchronization phenomena under direct influence of AVS.

EEG data came from 6 healthy volunteers repeatedly exposed to 20 min AVS program with intervals with stable stimulation at 4 and 17 Hz. Visual stimulation was realized by glasses with red light-emitting diodes in a form of rectangular pulses with a number of switches determining the stimulation frequency. Sound beats of a particular frequency were produced by headphones from three sine-wave pulses with close frequencies around 280 Hz. EEG data of relaxed wakefulness were recorded from 6 scalp locations (both left and right frontal, central and occipital) prior and during AVS.

Below, a recent method for identification of phase synchronization between two complex biophysical time series is introduced. Here, one looks for phase locking in the simplest form when preservation of constant difference between phases of two signals is under consideration.

In the first step, instantaneous phases are derived from Wavelet transform method (Lachaux et al., 1999). Complex wavelet transform of EEG signal was applied with several relevant parameters: Morlet wavelet type, its length (8192 data points) which is interconnected with frequency width of Morlet wave derived from its Fourier transform (0.15 Hz was chosen as spectral peak in EEG due to AVS was safely comprised in such interval width). The transform is realized by convolution of EEG with chosen wavelet. Then instantaneous phases were derived by taking angular component of the complex factors. Afterwards, phase differences from 2 EEG signals in "unwrapped" mode were constructed (Figure 1). By this one is able to track the evolving phase dependence, determining periods with temporarily increased synchronization for just a few seconds. The periods where the phase differences are relatively stable (more less constant) are the most appropriate candidates for synchronized episodes.

The phase differences are then "wrapped" into (0, 2π) interval. For asynchronous signals, statistically, histograms of the phase difference values from certain time window form on this interval distribution similar to uniform one, while for synchronous it's different. From several indexes introduced for evaluation of irregularity of the distribution we used mean phase coherence (MPC). MPC acquires values between 0 (uniform) and 1 (fully concentrated) and reflects how the relative phase is distributed over the unit circle (Pereda et al., 2005).

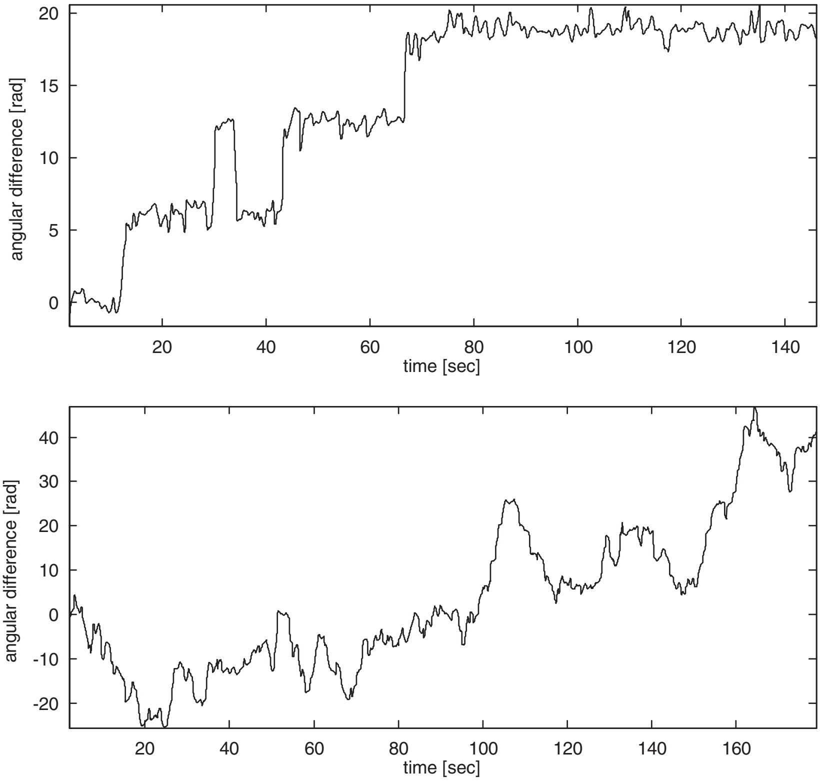

Figure 1. Examples of phase difference in unwrapped mode. Upper: during stimulation, lower: before stimulation. While flat regions represent synchronized periods, slopy intervals mark phase slips.

Change in synchronization during stimulation in respect to conditions prior to stimulation was analyzed in 40 EEG paired records. For each EEG time series mean from MPC obtained from consecutive time windows was derived. Nonparametric Wilcoxon paired test was applied to test whether values of such synchronization measure were significantly different under two different conditions.

Results

In most of the single records phases, synchronization during AVS increased in terms of MPC measure in comparison to non stimulation conditions. Wilcoxon test revealed synchrony changes in all six cortex location and both stimulation frequencies as significant. The highest *p*-value, but still very significant ($p < 10^{-4}$), resulted for frontal F3C3–F4C4 connections. Figure 2 presents differences in medians derived from the both conditions. According to expectation, the lowest increases in synchronization occurred in frontal areas as they are situated further apart from visual and sound processing centers. Interestingly, synchronization dumping is not much recognizable in central region (C3P3–C4P4) in comparison to backward P3O1–P4O2 locations.

In conclusion, introduced approach was demonstrated to be usefull in determining phase synchrony level of EEG signals. In the case of audio-visual stimulation we were able to determine regions with different synchronization relations. Functionality of the whole cortex may be affected by AVS, not only the area around primary sensorial

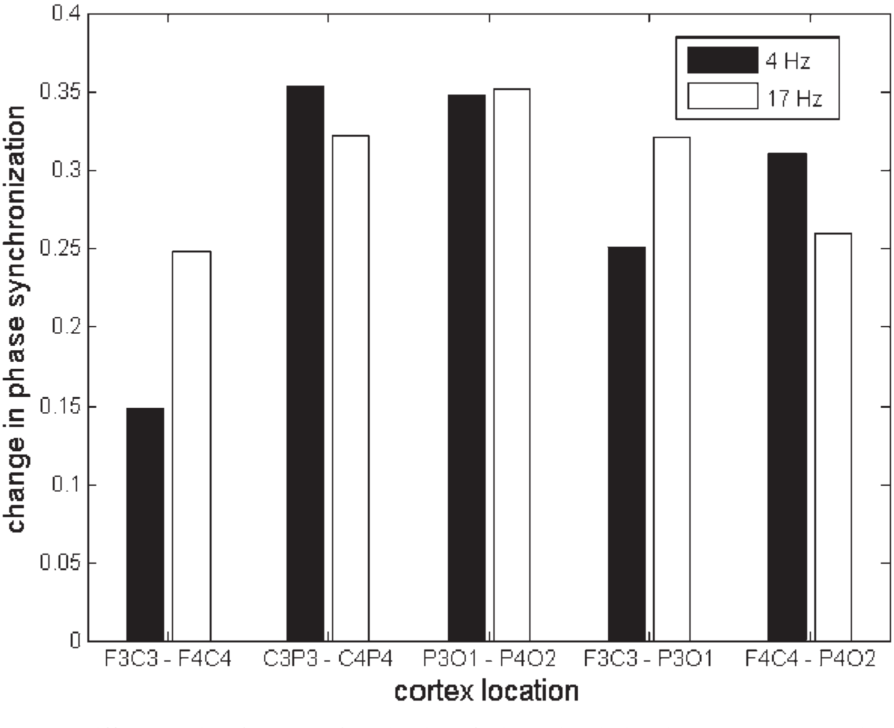

Figure 2. Differences in phase synchronization during stimulation in respect to nonstimulation conditions: Differences of medians of MPC measure evaluating mutual dependence of the phases. Higher values mean stronger increase of synchronization during the stimulation.

centers. Further analysis will focus on computing directionality index that is capable of estimating direction of the information flow.

Acknowledgments

This work was supported by Slovak APVV grant No RPEU-0008-06 and by Bilateral project between Slovak Academy of Sciences and Academy of Sciences of the Czech Republic "Modern methods for evaluation of electrophysiological signals."

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