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Topographic distribution of EEG alpha attractor correlation dimension values in wake and drowsy states in humans

Aleksandar Kalauzi [a,*], Aleksandra Vuckovic [b], Tijana Bojić [c]

[a] Department for Life Sciences, Institute for Multidisciplinary Research, University of Belgrade, KnezaVišeslava 1, 11000 Belgrade, Serbia
[b] Center for Rehabilitation Engineering, University of Glasgow, James Watt (South) Building, (Rm605), G128QQ Glasgow, UK
[c] Laboratory for Radiobiology and Molecular Genetics — Laboratory 080, Vinča Institute of Nuclear Sciences, University of Belgrade, 11001 Belgrade, p.fah 522, Serbia

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ABSTRACT

Organization of resting state cortical networks is of fundamental importance for the phenomenon of awareness, which is altered in the first part of hypnagogic period (Hori stages 1–4). Our aim was to investigate the change in brain topography pattern of EEG alpha attractor correlation dimension (*CD*) in the period of transition from Hori stage 1 to 4. EEG of ten healthy adult individuals was recorded in the wake and drowsy states, using a 14 channel average reference montage, from which 91 bipolar channels were derived and filtered in the wider alpha (6–14 Hz) range. Sixty 1 s long epochs of each state and individual were subjected to *CD* calculation according to the Grassberger–Procaccia method. For such a collection of signals, two embedding dimensions, $d = \{5, 10\}$, and 22 time delays $\tau = 2$–23 samples were explored. Optimal values were $d = 10$ and $\tau = 18$, where both saturation and second zero crossing of the autocorrelation function occurred. Bipolar channel *CD* underwent a significant decrease during the transition and showed a positive linear correlation with electrode distance, stronger in the wake individuals. Topographic distribution of bipolar channels with above median *CD* changed from longitudinal anterior–posterior pattern (awake) to a more diagonal pattern, with localization in posterior regions (drowsiness). Our data are in line with the literature reporting functional segregation of neuronal assemblies in anterior and posterior regions during this transition. Our results should contribute to understanding of complex reorganization of the cortical part of alpha generators during the wake/drowsy transition.

1. Introduction

Significance of the resting state functional networks on modulation of behavior is strongly supported by well structured functional organization of these networks (Fox et al., 2005; Laufs et al., 2006; Boly et al., 2007; Spoormaker et al., 2012).

Fundamental principles of metabolic coupling between different brain areas were studied by neuroimaging techniques, like PET (Maquet, 2000), BOLD fMRI (Goldman et al., 2002; Laufs et al., 2003a, b, 2006), NIRS (Sasai et al., 2012) and SPECT (Melie-Garcia et al., 2013) providing compatible data on brain topography of resting state networks. In the absence of any task (so-called "conscious resting state" of the brain) two networks could be differentiated: a group of posterior cingulate cortex, medial and lateral parietal and medial prefrontal cortices — "default mode network" vs. a group of frontal and parietal cortical regions — "anticorrelated network" (Raichle et al., 2001; Fox et al., 2005; Fransson, 2005; Spoormaker et al., 2012). They are very similar to self- and external awareness networks and show a pattern of anticorrelated competitive activity (BOLD signal analysis, slow frequencies below 0.1 Hz; Fox et al., 2005; Boly et al., 2007).

Temporal dynamics of an ongoing "stream of consciousness" (considered to be up to 500 ms; Libet, 2006) is much faster than the time resolution of BOLD and for that reason the EEG evaluation of resting brain network is more appropriate, in spite of its low space resolution.

Few studies correlated EEG and neuroimaging techniques (fMRI) to characterize the brain activity fluctuations in the wake resting state (Laufs et al., 2003a,b, 2006; Horovitz et al., 2008; O'Gorman et al., 2013). They found different dynamics (Laufs et al., 2006) but good topographical correspondence between fMRI and EEG registered resting state networks. Alpha activity, in terms of the Berger rhythm (Berger, 1929) was shown to be negatively correlated with cortical metabolic activity and consequently proposed as neural baseline of "inattention" (Goldman et al., 2002; Laufs et al., 2003a; Horovitz et al., 2008; O'Gorman et al., 2013).

Default mode network, defined originally as the network with the task-negative activity pattern (Fox et al., 2005; Spoormaker et al., 2012), was recently associated with internal awareness (introspection, self oriented process), while disengaged during external awareness (external monitoring, external stimuli perception, stimulus detection; Boly et al., 2007, 2008). These mutually competitive phenomena are

* Corresponding author. Tel.: +381 11 20 78 465; fax: +381 11 30 55 289.
E-mail addresses: kalauzi@ibiss.bg.ac.rs, kalauzi@imsi.rs (A. Kalauzi), aleksandra.vuckovic@glasgow.ac.uk (A. Vuckovic), tijanabojic@vinca.rs (T. Bojić).

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specifically associated to the first stages of hypnagogic period, Hori's stages 1 to 4 (Hori et al., 1994): decay of alertness, decrease of the level of attention (Ogilvie et al., 1991; Harsh et al., 1994), decrease of vigilance and sensory signal detection (Ogilvie and Wilkinson, 1984; Naatanen and Picton, 1987; Ogilvie et al., 1991) and dream like mentation (Nielsen et al., 2005). For that reason this period deserves special scientific focus.

Having hypothesized that the topographic distribution of complexity of alpha generators is essentially important for the modulation of awareness, the aim of our investigation was to study them in the wake resting state of the brain and drowsiness. In order to do that we examined the change in topography of alpha attractor correlation dimension (*CD*) in relaxed wakefulness (Hori stage 1) and drowsiness (Hori stage 4).

We based our analysis on constructing trajectories of these two states in the phase space. Dimensionality of their strange attractors was considered as a measure of the system complexity. The delay-time embedding scheme proved as a powerful method to reconstruct the phase space dynamics (e.g. Takens, 1981). Among different algorithms developed for one-dimensional signals (Farmer et al., 1983; Broomhead and King, 1986; Pradhan et al., 1995), the one most commonly used was designed by Grassberger and Procaccia (1983). This algorithm is applied only on one time series at a time. Critical parameters for estimating the EEG attractor *CD* are the embedding dimension d and time delay τ (Theiler, 1990; Liebert et al., 1991). Once determined, they can be used for numerical estimation of the correlation dimension which is a measure of actual attractor's fractal dimension. Existing literature provide recommendation of these two parameters for analysis of a single time series (Theiler, 1990). The embedding dimension d should be chosen so that $d > 2D + 1$, where D stands for the supposed but unknown attractor fractal dimension and d should be large enough so that a plateau of d vs. D can be reached, while time delay should be chosen to match the first zero-crossing of the autocorrelation function (ACF) (Frank et al., 1990; Pritchard and Duke, 1995), although other criteria exist as well.

In this paper, we propose a modified criterion, adapted for the collection of mutually related signals, which takes into account their collective characteristics, such as subtle regularities in topographic distributions of EEG signals.

Beside a relative abundance of studies dealing with task-related measurements of *CD* of human EEG signals (Lutzenberger et al., 1992; Lamberts et al., 2000; Hashimoto et al., 2002; Stam et al., 2002; Stam and van Dijk, 2002; Stam, 2003), there is a lack of systematic analyses of their values depending on topographic position of scalp electrodes, particularly in case of monopolar and bipolar EEG registration in different brain states. This issue is not trivial, since in case of bipolar EEG montage, if a statistically significant dependence of bipolar *CD* values could be linked with electrode distances, this would point to the fact that attractor *CD* is linked with complexity of the neural circuitry generating the signal (Tononi et al., 1998). We wanted to test whether, in case of multichannel recordings covering the whole cortex, resulting complexity of different alpha generators, regardless of their cortical positions, recorded between electrodes of a bipolar EEG channel, will be positively correlated with the electrode distance. In case that such positive correlation exists, the next step would be to test if it is invariant or dependent on the brain state, such as e.g. wake and drowsy (Bojić et al., 2010; Kalauzi et al., 2012). Consequently, by mapping topographic distribution of bipolar channels with above/below median *CD* values, in each of these two brain states, a new information about brain areas that exhibit a resulting more (or less) complex alpha activity could be extracted. Existence of nonlinear mechanisms underlying the recorded alpha activity was demonstrated by testing differences in *CD* probability density distributions between original signals and surrogates generated with Iterative amplitude adjusted Fourier transform (IAAFT) algorithm (e.g. Theiler et al., 1992; Schreiber and Schmitz, 2000). Further, in order to test stability of the results within the 60 s signal duration, we split the whole signal into two equal halves, each containing 30 randomly selected epochs. Random choice was different for each individual. Following identical procedures as for the whole signal, we constructed topographic distributions of channel pairs with above/below median *CD* values and demonstrated that they did not differ significantly between each half as well as from the whole signal. We also aimed to study the effectivity of using short 1 s epochs for *CD* calculation.

2. Material and methods

2.1. Subjects and data preparation

The EEG signals analyzed in this work were originally recorded for the purpose of our previously published study on automatic classification of wake and drowsy states (Vuckovic et al., 2002). All measurements were done in accordance with the medical ethical standards after the subjects signed the informed consent form approved by the local ethical committee. Ten healthy adult human subjects (seven male, three female), aged 25–35 (mean 28) years, of normal intelligence and without mental disorders were recorded after passing a neurological screening. The subjects were positioned to lie in a dark room with their eyes closed (standard eyes closed no-task condition; Stam et al., 2002; Stam and van Dijk, 2002; Stam, 2003). A neurologist was engaged to monitor their state of alertness and prevent them to fall asleep beyond S1 of non-REM sleep.

The individuals were not previously subjected to any sleep deprivation or deviation from their circadian cycles and have not been taking any medicine. EEG electrodes were positioned at 14 locations (F7, F8, T3, T4, T5, T6, F3, F4, C3, C4, P3, P4, O1 and O2) according to the International 10–20 System with an average reference. Signals were sampled at a rate of 256 samples/s, band pass filtered between 0.5 and 70 Hz (with a software 50 Hz notch) and artifacts were removed manually based on a visual inspection. Other details about data collection and preparation can be found in Vuckovic et al. (2002). Signals from all individuals were classified into wake and drowsy periods independently by two neurologists. Only those signal sequences for which both experts agreed as being either clearly awake or drowsy were used in the study (60 s for each state and each subject).

2.2. Data analysis

Based on our previous results, specifically profiles of FFT amplitude spectra of the analyzed signals, we applied off-line band pass filtering (4th order Chebyshev filter) on all EEG signals in the range 6–14 Hz. This wider alpha range was chosen to incorporate small differences in carrier alpha frequency that exist between individuals (Bojić et al., 2010; Kalauzi et al., 2012).

EEG attractor correlation dimension of one-dimensional time series was based on Albano et al. (1988) algorithm that is a modification of the original Grassberger and Procaccia method (Grassberger and Procaccia, 1983). It was implemented in MATLAB 6 “Chaotic System Toolbox” using a freeware *.m file “gencorint.m” downloaded from the corresponding MathWorks web site (listed in the references).

Although they were recorded as monopolar, we analyzed only bipolar EEG signals, due to volume conductance issues (Nolte et al., 2004; Srinivasan et al., 2007; Tenke and Kayser, 2012). However, additional monopolar analyses were performed to test volume conduction on *CD* calculations.

All statistical tests were performed using IBM SPSS, Version 20.0.

2.3. Analysis of bipolar EEG derivations

When analyzing signals recorded with a monopolar montage, entire ensemble consisted of 280 recordings (10 individuals × 14 electrodes × 2 states), each 60 s long. Each recording was obtained by concatenating sixty one second epochs, previously classified as wake or drowsy

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