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Intra and inter-individual variability in the chaotic component and functional connectivity of the EEG signal in basal eyes closed condition

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Abstract

Individuality has to do with our differences and similitudes, our phenotype and genotype characteristics that make us unique in some ways, and common in others. In this study we applied linear and non-linear quantitative description of the EEG signal of 8 subjects in closed eyes, basal conditions, three times at a day (at 10:00, 13:00, and 16:00 hrs. UTC -04:00 Santiago), to provide evidence that allows us to narrow the boundaries of intra and inter-individual differences in the behavior of the oscillatory electrical signal of the brain. We applied two versions of Hurst exponent estimator of persistence/anti-persistence of the brain signal, and a Spearman R inter-correlation analysis between pairs of EEG channels to quantify and allocate the magnitude of highly correlated pairs of electrodes as an indicator of enhanced brain synchrony. Results showed differences and patterns in laterality/symmetry associated with magnitude, self-organized long-memory processes; and brain synchrony.

Keywords: Individual differences; Basal; Closed eyes; EEG; Hurst, R Spearman correlation; Brain Synchrony; Connectivity modes.

1. Introduction

Intra and inter-individual differences are important because they set the boundaries for the similarity and individuality of people. A good individualizer exists when there is high inter-individual variation, and low intra-individual differences, in such a manner that the marker is highly similar to himself and highly different from their partners in the surroundings.

When comparing and classifying individuals, it is necessary first to have an idea of the natural unevenness of the variables chosen to be classifiers. To see how precise or fuzzy are the boundaries that arbitrary separate the limits of pre-defined categories.

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For a control group, variables need to be very similar to themselves and homogeneously enough with respect to a population average.

But, what happens when the control group is the same that the experimental, but in two different instants, pre- and post-experiment? This is a very common state of things when studying the human brain. The conditions pre- and post-experiment are the control variables state to quantify changes associated with the experiments.

Basal closed eyes (CE) condition is one of the standardized control brain reference used to compare and evaluate the effect of any change caused or correlated with an independent variable of interest.

In this paper we evaluate the stability of the quasi-chaotic EEG signal content, in 8 subjects, during three events of electroencephalographic recording during the same day, am (10:00); noon (13:00); and pm (16:00).

1.1. Chaotic component of the EEG signal

Many natural phenomena occur under the influence of the 1/*f* law which states that in nature things happens in such a way that big, high amplitude and disruptive events occur at a much lower frequency than those more frequent, small, low amplitude, and normally neglected incidents [1]. The EEG signal is one of those natural phenomena that follow this tendency, falling in the category of a quasi-chaotic signal with boundaries between total randomness (white noise), and statistical random noise (brown noise).

While white noise has a flat, equal representation of energy along with the axis of the frequency, brown noise has a slightly 1/*f* statistical tendency to break down this flat representation of energy along with the domain of frequency of the events.

In between white and brown noise, there is a colored noise area termed pink noise (or fractal noise), which is a phase state of strong 1/*f* influence which generates emergent complexity that can generate spontaneous, persistent, self-organized, self-similar, long memory, constructive or destructive processes, that sub-surface and roots the manifested phenomena.

The brain quasi-chaotic EEG dynamics moves permanently flanked by these two unpredictable boundaries in such a way that between brown and white noise, the system tend to keep in anti-persistence, having short memory processing, and remaining relatively stable around certain central average attractor value. The closer this value be to the border with chaos, the more the probability for emergence of complex dynamics, capable to exceed the limits of anti-persistence and engage in constructive, or destructive, persistent, long memory and self-similar processes.

1.2. The Hurst Exponent

The Hurst exponent is a non-linear statistic designed to evaluate the degree of persistence or anti-persistence of a time series based on its internal self-similarity, evaluated and compared at different scales. Edwin Hurst (1951) developed this method while trying to decide where to install water reservoirs along with the Nile River course, according to with the unpredictable variations of rains and droughts and the places that were more affected by this dynamics [2].

The Hurst Exponent varies between 0 and 1, being 0 equals to total unpredictability, or chaos (or white noise), and 1 equal to the total order. At H value = 0.5, the Hurst Exponent indicates a brown noise dynamics, and between the boundaries of white and brown noise, the phase state of fractal noise, who moves in the border of two natural attractor chaos. Its range in H values is $0.15\text{-}0.20 < H < 0.45$ [3].

When $H > 0.5$, it is called the "Hurst effect" that consists in the generation of persistent, self-similar, follow-a-tendency dynamics, which moves between the upper border of brown noise ($H > 0.55$) and the total order ($H=1$).

1.3. The chaotic frequency band components of the EEG signal

Classic EEG frequency bands: Delta (0.1-4 Hz); Theta (4-8 Hz); Alpha (8-12 Hz); Beta (12-30 Hz); and Gamma (> 30 Hz), are the frequency components of the raw electrical signal recorded from the scalp through an electroencephalograph. The extent of the gamma frequency components in the original signal depends on the sampling frequency used to record the data. With a sampling frequency of 128 Hz, the maximal resolution, according to Nyquist theorem, to avoid the aliasing of the signal, is half of the sampling frequency. That is, for a 128 Hz sample rate, from 0.1 to a maximum of 64 Hz, with a Gamma frequency range of 31-64 Hz [4].

By mean of FFT process, the original signal is decomposed in these five EEG frequency bands which participate in many brain/mind processes, ranging from relatively simple, short, motor, stimulus-response or evoked potential protocols, to more mid-long lasting mind, cognitive, and behavior paradigms [5-7].

In spite of that, all EEG bands are present during the day/night cycle, it is the amplitude and recurrence of each of them that varies. Delta waves are abundant and predominate during sleep, Theta waves are implied in many and varied processes [8] from simple motor reflexes, to elaborated searching cognitive maps in behavioral contexts. Alpha waves are known to be the first brain wave described by Hans Berger (1929), the inventor of the EEG [9], and is detected as a spontaneous synchronization of brain waves of the occipital region when they are released from its task of visual-perceptual-cognitive processing. In the EEG of a healthy person, alpha waves arise in the occipital channels when they keep quiet, in a resting awake state, with the eyes closed. Beta wave is predominant in our actual normal standard conscious daily state of awareness [10] in which we perform the majority of our neuro-behavioral thoughts and acts. Gamma wave is the band that includes the highest frequency oscillation of the brain, and depending on the sample rate can be explored with a time resolution of 500 Hz or more. It is the less known band of the EEG frequency spectrum and it is usually associated with brain/mind states of profound introspection, as in meditation, in close relationship and connection and a sense of insightful communication [11].

1.4. Inter-correlation analysis and brain interconnectivity network modes

Spontaneous synchronization occurs in multi-oscillatory systems when large ensembles of unitary oscillators start to oscillate at a similar frequency. The temporal coincidence of its oscillatory patterns makes them progressively summed up to a maximal amplitude that depends on the number of oscillators, around the same pacemaker.

Synchronization is a natural attractor to a state of being together summing up energy. Total anti-synchrony implies the contrary, the total annihilation of the spreading energy because of the anti-phase of waves with equal frequency. The former condition implies a state of a majority doing something similar at the same rate, while the latter moves towards a spectrum of progressively less synchronization caused by the disassembly of major oscillatory groups towards more localized energy allocation on focal processes.

Pearson correlation coefficient measures the degree of association between two continuous variables, in this case, a pair of selected electrodes measuring the oscillatory EEG activity at both hemispheres of the brain, at AF3-AF4; T7-T8; and O1-O2, frontal, temporal and occipital regions, respectively.

The resulted 7x7 matrix of Pearson´s R values between all possible combinations of pairs of 14 electrodes, give us three modes of connectivity: i) 21 possible paired electrodes interconnections inside the left hemisphere of the brain (LH); b) 49 possible paired electrodes interconnections between left and right (inter) hemispheres (IH); and c) 21 possible paired electrodes interconnections inside the right hemisphere of the brain (RH).

It is possible to search similitudes and differences in these three confined modes of interconnectivity, in terms of the spatial network map that emerges; the nature of the channels constituents of this map; the specific pattern of interconnectivity of the map; and the magnitude and spatial distribution of the synchrony/asynchrony/anti-synchrony of the electrodes' EEG signal involved.

1.5. The chaos of the signal and the chaos of the chaos

In the first instance, the Hurst exponent evaluates the degree of self-similarity and persistency of a time series. We tested several timeframes for our measurements and defined [12] three ways to take the Hurst exponent; the first one takes the Hurst exponent as usual, taking all the data of the time series. In a standard recording, 2 minutes of EEG data, captured at 128 Hz sample rate, give us 15,360 data points where to estimate the Hurst exponent. This is our first, standard, Hurst exponent value (H). The second Hurst estimation considers a timeframe of 1 second as a standard time window where to estimate the minimal Hurst exponent, as a "preset-moment" time window. This second Hurst estimation for the 2 minutes of EEG recording, is the average of 120 1s-estimated standard Hurst exponent. This second Hurst value, being an average is represented as μ-Hurst. Both ways to calculate Hurst concern directly to the original data values, the only difference is the timeframe window used to estimate it.

When the 120 1s-Hurst values are plotted in time, what appears is a chaos oscillation, a range of successive variable Hurst exponent values, each one representing the degree of self-similarity and persistency estimated for each second of EEG data. We proceed with this new chaos oscillation time series as a new source of information about the course of stability/instability of the chaos itself. We termed this new Hurst exponent estimation, that doesn't have to do with the data, but with the chaotic dynamic of process involved, meta-Hurst or HH for short [12-14].

2. Methods

2.1. Subjects

Eight (N=8) healthy students of physical education between 18-25 years old, accepted to participate in this pilot exploration protocol consisting in to measure a basal, eyes closed, EEG sample recording, during the same day, every three hours, at AM (10:00); NOON (13:00); and PM (16:00) UTC-04:00 Santiago, Chile.

Participants were comfortably sat in a chair and were asked to keep awake, quiet, in a resting-relaxed attitude, during three minutes of EEG recording. Conditions and protocol were repeated the three requested times.

2.2. Data

Data collected from subjects consisted in a total of three trials of three minutes each, of 14 channels EEG recording by subject. Data were frequency band filtered and pre-processed by visual inspection and artefactual component cleaning with automatic detection and assisted rejection (ADJUST, SASICA, MARA), using EEGLAB toolbox on MatLab 2008A.

After inspection and artifact removal, we obtained 2 minutes of clean EEG data in basal closed eyes condition, for each participant and recording session.

Fast Fourier Transform (FFT) filtered bands gave as five EEG time series (delta, theta, alpha, beta, and gamma), of two minutes length, where to evaluate the stability of the chaotic component of the EEG signal from the brain when it is requested to perform the simple activity (basal conditions, closed eyes state, for three minutes, in the same place), but in three different moments of the day.

EEG data was captured using Emotiv Epoc® Research Edition, at 128 Hz sampling rate, for 14 EEG locations (AF3-AF4; F7-F8; F3-F4; FC5-FC6; T7-T8; P7-P8; O1-O2), according to the 10/20 international system, and referenced to mastoid bones. We evaluated three out of the seven pairs of electrodes: AF3-AF4, for brain frontal section; T7-T8, for the temporal region; and O1-O2, for the occipital area.

2.3. Analysis

Each frequency band, for each individual, and for the three instances of EEG basal recording, were evaluated using the re-scaled (R/S) analysis to obtain the Hurst exponent (H) out of the EEG signal. The Hurst exponent is an estimator of the balance between chaos and order of a time series composed by the electrical oscillatory signal produced by the brain, whose frequency constituents are separated in each of its EEG bands by mean of FFT.

For the total two minutes of the EEG time series data we performed 120 Hurst calculations, 1 for each second (128 data points) of EEG recording. This time scale gives us an averaged H (μ-Hurst) obtained from 120 H values coming from 1-second length data sample each.

We compared and tested statistically the differences found between these μ-Hurst values estimated for each EEG band, for each participant, and for each recording session to evaluate the degree of intra- and inter-individual differences according to those parameters. An expression that give us an Index of Identity (I_i) for individual recognition. This I_i index is expressed as the ratio $CV_{between}$ / CV_{intra} (mean) [15]. With coefficient of variation CV = 100 (1 + 1/4N) x (SD / X mean) [16].

We estimated the degree of persistence/anti-persistence of the chaotic oscillation in time and its symmetric/asymmetric configuration and magnitude distribution in the whole brain and the three connectivity modes intra-left hemisphere (LH); inter-hemispheric (IH); and intra-right hemisphere (RH).

The analysis, and subsequent interpretation of results, considers the fact that the basal recording closed eyes condition is the best circumstance the brain have to relax, and avoid any disrupting feeling or thoughts. Participants are asked to remain quiet, relaxed, in present-awake state, free of anxiety or worries, with eyes closed, during three minutes. In this condition, if it is fulfilled, we expect that the natural tendency (a chaotic natural attractor) progressively drives the brain dynamic to a maximal possible synchronicity, allowed by the fact of asking to the brain to be, as far it can be, from any preoccupation and to remain in this calm, awake, in a free running basal state for at least three minutes of EEG recording.

Under this conditions we expect to find maximal generalized brain synchronicity (high inter-channel correlations) in the brain of those participants that could follow the instructions by mean of acceptably disposing its brain's ongoing processing under the requested state of awaked calm for three minutes. We also expect less degree of generalized synchronicity in the brains of those participants that cannot reach the mind/brain state requested, by mean of avoiding the natural attractor tendency of an oscillatory system to rise synchronicity when released from not natural, self-generated attractors that keep away the system from more chaotic and naturally-driven free running state, manifesting less synchronized inter-correlations in the brain.

3. Results

Figure 1 shows an example of participants # 7 (Left), and 8 (Right). Graphs show the averaged 1-s, μ-Hurst, estimated for the EEG selected channels frontal AF3 and AF4, temporal T7 and T8, and occipital O1 and O2. Significant statistical differences are marked with asterisk at $\alpha = 0.05$ confidence level. Inter and intra-individual differences are evident among and between participants. In spite of the statistical differences found among subjects in the three EEG recording events (AM, NOON, and PM), these differences are significant when the μ-Hurst average values apart each other having around a 5% of difference (i.e. a 0.05 difference in the Hurst exponent range), which is similar to the range of natural uncertainty shadow of instability around the border of chaos state.

The chaos oscillation of the gamma band was the most heterogeneous and variable in all participants. Theta band consistently felt slightly above H = 0.5, in the phase space favored with the Hurts effect towards persistence and long-memory processes.

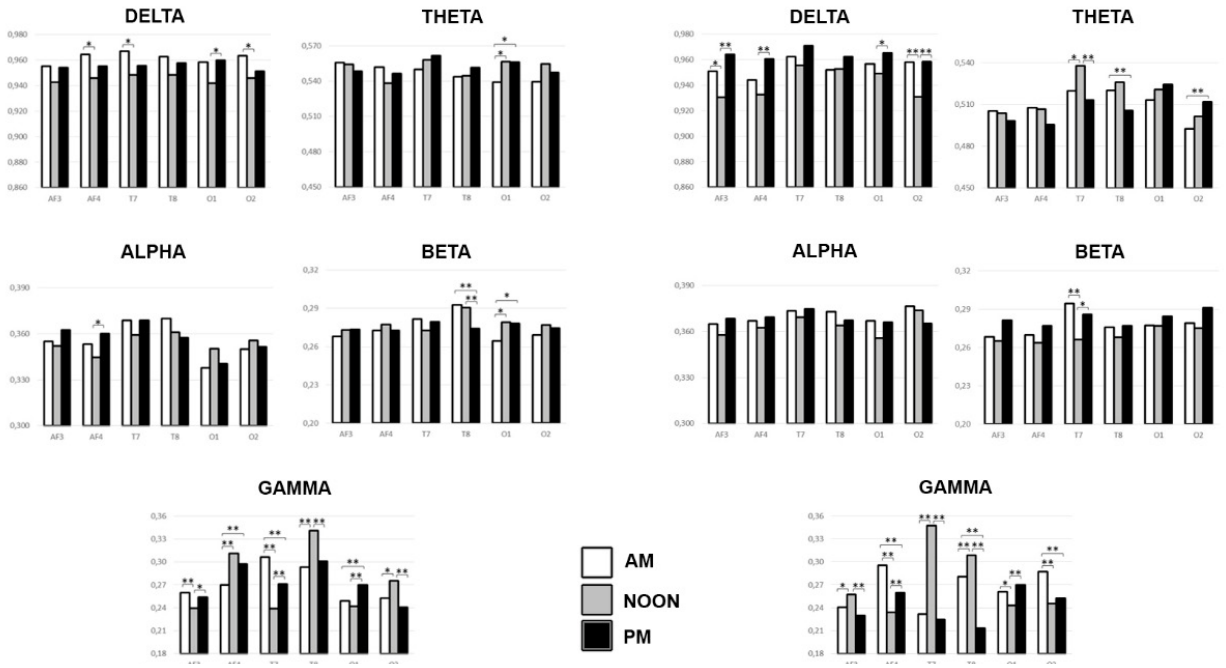

Fig. 1. Examples of participants #7 (Left), and #8 (Right). µ-Hurst evaluated by EEG band; pairs of equivalent frontal, temporal, and occipital hemispheric EEG channels (AF3-AF4; T7-T8; and 01-02, respectively), and time of the day of the measurement (AM; NOON, and PM). Significance level: * $p<0.05$; ** $p<0.01$.

Inter-correlation analysis show that EEG bands have different preferential connectivity modes (LH, IH, and RH) as shown by the example of participant #1 when evaluated according to the values of Spearman R correlation of the EEG activity between pairs of electrodes (Figure 2).

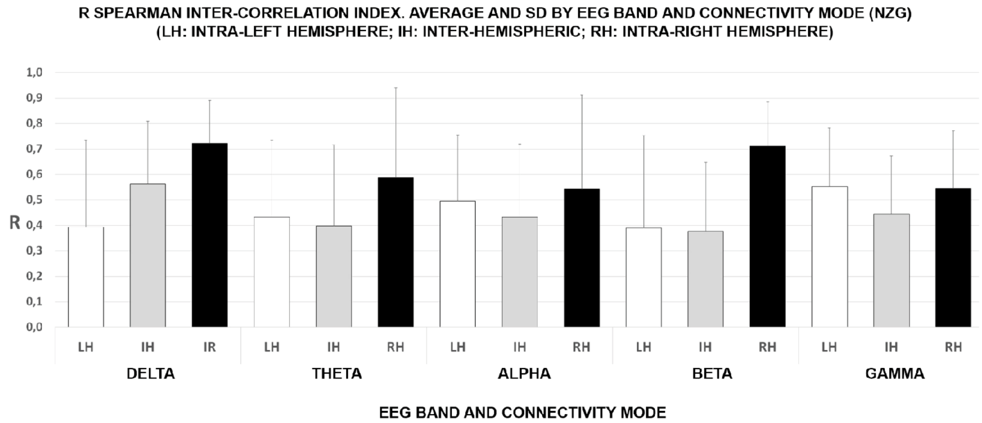

Fig. 2. Spearman's R averages and SD by EEG band and connectivity mode (LH, IH, and RH) for the 1st recording (AM) of subject NZG.

In basal, closed eyes conditions, channels in the right hemisphere show higher inter-correlation average in all the EEG band for the subject selected.

The HH analysis of the stability and course of the chaos oscillation of the selected inter-correlated pairs of electrodes (AF3-AF4; T7-T8; and O1-02) (Figure 3), shows high values of HH chaos persistence in the frontal correlated electrodes AF3-AF4 for almost all the EEG bands. Temporal and occipital pairs of electrodes, T7-T8, and 01-02, respectively, tend to oscillate in anti-persistence mode around a fractal noise oscillation stable attractor with HH values close to 0.3.

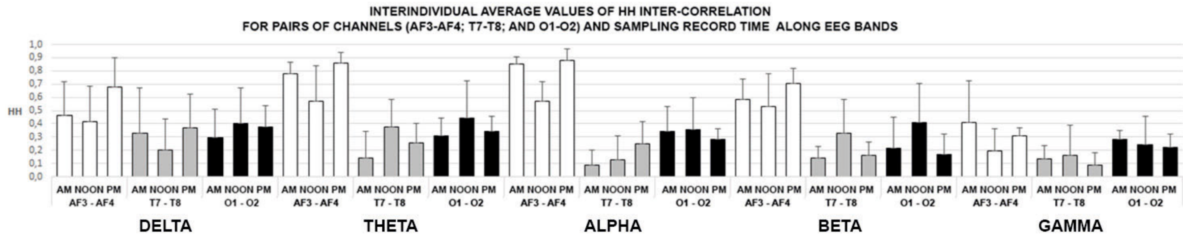

Fig. 3. Averaged HH values of the three inter-correlated pairs of channels (AF3-AF4; T7-T8; and O1-O2) evaluated across EE recording time (AM; NOON; and PM), and EEG band.

4. Discussion

Closes eyes, basal state, multiple EEG recordings, analyzed with linear and non-linear tools, revealed a set of patterns, or regularities, useful to characterize a deep description of the inter- and intra-individual differences in humans, in the context of the EEG band frequency brain channels of communication and processing. Delta waves, being the slower oscillator clock of the brain, set the persistence, long-memory, self-similar and self-organized behavior of the brain as a whole. Alpha waves slightly more organized than Beta waves (in closed eyes, basal conditions) moving around fractal (pink noise), next to the edge of chaos environment. Gamma was the most variable and heterogeneous of the five EEG bands, probably more dependent on the individual.

In the time domain description of the phenomena, a right hemisphere preference to allocate highly synchronized groups of paired electrodes was observed in almost all the individuals. Left allocation and interhemispheric communication varies among and intra individuals.

Finally, the general HH chaos tendency of the data chaos, revealed differences in the major degree or persistence and long-memory processes in the frontal areas AF3-AF4, followed by occipital (O1-O2), and temporal (T7 and T8).

5. Conclusion

The use of multiple ways to analyze and visualize the relationship between linear and non-linear description of the brain oscillatory phenomenology, in a simple and standard closed eyes basal condition, allows the discovery of insightful observations of regularities that differentiate and uniform people. The dynamics of the brain oscillations, and the interconnected relationships stablished between and among brain areas, through the three general modes to connect and process brain information (LH, IH, and RH), may reflect the general and particular boundaries of variability that a particular brain have with respect to the others. Our preliminary observations point to, at least, 4 ways to be different in this terms: i) Lateralization: Brain have determined preferred areas (or a spatial pattern of localizations) in the left or right hemisphere, where to allocate the major number of correlated/uncorrelated/anti-correlated oscillatory interactions during processing: ii) Intensity: The differences in magnitude of linear and non-linear parameters; iii) Symmetry: Related to (i) and (ii), reflects the degree of bias (left or right) in the way of processing information and taking decisions; and iv) Synchrony: The network map pattern, the magnitude, and duration of correlation between brain areas.

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