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Intra and inter-hemispheric correlations of the order/chaos fluctuation in the brain activity during a motor imagination task

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Abstract

The objective of the present study was to explore the degree of synchrony manifested by the fluctuation of the order/chaos oscillation between different areas of the brain (frontal, temporal and occipital). We made this exploration during the execution of the mental visualization of a motor task consisting of performing a self-invented ordered sequence of body movements. The sample consisted in the EEG of 9 professional dancers recorded during the process of imagining the sequence of movements. To study the variation of the order/chaos activity and the synchronic relationship of this balance between different regions of the cerebral cortex, we estimated the Hurst exponent and used linear Spearman correlations to evaluate order/chaos fluctuations synchronicity. The results showed H>0.5 values in all the electrodes, showing a strong self-similar and persistent brain activity during the imagination process. In addition, high order/chaos fluctuation synchrony indexes were found for the inter-hemispheric frontal and occipital areas in all the subjects, but poor order/chaos synchrony between temporal areas.

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Keywords: EEG, Order/Chaos, Hurst, Movement, Imagination.

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1. Introduction

Electroencephalography (EEG) is a procedure by which, through the location of electrodes on the scalp, it is possible to detect, amplify and record the electrical activity coming from the cerebral cortex of the brain. Each electrode, or channel, allows to register the brain electrical activity generated mainly by the pyramidal neurons of the cerebral cortex [1]. In 1929 Hans Berger was the first to publish studies on the activity recorded by the EEG in humans, starting to establish a relationship between behavior and brain activity [2]. According to frequency ranges, the electrical recording of the brain activity is classified into delta waves with a range of 1.5 to 3.5 Hz. It arises predominantly during deep sleep [3]. Theta waves with a range of 3.5 to 8 Hz, it characterizes the early stages of sleep (light sleep). Alpha waves with a range of 8 to 12 Hz, being characteristic of a wake subject, in relaxed wakefulness and with closed eyes. Beta waves which ranges between 13 and 30 Hz, and that identifies an awaken subject receptive to environmental stimuli. And gamma waves with a range > 30 Hz, it is usually associated with highly conscious perception, states of deep concentration or meditation [4].

A review by Maureira and Flores [5] shows few investigations that use the EEG to study its relationship with the task to imagine a sequence of movements. Some works focus on the comparison of brain activity between athletes and non-athletes using the same stimulus [6-8]; others analyze the effects of a physical exercise session on the neurophysiology of the cerebral cortex [9-11]; and a few others study cortical activity when participants imagine a movement [12, 13].

In recent decades, we have begun to understand the dynamics of EEG activity, by assuming non-linear understanding of the electrical signals coming from the brain [14]. Some findings indicates that a regular and persistent and repetitive synchronization correlates with the crystallization of pathological rhythms such as Parkinson's or epilepsy [15] which accounts for the role of the desynchronizing activity of the cerebral rhythms necessary for the normal functioning of the system [16]. Systems that obey a deterministic chaos possess an aperiodic dynamic, which are extremely sensitive to initial conditions [17]. In these conditions, the Hurst exponent (H) is a measure to analyze the chaotic behavior of a system over time. This index varies between 0 and 1, with a phase change in the H value = 0.5 indicative of a totally random series, equivalent to brown noise or random walk with no information content. When $0 \leqslant H < 0.5$ the system presents an anti-persistent behavior, that is, the past activity of the system is followed by an activity with opposite tendency. When $0.5 < H \leqslant 1$ the system presents a persistent and self-similar behavior, that is, the past activity of the system follows an activity with a similar tendency. For example, if the activity of the system is increasing, in the future, it will continue to increase or vice versa [18].

In the dynamics of any system, H=0.5 reflects states with maximal information entropy, a deterministic chaos of random walk (Brownian motion), plenty of consecutive, equally possible states. To account for such an uncertainty, the system develops information that is useful to gain probabilistic certainty about the states of the things. Both entropies, thermodynamic and informational, grow and behave in the same manner, always increasing, ridding off from the universe all the “able-to-be-organized” energy.

By mean of generating information, organized, persistent and potentially more predictable states arises in the brain. A H<0.5 accounts for an opposite process that decreases information entropy by means of maintaining a normalizing activity attracting the whole function state of the system around a particular H<0.5 value. This tendency to abolish constructive information by pulling the future fluctuations to an average, defines what it is called an anti-persistent state [19].

Previous studies [20-22] show that H values for EEG activity reflect the order/chaos balance of brain frequency waves. Another study [23] with a sample of 10 dancers with a similar task of imagine the performance of a future dance, showed high values of H in all these subjects, indicating a high self-persistent activity for beta and gamma waves. These finding were negatively correlated with the number of pairs of electrodes with significant high Spearman’s r correlations in the variation of intensity of the electrical signal between them., In that case, general desynchronization accompanied the increased self-organizational dynamics of the EEG in both frequency bands in accordance with an increase of the values of H during the imagination of the dance [22].

The present study aims to know the inter- and –intra hemispheric cross-correlation of the order/chaos fluctuation in the brain between three pairs of electrodes (two frontal, two temporal and two occipital). The sample consisted of 9 subjects during the mental task of imagining a sequence of body movements.

2. Method

2.1. Design and sample

A quantitative study of transversal comparative type was carried out. The sample was constituted by nine professional dancers with ages between 20 and 30 years. Of the total five (62.5%) are women and four (37.5%) are men.

2.2. Instruments

For the EEG recording, the Emotiv Epoc® device with a sampling frequency of 128 Hz was used for 2 minutes of projective visualization with the eyes closed. The EEG records 14 channels through electrodes positioned according to the 10/20 system (Fig. 1) using the mastoid bone electrodes as a reference. The EEG data were processed with the EEGLAB program and executed in the MATLAB 2008 platform. We used data coming from the frontal lobes (AF3 and AF4), temporal (T7 and T8) and occipital (O1 and O2).

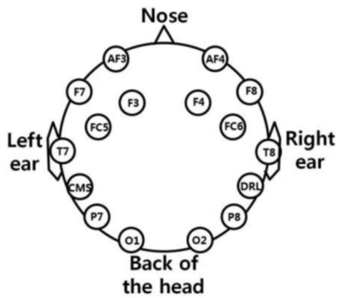

Fig. 1 Locations of the Emotiv Epoc® electrodes during the study.

2.3. Procedure

During three minutes each subject of the sample remained relaxed with the EEG on his head in a room lit and without environmental noise. After this, with eyes closed and two minutes, each one had to imagine himself executing a sequence of self-created body movements. The whole EEG frequency range from 1 to 64 Hz was analyzed.

2.4. Data analysis

The Hurst (H) exponent was used as an indicator of the order/chaos balance in the EEG records in the frontal, temporal and occipital lobes. Linear Spearman correlation tests were used to establish synchronic relationships between and among the two brain hemispheres.

3. Results

We proceeded to calculate Hurst values (H) for each running second (moving H) of the two frontal electrodes (F1-F14), the two temporal (T7-T8) and the two occipital (F7-F8). This process delivered 120 H values (one per second) for each electrode in each subject. Then we proceeded to calculate the average of this 120 H values (μ-Hurst) for each electrode to obtain the order/chaos 1-second average trend of each brain area during the two minutes of the EEG recording. Figure 2 shows these mean values of H for the left frontal area (CH1) and right (CH14), where values $H>0.5$ are observed. Therefore, we found a persistent behavior, where each H values per second reveals strong organizing processes undergoing.

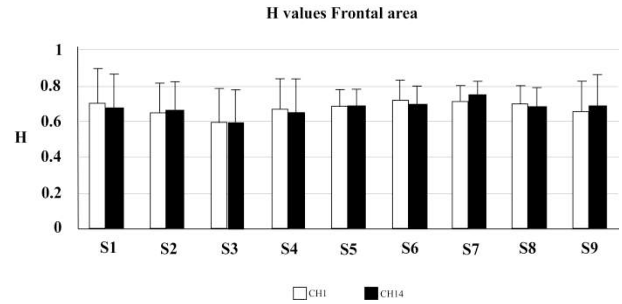

Fig. 2 Mean values of the Hurst index for each subject during two minutes of movement imagination for the two frontal electrodes.

Figures 3 and 4 show these mean values of H for the left temporal area (CH5), right (CH10), left occipital (CH7) and right (CH8). H>0.5 values are observed in all subjects, in all the electrodes, showing a persistent behavior of the cerebral cortex activity.

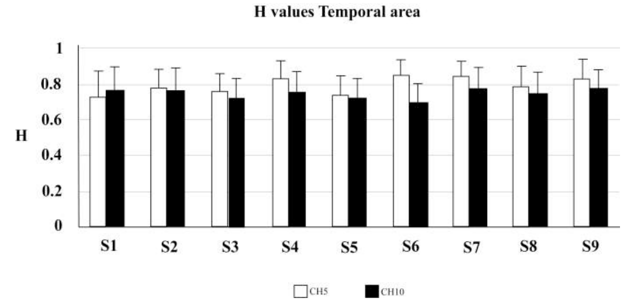

Fig.3 Mean values of the Hurst index for each subject during the two minutes of movement imagination for the two temporal electrodes.

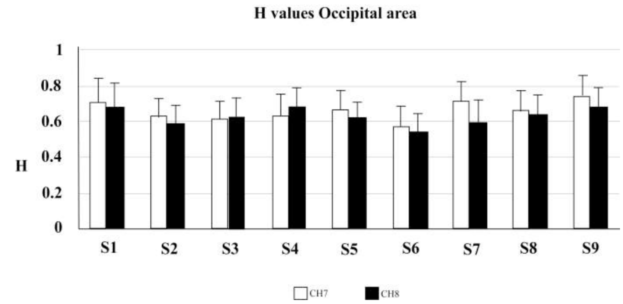

Fig. 4. Mean values of the Hurst index for each subject during the two minutes of movement imagination for the two occipital electrodes.

Table 1 shows the average values of the Hurst exponent of each electrode according to the gender of the sample, where significant differences are observed in CH14, CH 10, CH 7 and CH8 in favor of women.

Table 1. t-Tests for independent samples comparing the means of the H index between women and men.

Electrode	Groups	Descriptive statistic	p value
CH1	Female	0,669±0,155	0,992

	Male	0,670±0,142	
CH14	Female	0,677±0,160	0,003**
	Male	0,647±0,144	
CH5	Female	0,789±0,115	0,387
	Male	0,795±0,106	
CH10	Female	0,760±0,111	0,0001**
	Male	0,713±0,111	
CH7	Female	0,684±0,122	0,00001**
	Male	0,617±0,113	
CH8	Female	0,643±0,117	0,00001**
	Male	0,604±0,113	

**Significant differences at p level < 0.01

Once the H values for each electrode were calculated, Spearman correlations were carried out to study the order/chaos cross-correlation during the imagination process. These particular correlations are calculated from the time series that describes the order/chaos balance variation for each second (moving H), That is, they are a measure of the persistency of the order/chaos synchronic relationships ($H > 0.5$, $r > 0.7$) between the areas studied. Figure 5 schematizes this order/chaos balance cross-correlations for the time series with H values obtained for each second during two minutes of EEG recording and between the pairs of electrodes studied. High order/chaos correlation values ($r > 0.7$) are observed between the right and left frontal areas in almost all subjects. Order/chaos correlations of smaller magnitude are also present between the right and left occipital areas in all the subjects and only the right and left temporal areas shows low correlations in six subjects and absence in others.

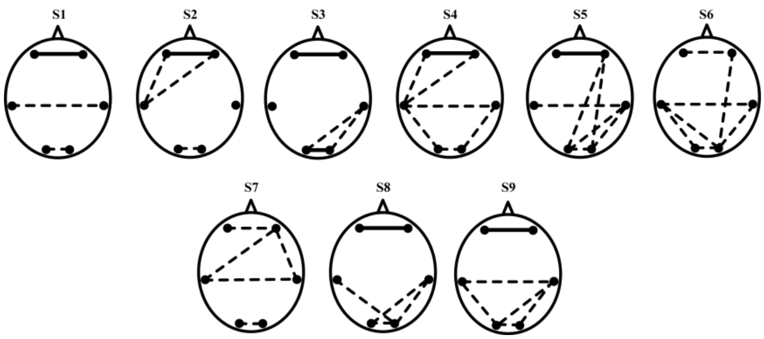

Fig. 5 Spearman correlations for the order/chaos fluctuations between pairs of EEG electrodes. The solid line indicates values of r>0.700, while the dotted line indicates r values between 0.198 and 0.699. The first six subjects correspond to women and the last three correspond to men.

4. Discussion and conclusions

The main purpose of the present study was to explore the degree of correlation existing in the dynamic balance between order and chaos in the brain over time. We estimated it from the time series generated by the electric intensity values measured in the cerebral cortex of 9 subjects during the task of imagining a sequence of motor movements.

Traditionally, it has been considered that the degree of synchrony between regions of the brain is an indication of the functional coordination of the different areas of the cortex [16] that come into play when carrying out a common process. At the same time, it is known that the synchronization phenomenon of connected oscillating systems is a natural tendency that leads to two or more oscillators to spontaneously synchronize by virtue of small disturbances that minimize and correct slight time lags until reaching a synchronous oscillation persistent [24].

On the other hand, depending on the spatial scale, it is possible that the synchronization observed in the cerebral cortex at the macro level is also the result of the cessation of the processing load that an area performs, as it is observed in the occipital regions of visual processing, when eyes are closed. In this condition, being relaxed but awake, a predominant alpha wave synchronization (8-12Hz) starts to appear. In these same circumstances, the beginning of a cognitive mental activity such as mathematical mental calculation eliminates the synchronization of the alpha wave in the occipital area [25].

In previous works [23, 26] we have found that the number of sync-paired channels with high Spearman linear correlation indexes correlates negatively with Hurst values found in the same pair of electrodes under consideration, that is, the higher the value of the Hurst exponent estimated from the electrical activity of the EEG, the lower the number of pairs of channels correlated with high values of Spearman linear correlation.

The results of the present study showed that, in the frontal areas, for the mental task of imagining a sequence of body movements, all the subjects showed higher values in the Hurst exponent (H> 0.6) estimated from the brain activity in the range 1-64 Hz. Except for the left front channel (CH1), in all other electrodes, women have a significantly higher Hurst average value than men.

The right frontal lobe is associated with planning and decisions in new conditions and unknown spaces [27], where women seem to have an advantage over men, with a greater capacity for improvisation when imagining a sequence of body movements. The temporal region plays an important role through the memory and the musicalization in the imagination process, where women seem to be more efficient with the musical, artistic sense and imagination, skills better represented in the right hemisphere [28]. The visual areas in charge of spatial recognition, colors and movement [3] seem to have a more self-similar and persistent activity in women, which is possible to associate with a greater ability to discriminate colors and visualize rhythmic movements [29].

During the imagination of a sequence of body movements, the frontal areas (CH1 and CH14) are responsible for focusing attention, planning and regulating cognitive processes [30], while the temporal region (CH5 and CH10) is relates to memory (hippocampus), face recognition and hearing (Wernicke's area and primary and secondary auditory cortex) are fundamental to the process of imagining a dance [31], finally, the occipital area (CH7 and CH8) is responsible for visual processing [3].

Correlation analyzes of the order/chaos balance between pairs of electrodes show that the right and left frontal regions correlates strongly in all subjects, the same situation that occurs with the occipital regions although with a lower Spearman correlation index r. This indicates that in terms of the dynamic balance between order and chaos of the brain, for this task, the frontal processing areas correlate more synchronously in the body motor imagination task than the other regions of the brain considered. The results show that, for this task, the order/chaos cross-correlation between temporal regions is less relevant than for the other two regions studied. Interestingly, by themselves, temporal areas showed the higher average of H values in all subjects (Fig. 3), suggesting an active involvement but not at the level of constructive synchronization.

In light of these new exploratory findings, it is relevant to reformulate the functional meaning of brain electrical activity in its various states, both linear and non-linear domains. In order to understand what the dynamic balance of order/chaos fluctuation, and the degree of synchrony observed between different areas of the brain during specific circumstances, means in this context, it is necessary to know under what circumstances, these linear and non-linear variations give an account for a better or worse end result of a more specific task requested.

New studies are needed to deepen these brain processes underlying the imagination of coordinated motor movements, such as in dance choreography, in non-expert subjects or in dancers or physical performers with several years of professional practice, as a way to contrast the results in a longitudinal study.

The results obtained contribute providing more elements of judgment in this exploratory area and suggest interesting lines for future research to expand the knowledge we have on the functioning of the brain.

So far, our model has considered the structure and brain functioning of specialized subjects in the execution of some task. It is also supposed that specialized brains should deal more easily with more specialized or complex tasks. And if this is so, it can be possible to manage the all known resources of the brain in a purposeful way, so collaborating in this way with the order/chaos fluctuating process that contributes constructively to get an achievement. The incorporation of new emerging perspectives and paradigms hitherto little addressed such as the theory of chaos and complexity applied to dynamic biological systems in various circumstances of life and daily activities, will allow us to approach a more engineering vision of brain functioning and human behavior generated for a field of study and emerging application such as neuro-management.

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