TOWARDS FRACTAL PROPERTIES OF COGNITIVE PROCESSES IN THE HUMAN BRAIN UNDER THE COMPLEXITY SCIENCE APPROACH

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ABSTRACT

The systems movement experienced four waves in 20th century: the first wave stemmed from the debate on the nature of life between vitalism and mechanicalism. The second was the interdisciplinary research arising after the World War II, with General System Theory and Cybernetics, with the help of Information Theory, Operational Research, and Systems Analysis. The third one was the establishment and development of the Theory of Self-Organization. And the fourth wave of systems movement was the rise of Complex Systems Science, which mainly referred to the systems research movement in 1980s with the Chaos Theory and Complexity Science, including some new concepts such as emergence and chaos, appeared with the accompaniment of some new methods of mathematics and computation such physical theories of nonlinear dynamics (e.g. Fractal geometry) and multi-agent-based computer simulation.

The human brain has been the subject of study among different branches of knowledge, describing their physiological and cognitive processes from data treated with qualitative tools and linear quantitative variables, seeking to obtain a determined average behavior and the causality of the same. However, living systems do not obey linear issues. The actions that emerge from them have complex characteristics, which explanations or understanding is far from being able to be represented from their components and their individual behavior, reason why their study and understanding requires the application of Chaos Theory and Complexity Science.

Cognitive processes are the ones that allowed human beings to differentiate them from other animals in ways that give them the opportunity to own, modify and live in any environment on the planet. This research focuses on the nonlinear quantitative characterization of cognitive processes. In order to do this, it was applied fractal geometry as an alternative tool for the characterization of cognitive (non-linear) processes that emerge from human brain. With this quantitative tool it was studied data signals of EEG (voltage generated by the interrelation among neurons as a function of time) from cognitive processes.

Fractal geometry could allow to eliminate the biases and tendencies in the signals of the cognitive processes to increase the visualization and suggestion of the real dynamics of these processes, in order to complement the experts opinion in a discipline or medical field that interpret the results.

In this research it was applied fractal geometry to study the fluctuations dynamics of stochastic time series (EEG) of a patient with reading and spelling disorders, which can be a reflection of difficulties in some of the cognitive processes such as language, learning, memory, intelligence, perception sensation or attention. Data were taken from 19-channel EEG (electrodes), which were treated as time series: voltage vs. time, each time series was 6453 data length. For each channel it was constructed 198 time series of fluctuations (standard deviation), for different time lags (τ). From each fluctuation time series, there were constructed other 198 time series (fluctuation of deviation fluctuation), also for different τ. Based on all-time series of generated fluctuations (39,204), there were determined two scaling exponents: the roughness exponent (H) and the fluctuation growth, for each of the 19 channels.

By applying fractal geometry, it would be possible to establish (from statistical point of view) the probable future states of cognitive processes, that help to discovering new forms of treatment, therapies and contribute with ideas about the dynamics of cognitive processes.

Keywords: cognitive processes, fractal geometry, system thinking, complexity

Introduction

Cognitive processes are an adaptive complex system settled in the consciosphere and the biosphere. In the consciosphere due to its emerging properties like will, emotion, consciosness, mind and behavior. And the biosphere, due to its processes are made through no linear interrelations that are part of the six types of neurons in human brain. Cognitive processes are the way to the human body to maintain stability both psychological and physical, the first performing the basic and superior cognitive processes and the second one executing the eight processes nutrition, excretion, growth, nervous function, respiration, hormonal function, circulation and reproduction). Both of them work as a whole, however the information necessary for the physiological ones are made is obtained through the cognitive ones (see figure 1). To understand its dynamics different scientific approaches have studied these processes, either from the point of physical and / or psychological view, by gathering data through the application of behavioral methods to subjects (healthy or sick) and by quantifying brain activity through correlational neural methods (EEG) to finally apply linear tools such as inferential or descriptive statistics which results in an average behavior leaving out the characteristics inherent in complex adaptive systems such as non-linearity this makes necessary to consider other types of tools that allow to complement knowledge up to now achieved by linear perspective.

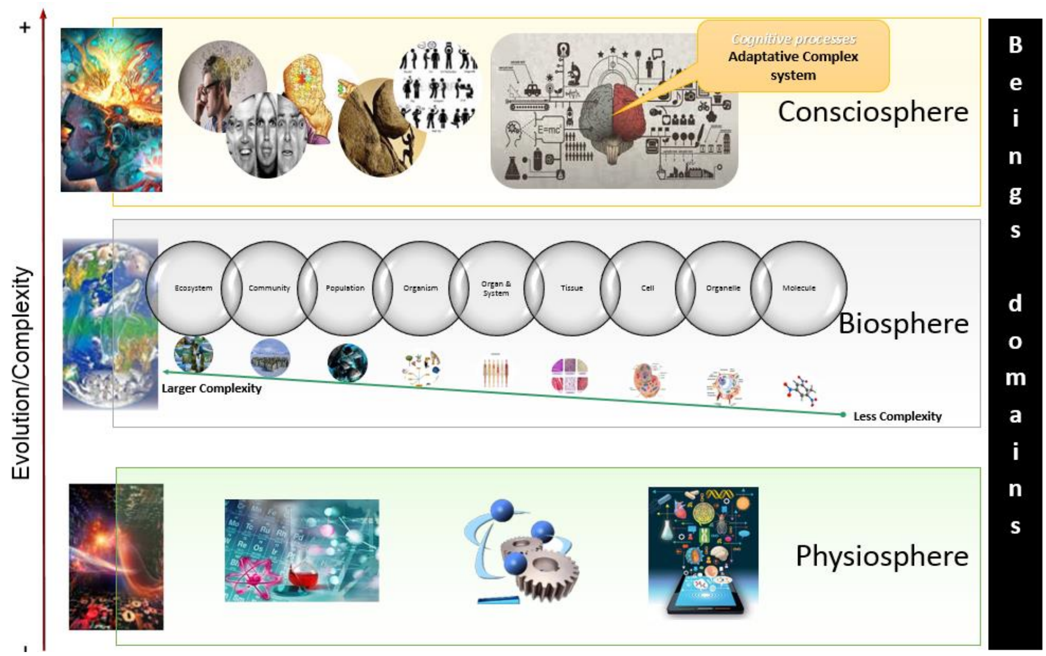


Figure 1. Cognitive Processes on being domain (Lina, 2018).

Context

Cognitive processes are the way in which the human brain provides psychological and physical stability to the body. To the eight physiological processes take place it is necessary for cognitive processes to be performed. In the literature there are two types of cognitive phases the basic (sensation, attention, perception) and the superior (intelligence, memory, learning and language). (Davidoff, 1984). See figure 2.

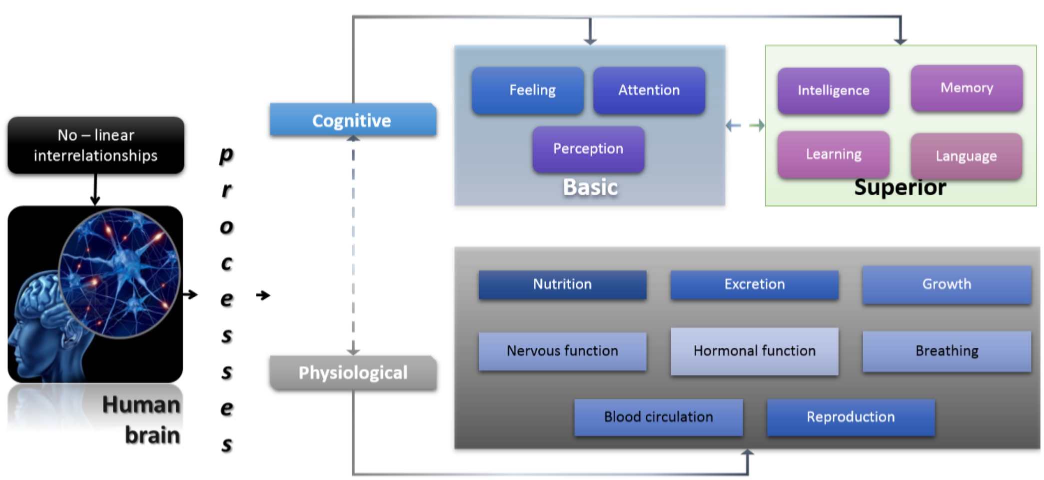


Figure 2. Cognitive and physiological processes (Lina, 2018).

Towards fractal properties of Cognitive Processes

This complex adaptive system that are the cognitive processes has been studied by different scientific approaches either from a perspective that seeks to respond to question of how processes work physiologically, or psychologically by gathering data by means of behavioral methods that are quantified with correlational neural methods. The obtained information is processed with linear tools such as descriptive and inferential statistics.

The measurement of cognitive processes is done by quantifying brain activity, by using six methods, of these ones, the electroencephalogram (EEG) is the most commonly used due to its excellent temporal resolution, low cost and harmfulness, although it has a poor spatial resolution (Smith y Kosslyn, 2008).

The approximation of the linear perspective to approach the complexity of cognitive processes has helped to get knowledge about them and suggest how is the operation of them, by gathering information of patients and healthy subjects quantifying it with the EEG and analyzing it with linear tools which results are interpreted based on the experience of the person doing the research or consulting an expert from a single disciplinary approach.

Since the processes are of non-linear character with different properties from those considered in the reductive part that divides the elements that make them, it is important to search characterization alternatives that consider complexity and complement existing knowledge. This characterization is limited to the domains of the being of the biosphere and the physiosphere, the first to make use of the EEG to quantify the cerebral activity and the second because it seeks to provide knowledge of the collective behavior of neurons. See figure 3 and 4.

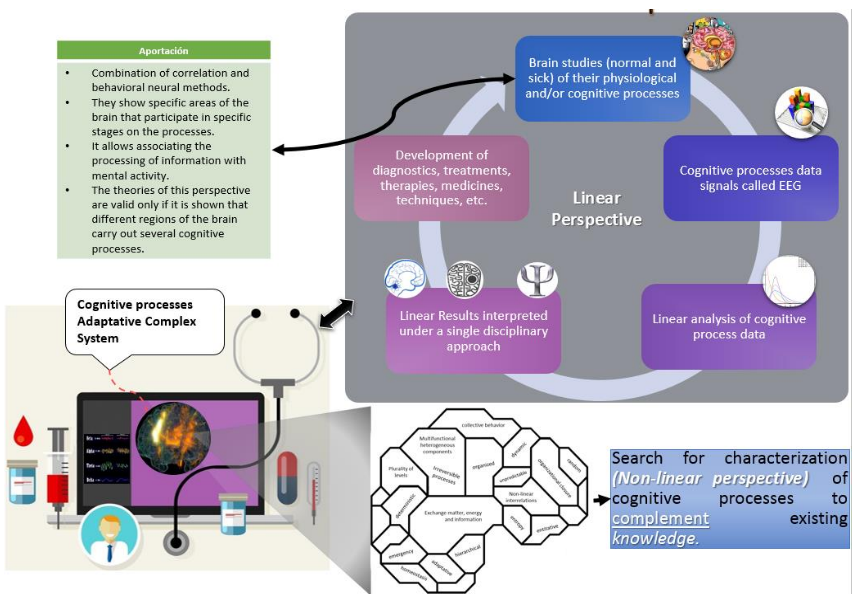


Figure 3. Linear and non-linear perspective (Lina, 2018).

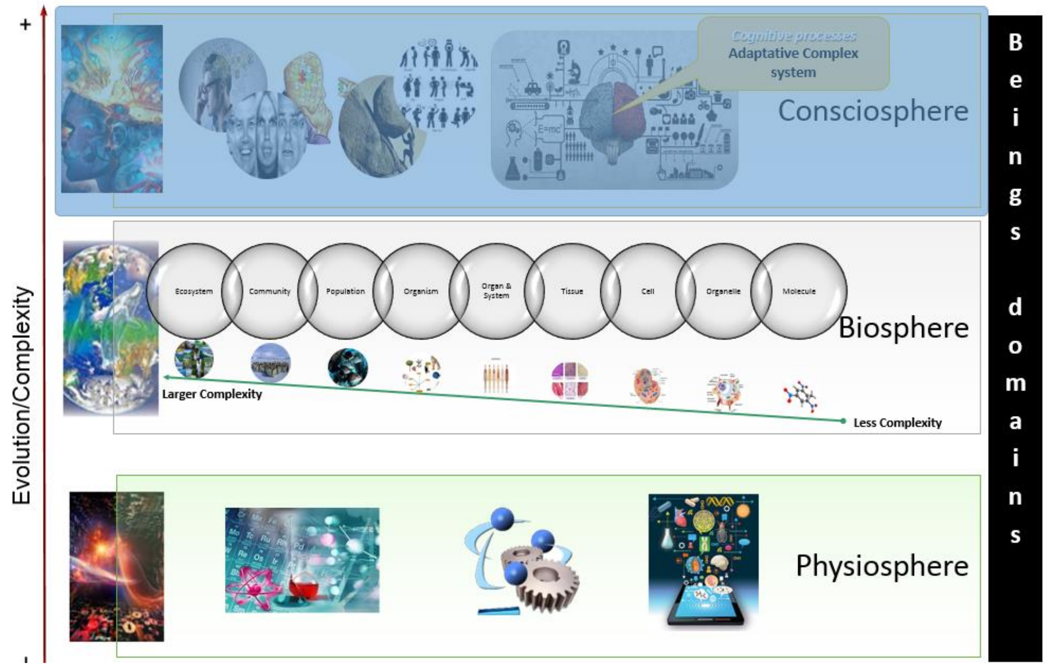


Figure 4. Domain of characterization (Lina, 2018).

With the above in mind, there are raised research questions related to the characterization: (i) in what way could fractal characterization help enrich the knowledge already generated from the application of linear tools? (ii) The fractal characterization of cognitive processes would elucidate its functioning and suggest the dynamics of the human brain at different scales?

Based on these questions, it is possible to establish the hypothesis that the fractal characterization of cognitive processes that emerge from the human brain enriches the knowledge about them at different time scales.

State of art

Cognitive processes as a system have been approached by different scientific approaches such as neurology and psychology, looking for how they work from a physiological or psychological perspective, quantifying them with tests or questionnaires and / or with neural methods such as EEG, which detect the different brain waves through electrodes located in the leather scalp To the all information obtained by researchers it is applied linear tools as descriptive and inferential statistics.

Studies based on traditional thinking approach one or two cognitive processes use correlational behavioral and neural methods to define the activities that will allow the measurement of a certain variable in the subject under investigation. The behavioral method determines the behavior that can be observed directly, chasing draw conclusions about internal representations and processing from the answers directly observable, based on the accuracy with which the subjects study perform a task and the measurement of how long it takes the subjects to respond. To quantify the variable researchers use qualitative techniques such as batteries or the record of brain activity with the help of an electroencephalograph, which is more frequently used due to its excellent temporal resolution, low harmfulness and cost, compared with others such as magneto encephalography, emission tomography positrons, optical ultrasound, provoked potentials, nuclear and functional magnetic resonance (Smith y Kosslyn, 2008).

Based on this, the researchers have been able to: (i) generate opinions about the performance of electroencephalography and compare it with the rest of the existing ones, (ii) suggest possible parts of the brain involved in the cognitive processes that are being observed and (iii) employ neurological and psychological tests that have ranges and they serve as a parameter to perform interpretations, together with the knowledge generated of the experience of researchers or experts in the field and, with that, obtain findings. The interpretations use cognitive theories that are limited by the data that have been possible to obtain from the human brain; although these theories do not determine the assumptions, if they limit the scope of what can be proposed, since they are valid only when researchers show that different regions of the brain carry out one or several cognitive processes (Francois, 2004) (Smith y Kosslyn, 2008).

The application of non-linear tools to quantify the electrical activity of the neurons and the heart and the possible characterization of the systems has been done with the use of electroencephalograms (EEG) and electrocardiograms (ECG). These investigations have allowed: (i) to characterize the collective dynamics of specialized cells at different time scales, (ii) the timely detection of a pathology without being essential for an expert to interpret the data, (iii) identification of patterns of behavior that determine the dynamics of physiological processes and visualize and to a certain point predict the development of a disease and, (iv) provide ideas for treatments or therapies and / or set prevention and control mechanisms (Fuchs et.al, 2010) (Penzel et.al, 2003) (Schumann et. al, 2010).

It is necessary to use complementary approaches that allow advances from the traditional and systemic point of view generating transdisciplinary knowledge. This implies knowing the psychological, physiological and neurological aspects of the processes, as well as establishing from the systemic its properties as a complex adaptive system. In order to do this, it is set a general objective: to generate a quantitative explanation of the fractal dynamics of the cognitive processes of the human brain at different time scales, based on the theory of fractals and within the framework of the systemic, that it can be achieved by (i) establish the conceptual theoretical framework that supports the research, (ii) define the methodological framework that supports the research, (iii) characterize the fractal dynamics of cognitive processes in the human brain and (iv) analyze and discuss the obtained results. See figure 5.

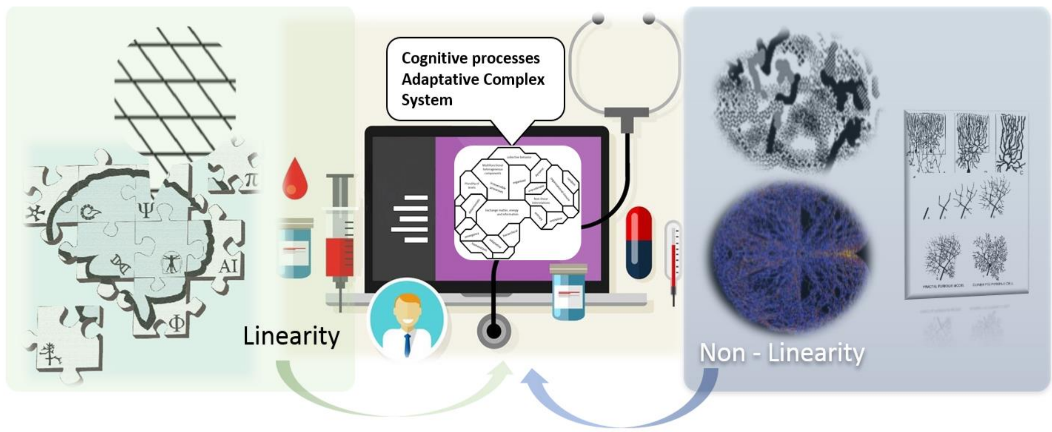


Figure 5. Complementary approaches (Lina, 2018).

Theoretical Framework

As part of the theoretical framework, the stages of the Systemic development were included together with the most representative theories. Are also discussed the principles of systems to determine the particularities of complex adaptive systems, category where cognitive processes are located (Mobus y Kalton, 2015). See figures 6 y 7.

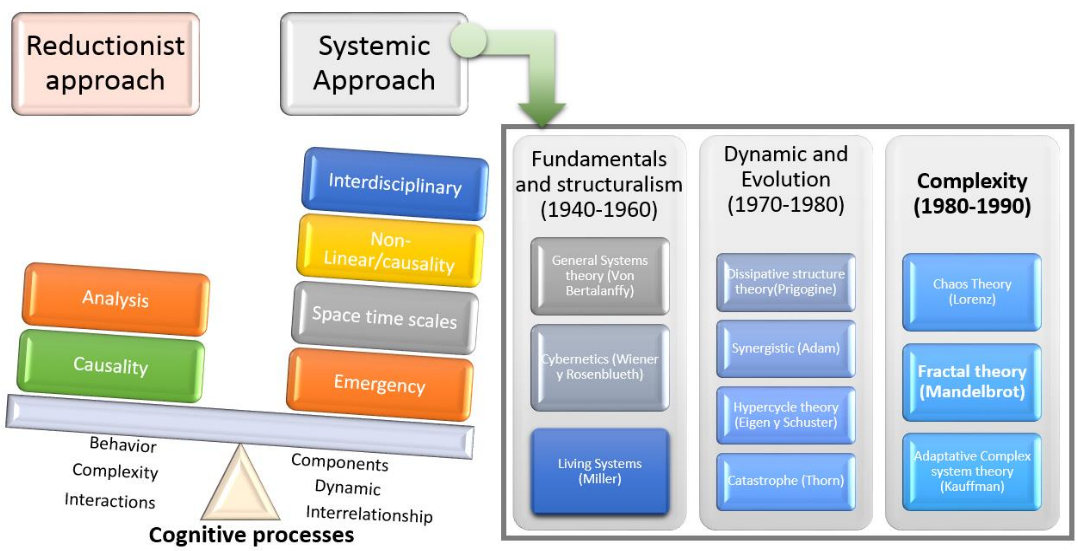


Figure 6. Development stages of Systemic (Lina, 2018).

Figure 7. Systems principles (Lina, 2018).

Cognitive processes as an adaptive complex system

It is possible to define the cognitive processes as a system realized by random relational networks of neurons with diffuse limits, this tissue fulfills transformations organized in structural hierarchies giving rise to the emergence of activation patterns that trigger dynamic interactions and connection between high levels of order of emergency by dissipative structuring. The formation of a nucleus, on the one hand, and successive levels of organizational closure, on the other, giving rise to processes that are organized circularly and show dependency and recursive closure, which as a whole indicates diverse hierarchical organization, in terms of autopoiesis (Francois, 2004).

These networks of neurons have two principles that are complementary to each other: principle of convergence (since many nerve cells can project to a single neuron) and that of divergence (where the branches of the neurons are widely distributed to other neurons). These networks present the peculiarity of being algorithmized by selection, since some neural zones may have greater dominance in some processes or be reactivated by impulse signals, resulting in the generation of specific patterns of perception and ordering that form the basis for future evaluations and the progressive construction of various frames of reference; based on them, knowledge is generated that is used depending on the success of the learned behavior in different situations. By having hypercycles, these neural networks go through the process of morphogenesis and, in this way, have the possibility of differentiating their elements, increasing their structural organization and their interrelations (Francois, 2004).

Cognitive processes have an anatomical and psychological component that can be modified by knowledge, since when obtaining and processing information (sensory inputs) in a distributed form and in parallel to communicate it to the efferent elements of the organism implies that there is a limit in the deterministic nature of its activity and gives them certain randomness (Mobus y Kalton, 2015) (Popper y Eccles, 1993).

Cognitive processes make use of the spatial domain to recognize patterns and temporary to be anticipative; both allow it to recognize points, generate maps of different spaces and, depending on the associations and emotions printed in each of experiences, structurally and organizationally limit the set of internal factors or external factors that propitiate, direct and maintain (motivation) the behavior in the human body (Mobus and Kalton, 2015). Due to its semantic architecture (cybernetic, symbolic and self-referential), recursion, fluctuations, synergy, non-inseparable causality, non-continuous, self-generative, unpredictable and with uncertainty, propitiate characteristics of dependence and autonomy, leading to cognitive process to a consequent creation of emergencies that give rise to properties newfangled such as consciousness or mind (Francois, 2004). See Figure 8.

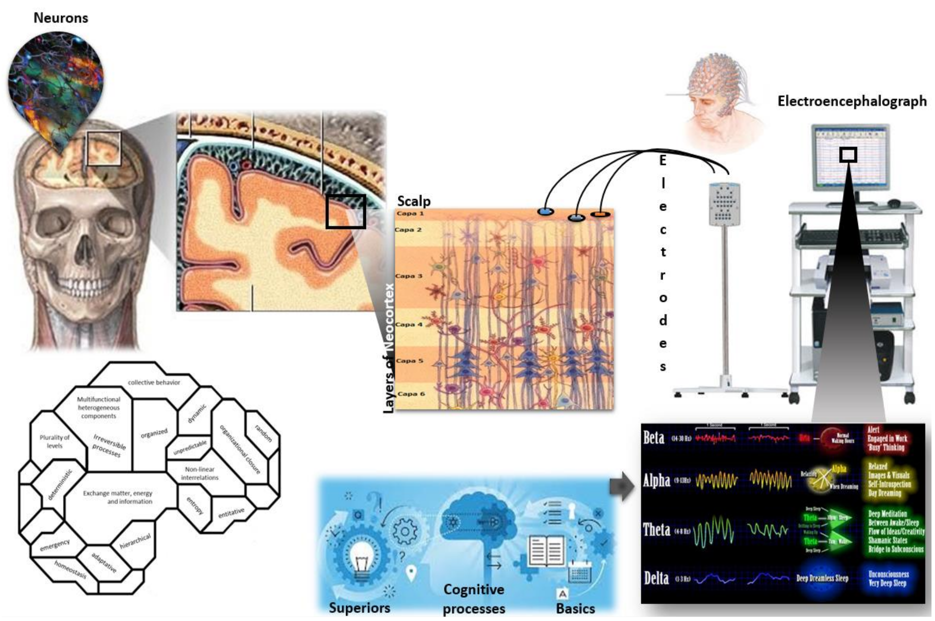


Figure 8. System definition (Lina, 2018).

Based on these properties, it is necessary the use of complementary approaches between the traditional or reductionist thinking that occupies linear tools and thinking systemic framework whose theoretical framework calls for transdisciplinary and allow the application of knowledge in a wide range of fields in any plane of the domain of being seeking to discover order, regularity, invariance, etc. (Francois, 2004).

Fractal geometry

Fractal Geometry is found within the postmodernist thinking of the Systemic, which was born in the fourth wave of systems movement. This quantitative tool allows modeling the recurrence of similar patterns at different scales. Some types of fractals are self-similar and other self-related. Some examples of self-related series are the EEG and the ECG. This type of signals that have been used for studies with non-linear quantitative tools, were investigated in different time scales to recognize if there are patterns of behavior. (Fuchs et. al, 2010) (Kantelhardt et. al, 2015) (Penzel et. al, 2003) (Schumann, et. al, 2010). See figure 9.

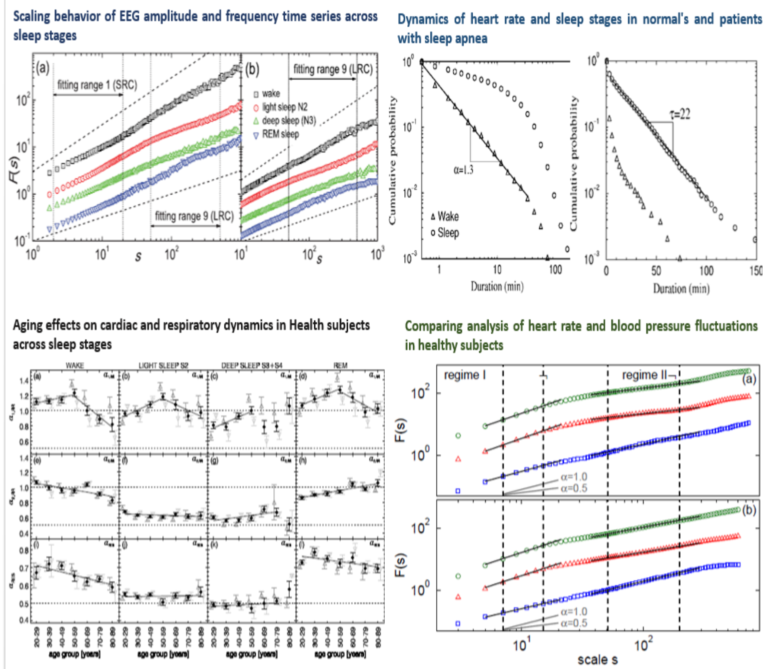


Figure 9. Examples of studies that applies non-linear quantitative tools (Lina, 2018).

The internal dynamics of many complex real-world systems is often studied by analyzing the fluctuations of the output time series (Bouchaud, Matacz & Potters, 2001) (Kantz y Schreiber, 1997). Recent investigations have pointed out that financial systems do not immediately respond to an amount of information flowing in it, but react to it gradually. Accordingly, the analysis of the scaling properties of the fluctuations in financial systems has given important information regarding the underlying processes responsible for the observed macroscopic behavior of these systems (Bouchaud, Matacz & Potters, 2001) (Kantz y Schreiber, 1997) (Constantin & Das, 2005) (Wang et. Al, 2005) (Balankin et.al, 2005) (Kalisky, Ashkenazy & Havlin, 2005).

The long-term memory in the time series fluctuations of emerging cognitive processes can be analyzed through a study of their structure function, defined as $\sigma(\tau,\delta t) = \overline{\langle[V(t+\delta t,\tau) - V(t,\tau)]^2\rangle}^{1/2}$, where the overbar denotes average over all t in time series of length $T-\tau$ [T is the length of original time series$z(t)$] and the brackets denote average over different realizations of the time window of size δt (Andersen, Bollerslev & Diebold, 2002). The structure function of the fluctuations can exhibit the power law behavior (Balankin, 2007).

$$\sigma \propto (\delta t)^{\zeta}, \qquad (1)$$

The scaling exponent ζ, also called the *Hurst exponent*, characterizes the strength of long-range correlations in the fluctuation behavior (Ramasco, López y Rodríguez, 2000). The scaling behavior (1) characterizes the correlations in a time series of fluctuations treated as an analog of rough interface in (1+1) dimensions (Barabási & Stanley, 1995) (Ramasco, López y Rodríguez, 2000) (De Queiroz, 2005).

Methodological framework

Once the characteristics of the system under study were obtained, the appropriate systems thinking was analyzed to set the complexity of the cognitive processes using the metamethodology of Total Systems Intervention (TSI). Through the attributes of complexity and type of interrelations this suggests the context in which the system is located, for the case of cognitive processes proposed the complex-coercive context and indicated that the perspective option is Postmodern Systems thinking, due to the diversity of Systems theories with high complexity and coercion, section where Fractal Geometry is placed as a non-linear quantitative tool option to be applied in the EEG of cognitive processes (Jackson, 2003). See Figure 10.

	Unitario	Pluralista	Coercitivo
Simple	Simple-Unitary	Simple-Pluralist	Simple-Coercive
Complejo	Complex-Unitary	Complex-Pluralist	**Complex-Coercive**

	Unitary	Pluralist	Coercive
Simple	• Hard Systems Thinking	Soft Systems Approaches	• emancipatory Systems Thinking
Complex	• System Dynamics • Organizational Cybernetics Complexity Theory		• Postmodern System Thinking

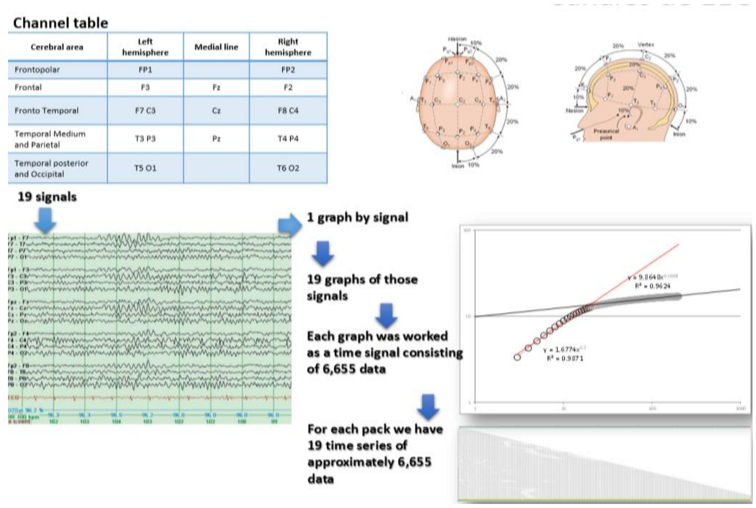
Figure 10. Systems approaches related to problem contexts (Jackson, 2003).

Results

In this work it is proposed to study the cognitive processes, keeping it out of the consciosphere, through the quantification of brain activity with EEGs, convert the information into time series for applying it non-linear quantitative tools after this, the obtained results will be interpreted from the mathematical, psychological and physiological point of view with the help of an expert.

EEGs were obtained from subjects with reading and writing problems, it involves both, the basic cognitive phases and the superior ones. Each EEG considered comes from a child with literacy difficulties in the third grade of primary school, with an IQ greater than or equal to 85 and without visual, motor, articulation of sounds, neurological or psychiatric problems.

The electroencephalogram was taken with the international system 10-20 by means of the placement on the scalp of 19 electrodes (channels), so that, there were recorded 19 signals (voltage) to get 19 graphics (voltage vs. time), each graph was worked as a time signal consisting of 6,655 data. See Figure 11.



Cerebral area	Left hemisphere	Medial line	Right hemisphere
Frontopolar	FP1		FP2
Frontal	F3	Fz	F2
Fronto Temporal	F7 C3	Cz	F8 C4
Temporal Medium and Parietal	T3 P3	Pz	T4 P4
Temporal posterior and Occipital	T5 O1		T6 O2

Figure 11. EEG, signals, time series (Lina, 2018).

Statistical treatment

The time series of fluctuations from cognitive processes were treated as a moving interface $V(t,\tau)$, where the sampling time interval τ played the role of time variable, whereas the physical time t played the role of spatial variable (see Figures 12a, 13a, 14a). It was found that time series of their fluctuations exhibit long-range power-law correlations and scaling behavior (1) with the Hurst exponent $\zeta = 0.56$, i.e. the fluctuations of the cognitive processes display persistence or positive long-term correlations.

The length of record of the time series of the absolute return volatility was $T = 6{,}655$ data. It must be appreciated the visual similarity between the absolute return volatility time series with different sampling intervals (see Figures. 12(b)–12(d), 13(b)–13(d), and 14(b)–14(d)). Quantitatively, the self-affinity of fluctuation time series is characterized by the scaling behavior (1), as is show in Figures 15a, 15b, 15c, 15d, 16a, 16b, 16c, and 16d, for the fluctuations of the cognitive process records shown in Figures 12a, 13a, 14a. Hence the structure function displays a power-law behavior (1) with $\zeta(\tau) = 0.56$, within positive long-term correlations (see Figures 15a, 15b, 15c, 15d, 16a, 16b, 16c, and 16d).

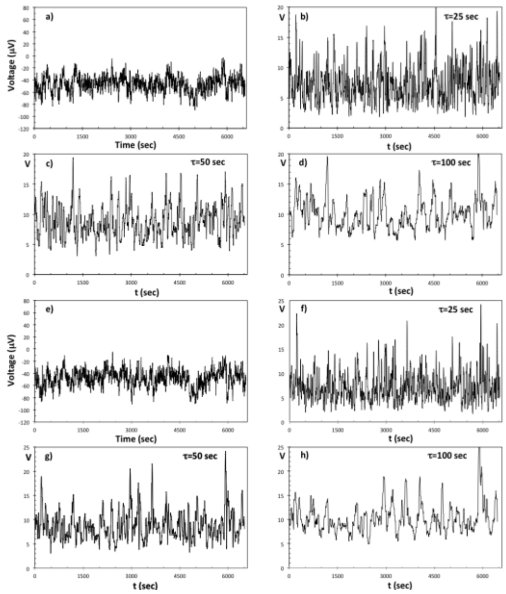


Figure 12. Time series for the channel signal fp1-a12. Time series of fluctuations of channel fp1-a12 with T = 6655 data with intervals of time (b): $\tau = 25$. (c) $\tau = 50$. (d) $\tau = 100$. (e) Time series for the channel signal fp2-a12. Time series of fluctuations of the channel fp2-a12 with T = 6655 data with intervals of time (f) $\tau = 25$. (g) $\tau = 50$. (h) $\tau = 100$ (Lina, 2018).

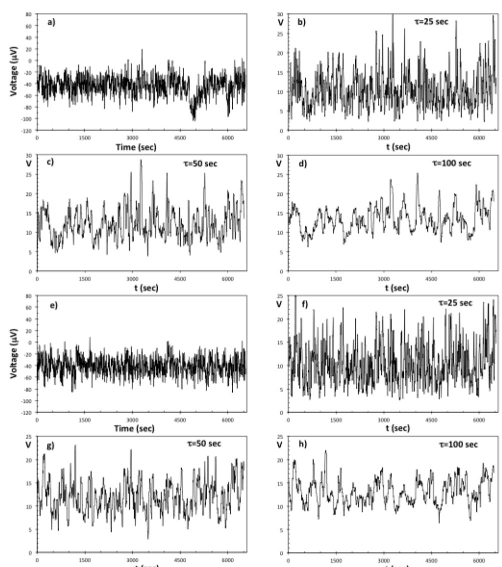


Figure 13. (a) Time series for the channel signal f3-a12. Channel fluctuations time series f3-a12 with T = 6655 data with time intervals (b): $\tau = 25$. (c) $\tau = 50$. (d) $\tau = 100$. (e) Time series for the channel signal f4-a12. Channel fluctuations time series f4-a12 with n T = 6655 data with time intervals (f) $\tau = 25$. (g) $\tau = 50$. (h) $\tau = 100$ (Lina, 2018).

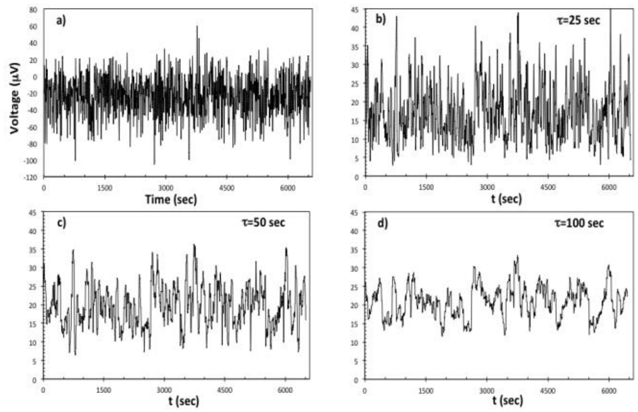


Figure 14. (a) Time series for the channel signal pz-a12. Time series of fluctuations of the channel pz-a12 with n T = 6655 data with intervals of time (b): τ = 25. (c) τ = 50. (d) τ = 100 (Lina, 2018).

Fractal Characterization

The graphs below show the dynamic scaling of the structure function for the patient, those on the right side show the fluctuation exponent for 25, 50 and 100 τ window. Those on the left have the roughness exponent for each channel which indicates if there are correlations and of what type.

Furthermore, it is observed that the structure function of the fluctuations of cognitive processes also scales with the sampling interval τ as

$$\sigma \propto \tau^{\beta}, \qquad (2)$$

where $\beta = 0.80$ is the fluctuation growth exponent [see Figures 15e, 15f, 15g, 15h, 16e, 16f, 16g, and 16h].

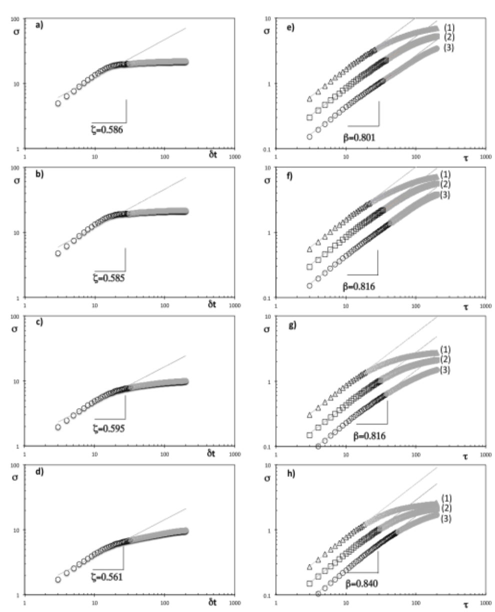


Figure 15. Dynamic scaling of the structure function for a patient with reading and writing difficulties. (a) Roughness exponent of the channel o1-a12. (b) Exponent of roughness of the channel o2-a12. (c) Roughness exponent of channel f7-a12. (d) Exponent of roughness of channel f8-a12. (e) Exponent of fluctuations for channel o1-a12. (f) Exponent of fluctuations for channel o2-a12. (g) Exponent of fluctuations for channel f7-a12. (h) Exponent of fluctuations for channel f8-a12 (Lina, 2018).

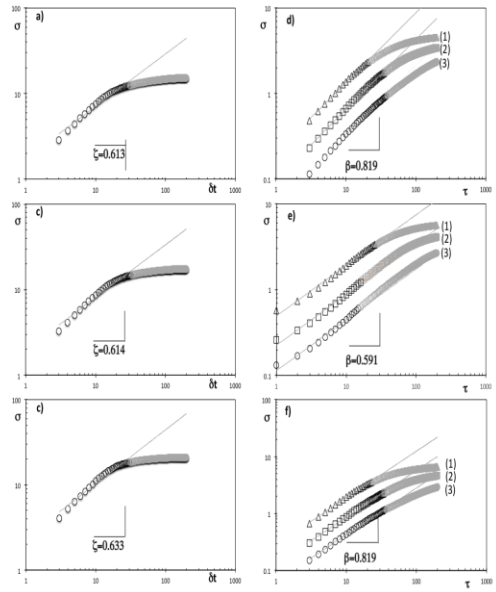


Figure 16. Dynamic scaling of the structure function for a patient with reading and writing difficulties. (a) Exponent of roughness of channel fz-a12. (b) Exponent of roughness of channel cz-a12. (c) Roughness exponent of channel pz-a12. (d) Exponent of fluctuations for channel fz-a12. (e) Exponent of fluctuations for channel cz-a12. (f) Exponent of fluctuations for channel pz-a12 (Lina, 2018).

These results point out the existence of dynamic scaling behavior analogous to the Family-Viscek dynamic scaling behavior for the disorderly surface growth (Coronel & Hernández, 2005). Indeed, the scaling relations (1) and (2) can suggest that the structure function of time series fluctuations of the cognitive processes from human brain exhibit the dynamic scaling behavior

$$\sigma(\tau, \delta t) \propto \tau^{\beta} f_l\left(\delta t / \tau^{1/z}\right), \qquad (3)$$

where the scaling function behaves as

$$f_l \propto \begin{cases} y^{\zeta} & \text{if } y < 1 \\ \text{const} & \text{if } y \gg 1 \end{cases}, \qquad (4)$$

And data were obtained with scaling exponent obtained with the scaling relation (2).

Identifying such scaling behaviors (3) and (4) it is possible to define universality classes regarding to disorderly surface growth. The values of the exponents ζ and β are independent of many 'details' of the system, e.g. the scaling exponents obtained for the fluid flow problem coincide with the scaling exponents obtained for the burning front, despite the rather different mechanisms leading to the actual interface.

Conclusions

Cognitive processes carry out physiological processes and allow the human brain to achieve psychological and physical stability, they are a complex adaptive system with characteristics proposed from the physiological, psychological and systemic approach.

The knowledge we have of how cognitive processes work and the physiological parts that participate in this function have been suggested by branches of science under a thinking approach of analysis using relational behavioral methods. Based on what previous and the peculiarities of the system, from the metamethodology of Total Systems Intervention, cognitive processes were located as a complex - coercive system that requires the theoretical framework of postmodernist thought, where it is located the fractal geometry

Fractal Geometry is proposed as a theoretical framework because the findings in systems investigations of the human body as seen in the state of the art have suggested the way of functioning and even diagnoses in advance without the immediate need of an expert in the field. The roughness exponent obtained for a patient suggests that there are positive correlations.

The knowledge of universality class allows us to understand the fundamental processes ruling the system dynamics. As we have seen, the representation of the time series fluctuations of the cognitive processes from the human brain as a moving interface can allow researchers to use the differential stochastic equations from the theory of kinetic roughening for modeling and predicting of fluctuation dynamics which belong to the same universality class.

In this way, and based on the values of scaling exponents obtained for the fluctuations of cognitive processes from the human brain, is possible to apply the kinetic roughening models (Barabási & Stanley, 1995) for forecasting the dynamics of cognitive processes from the human brain.

Acknowledgments

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