NEURAL BINDING, CONSCIOUSNESS, AND MENTAL DISORDERS: COMPLEXITY AS A COMMON ELEMENT

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Abstract

Concepts from complex systems have been widely used in model building and experiments in neuroscience. This article presents a short overview of synchronization and chaos theory in studies of perception, and consciousness. In addition, these findings seem to have serious implications for the understanding of mental disorders. Finally some consequences for the future of psychiatry are discussed.

Key words: Synchronization; Dynamical systems; Chaos; Complexity; Psychopathology; Mental disorders

1. INTRODUCTION

The human brain has a remarkable ability to manage the body functions, and process the information that allows us to act on a changeable external environment. To achieve these functions, it developed a large computing power during evolution as well as specialized functions, such as cognition, emotion, and consciousness. With approximately 86 billion neurons (Herculano-Houzel, 2009), each neuron having approximately hundreds up to thousands of synapses, the brain has high structural complexity, and non-linearity, that endows it with a rich dynamic.

Additionally, the brain is a physical system composed of neurons that communicate with each other through electrical discharges. With that in mind, it is no surprise that the main model used in neuroscience to describe the behavior of neurons was inspired by an electrical circuit model (Hodgkin & Huxley, 1952; 1990). The brain can also be seen as a physical system, since its functions are dynamical results of its components, the neurons (McKenna et al., 1994; Rolls & Traves, 1990; Hertz, Krogh & Palmer, 1991). For this reason neuroscience has been using concepts and models originating from physics as a fundamental part of the way to understand the brain.

In this short overview I will focus on two concepts coming from areas of mathematical physics, complexity theory or complex systems (Érdi, 2007; Mainzer, 2007; Mitchell, 2009; Holland, 2014), which aim to understand systems with the characteristics described above. According to Singer (2009) the traditional view of how the brain works as compartmentalized, hierarchical, and serial processing organ is illusory. In fact, brain is a distributed system with a

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large number of components that process information in parallel. This change of perspective demands the use of new concepts and tools. In this article, I will show that brain science has already achieved some benefits from using the complexity approach. Concepts such as attractors, chaos, synchronization, self-organization, emergence, complexity measures, resonance, basin of attraction, and others can easily be found in neurosciences literature nowadays (Chialvo, 2010). Another benefit of using complexity theory in neuroscience is an interdisciplinary research. In this context, complexity theory can act as a bridge between the various disciplines, since it has been used in the study of phenomena not only in physics, but also in chemistry, in biology, linguistics, economics, psychology and others. In particular, I will address the use of concepts related to synchronization and chaos theory in the studies of perception, consciousness, and mental disorders.

2. SYNCHRONIZATION AND BINDING PROBLEM

The so-called “Neural Binding Problem” is an important and unresolved problem in neuroscience (Burwick, 2014). This problem stems from the fact that neuroscientists claim that different brain locations represent the distinct features that are present in sensory stimuli. For instance, after we look a red triangle, one neuron assembly processes the red color, and another assembly processes the triangular shape.

From this perspective there is a question: how the brain *binds* these distinct neural representations and allows the notion of one single object. This problem becomes more apparent when we present to the brain more than one object, for example, a red triangle, and a yellow square (Raffone & Van Leeuwen, 2001b). How does the brain keep track of the features triangle, square, red, and yellow, in a way that avoid an incorrect combination?

If we consider a computer system such as a PC this would be no problem, due to the fact that the system allocates each piece of information in a specific memory address. However, in a distributed system, such as the brain, the solution is not trivial. Moreover, it is not a matter of finding a mechanism that works across a generic distributed system, but one that is appropriate for the brain. It is relevant to note, that when I say that every sensory feature would be identified with a specific assembly of neurons, it does not imply that these neurons need to be located next to each other.

An intuitive solution would be to imagine the existence of dedicated assembly connecting the different features represented in distinct brain locations. Another alternative would be the presence of specialized synapses connecting distinct feature assemblies. However, these options were discarded, since these solutions would involve creating specialized circuits in the brain. As a consequence of this inflexibility, the demand for memory storage and processing would be greater than even the brain’s capacity.

The hypothesis to solve the binding problem that has received the most attention involves the synchronization of neuronal assemblies, as the binding mechanism (Von Der Malsburg, 1995; Singer, 1999; Uhlhaas et al., 2009).

Notably, a rich dynamics such as, resonance, synchronization, solitons, chaos, among others arises from the nonlinear nature of these systems (Arenas et al., 2008; Chen, 2008a; Wang, 2002). Another way to describe this fact is to say that, these phenomena depend on the way in which the components of those systems are interconnected. In a complex network, such as the brain in addition to its large number of components, there are varieties of topologies that give rise to different complex dynamic patterns (Boccaletti et al., 2006; Arenas et al., 2008). For the solution of binding problem, synchronization makes possible the emergence of new “*virtual neural assemblies*” in the brain, without creating permanent neural circuits.

This suggestion received the support of various experiments carried out in animals, and humans. These experiments showed the presence of higher correlation between oscillations of neuron assemblies that represent the features of the object that gave rise to the stimulus. These

studies also showed that depending on the oscillation frequency, synchronization has characteristic spatial range, specific brain areas, and links to different cognitive functions (Engel, Fries, & Singer, 2001; Fries, Neuenschwander et al., 2001; Hipp, Engel, & Siegel, 2011; de Oliveira, Thiele, & Hoffmann, 1997; Varela et al., 2001).

According to this classification, alpha waves (8-12 Hz) were associated with all cortical regions, mainly thalamus and hippocampus, with a long-range synchronization. Synchronization in these frequencies is associated with attentional processes. Beta waves (13-30 Hz) were associated with all cortical regions, sub thalamic nucleus, basal ganglia, hippocampus, olfactory bulb, and they also have long-range synchronization. The principal associated cognitive processes are perception, attention, motor control, sensory gating, top-down control, and consciousness. Finally, Gamma waves (30-200 Hz) with their long-range synchrony act in all cortical regions: the hippocampus, retina, tectum, basal ganglia, and olfactory bulb (Uhlhaas, & Singer, 2013). Among the brain functions associated with this frequency are perception, attention, memory, consciousness, synaptic plasticity, and motor control.

Although several studies have shown that this proposal has a number of advantages, today no one knows for sure, which specific mechanism the brain uses to accomplish this binding by synchronization. In searching for an appropriate neural synchronization mechanism several theoretical models have been developed (Malsburg, 1995; Jalili, 2009; Suppes et al., 2012; Vassilieva et al., 2011; Zavaglia et al., 2012; Burwick, 2014; Raffone & Van Leeuwen, 2001b). These models have shown that employing synchronization it is possible to perform various types of computing. Examples of these types of computing are recognition of images (vision), recognition of attributes in sentences (language), logical operations, attention, associative memory, as well as perform all those functions under similar noise conditions of those found in the brain.

3. NOT BINDING - GLOBAL CHAOS?

Another view of how to deal with the binding problem suggests using the theory of deterministic chaos. Chaotic systems are characterized by stochastic behavior. However, they can be described by deterministic equations (Scott, 2007; Tabor, 1989). This means that in principle, it may be possible to determine the system evolution during the time. In addition, chaotic systems have the property of being sensitive to initial conditions, which implies that very slight changes in initial conditions can result in very different solutions. According to this proposal, the binding problem could be a pseudo-problem. The information related to an external object would be globally represented in the brain by a special dynamic neural pattern associated with that stimulus. (Raffone, & van Leeuwen, 2001a; Tsuda, 2001; Azhar et al., 2005; Freeman, & Barrie, 2001; Freeman, Gaál, & Jorsten, 2003).

In the same way as in the approaches of the previous section, these hypotheses presented use of synchronization as a fundamental component. But it seems that in these models the main mechanisms responsible for the integration of different features are the low frequency oscillations, which propagate over long distances in the brain. The different stimuli are combined in these low-frequency oscillations in the form of resonances (Freeman & Barrie, 2001; Freeman, Gaál, & Jorsten, 2003). In a similar way, in Raffone & Van Leeuwen (2001b), article the authors made an evaluation of the limitations of traditional proposals, based on periodic oscillations, and they suggested a model for the binding based on chaotic solutions. In addition, according to these authors, the because of increased sensitivity chaos increases the representation capability.

4. RELATION WITH CONSCIOUSNESS

There is a large literature focused on the relationship between binding and consciousness, since the binding problem addresses the integration of different sensory features, because consciousness requires the integration of various sensory experiences (Bob, 2011; 2015; Cleeremans, 2003; Crick, & Koch, 1990; Feldman, 2013; Revonsuo, 1999; Singer, 2001; Treisman, 1996; Zmigrod & Hommel, 2011). In these works, synchronization is the basis for binding mechanism.

However, the existence of synchronization is not a sufficient condition for identification of consciousness in brain signals. For instance, it is known that neural synchronization is possible in situations where people are not conscious. This conclusion is hardly surprising, since even in situations where people are not conscious the existence of feature binding is expected. Currently there is an intense debate about the possibility that some animals may have consciousness (Baars, 2005; Boly et al., 2013; Droege & Braithwaite, 2015; Fabbro et al., 2015; Seth et al., 2005). Although this discussion is still in progress, there is no doubt that many animals are capable of forming one integral image of objects observed in the environment. In other words animals have ability of binding different features in their brains. The current opinion is that consciousness is part of an advanced step in the evolution process, and therefore is a kind of higher manifestation of binding. In this context, although the binding (synchronization) is not a sufficient condition for the existence of consciousness, it is considered a necessary one.

For instance, one idea to measure consciousness that is currently under consideration uses the concept of mathematical information as a measure of consciousness (Tononi, 2004; 2005; 2007; 2008; Tononi & Edelman, 1998; Tononi & Sporns, 2003; Tononi, Edelman & Sporns, 1998). According to this proposal, the brain is a complex system that exhibits different degrees of organization depending on the function being performed at every moment (Tononi, Edelman & Sporns, 1998). As a result, this hypothesis assumes that during a state of consciousness, the brain has the highest levels of information. In this case, the information generated by the brain as a whole is greater than the sum of the information generated by each subsystem.

However, various authors have criticized the implementation of this proposal. According to them there are mathematical inconsistencies (Casali et al., 2013; Dehaene et al., 2014; Seth, Barrett & Barnett 2011; Seth et al., 2006). Most likely, the establishment of a measure of consciousness represents a significant step towards the establishment of a science of consciousness. However, the measure of consciousness is an index, and as an index it is unable to explain the mechanism that generates consciousness. For this purpose, the use of chaos concepts, and synchronization may become inevitable.

5. SYNCHRONIZATION AND MENTAL DISORDER

It seems that significant impairments in our perception or consciousness systems may implicate a mental disorder. In recent years, several studies have been reported where monitoring of neural synchronization activity was used as a tool to identify differences in the neural patterns between healthy subjects and others with mental disorders. For example, these studies have shown that schizophrenia arises due to the defective functional connections in networks generated through synchronization. (Uhlhaas, Roux, & Singer, 2013; Saalman et al., 2012; Ronenwett & Csernansky, 2010; Yu et al., 2014)

In particular, these studies have shown that synchronization in the beta frequency band in thalamocortical region was correlated with working memory. In addition, it was found that an activity reduction of mediodorsal thalamus and thalamus cortical areas leads to a deficiency in the processes of acquisition and maintenance of information. (Uhlhaas, Roux, & Singer, 2013). Besides the beta frequency synchronization, these studies showed correlation in the gamma

band with schizophrenia (Spencer et al., 2004; 2008; 2009; Uhlhaas et al. 2009; 2010; Lee et al., 2003; Wang et al., 2015).

In addition, various studies have reported that changes in synchronization patterns may be associated also with other disorders. Some of these studies have investigated such correlations in specific disorders such as, ADHD (Groom et al., 2010), bipolar disorder (Atagun et al., 2011; Chen et al., 2008b; Tan et al., 2014; O'Donnell et al., 2004; Özerdem et al., 2010; Özerdem et al., 2011), Alzheimer (Dauwels et al., 2010), first-episode psychosis (Flynn et al., 2008), mild cognitive impairment (Missonnier et al., 2006), Parkinson's disease (Hammond, Bergman, & Brown, 2007) or traumatic brain injury (Leon-Carrion et al., 2012). Other studies have shown the existence of this association between deficiencies in synchronization and various types of disorders, for example in Alzheimer's disease, mild cognitive impairment, attention, bipolar disorder and obsessive-compulsive disorder (Basar & Guntekin, 2013; Koenig et al., 2005; Leocani et al., 2001; Uhlhaas & Singer, 2006).

6. DIAGNOSIS AND TREATMENT

Until recently, unlike other medical areas, laboratory tests were not used in psychiatry as a method of diagnosis. Basically interviews and questionnaires were the unique ways to identify a mental disorder. This scenario is changing, and knowledge about the synchronization patterns may play an important role in this change.

For example, Leuchter et al. (2015) investigated the relationship of synchronization and depressive disorders, and suggested the use of neuromodulation as part of the therapy. In another study Jamal et al. (2014) studied synchrony for the classification of autism spectrum. Also other studies investigated the use of synchrony as a tool for diagnosis purposes (Strelets et al., 2006; Singer, 2012; Peled, 2004; 2012a; 2012b; Gandal et al., 2012; Hinkley et al., 2011; Adeli & Lichtenstein, 2011; Dauwels et al., 2010; Boutros et al., 2008).

In addition to the diagnosis, various techniques have been proposed using synchronization measures as a validation assessments for the treatment of mental disorders, for example using transcranial magnetic stimulation (Cohen et al., 1999; D'Alfonso et al., 2002; Hoffman et al., 2003; Jandl et al., 2005; Jin et al., 2006; Fitzgerald et al., 2008; Schneider et al., 2008; Freitas et al., 2009; Prikryl, 2011; Leuchter et al., 2013; Baruth et al., 2010), electroconvulsive therapy (Okazaki et al., 2015), Deep Brain stimulation (Beudel et al, 2015; Fitzgerald, 2011), to check the effectiveness of Deep Brain Stimulation surgery (Quraan et al, 2014), neurofeedback (Pineda, Juavinett & Datko, 2012), electrical stimulation (Jiménez et al., 2013), to check the effectiveness of a drug treatment via EEG analysis (Kikuchi et al., 2007) or functional neuroanatomy of neural oscillations (Ford et al., 2007).

7. CHAOS AND MENTAL DISORDERS

In 1992 Freeman has suggested the use of complexity theory for the study of schizophrenia and mood instability in bipolar disorders. (Freeman, 1992). According to Freeman, chaos underlies the brain's ability to respond flexibly to the outside world and to generate a rich variety of patterns, including those related to creativity. Therefore according to his findings the unpredictable underlying order in chaotic systems allows to model the complex behavior observed in the brain.

In fact, the dynamics of the underlying attractor reconstructed from the EEG data seems to be chaotic in nature. Freeman's later findings led to the hypothesis that each area of the brain, instead of each stimulus, has a chaotic attractor. A specific sensory stimulus leads the system to a localized region within the attractor associated with a particular stimulus. Furthermore, the attractors themselves must change as a result of new experiences.

Freeman also suggested a possible association of presence of chaos in the brain and the observed unpredictability in the mental and behavioral events (Namikawa, Nishimoto, & Tani, 2011). Those observations were correlated with changes in the spatiotemporal patterns of activity of chaotic systems (Freeman, 1999).

Other studies suggest a relationship of chaotic dynamics with a wide range of cognitive phenomena connected with characteristic changes during the manifestations of mental disorders such as depression or schizophrenia (Gottschalk et al., 1995; Barton, 1994; Huber et al., 1999; Korn & Faure, 2003; Melancon et al., 2000; Paulus & Braff, 2003; Freeman, 2011; Bob et al., 2009). There are also works that attribute the chaotic transitions to dissociative states in psychopathological conditions (Bob, 2009; Bob & Louchakova, 2015). They propose hypotheses relating the process of dissociation with the chaotic dynamics generated by discrete maps (Putnam, 1997) suggesting that the chaotic transitions may be related to dissociative states in the brain (Bob, 2003; 2007). In addition, there are studies linking bipolar disorder with chaos (Gottschalk, Bauer & Whybrow, 1995; Bahrami et al., 2005; Buckjohn et al., 2010; Hadaeghi et al., 2013). All these observations suggest a special role for the chaotic dynamics in various mental processes.

8. CONCLUSION

The basic intent of this overview has been to show that complexity may represent an essential part of future research in neuroscience, and may have special applications for the understanding of mental disorders. Synchronization appears as a unifying element in studies of “binding problem” mainly related to perceptual processes but also in principle related to basic mechanisms of consciousness and mental disorders. In this scenario mental disorders may be interpreted in terms of abnormal synchronization patterns among different brain regions. From this observation, a new understanding of the physical-chemical mechanisms in the brain responsible for these anomalies may emerge.

In the same way, the knowledge gained regarding the brain's chaotic properties has opened new directions, mainly linked to understanding of the systemic nature of brain functions and new insights into the brain stochastic patterns and chaotic dynamics in the brain that may be specifically associated with mental disorders.

Another important consequence is the use of mathematical models that may enable to describe various experimental data and help in clinical practice regarding predictions and treatment strategies.

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