The neurodynamic core of consciousness and neural darwinism

A. Ibáñez [a,b]

THE NEURODYNAMIC CORE OF CONSCIOUSNESS AND NEURAL DARWINISM

Summary. Introduction. *In the last decades, the scientific study of consciousness in the scope of the cognitive neurosciences can be considered one of the greatest challenges of contemporary science. The Gerald Edelman theory of consciousness is one of the most promissory and controversial perspectives. This theory stands out by its approach to topics usually rejected by other neurophysiologic theories of the consciousness, as the case of the neurophysiologic explanation of* qualia. Aim. *The goal of this paper is to revise the dynamic core theory of consciousness, presenting the main features of the theory, analyzing the explanation strategies, their empirical extensions, and elaborating some critic considerations about the possibility of the neuroscientific study of* qualia. Development. *The central and additional theoretical components are analyzed, emphasizing its ontological, restrictive and explanatory assumptions. The properties of the conscious phenomena and its cerebral correlates as advanced by the theory are described, and finally its experiments and empirical extensions are examined. The explanatory strategies of the theory are analyzed, based on conceptual isomorphism between the phenomenological properties and the neurophysiological and mathematical measures. Some criticisms could be raised about the limitations of the dynamic core theory, especially regarding its account of the so-called 'hard problem' of consciousness or* qualia. *[REV NEUROL 2007; 45: 547-55]*

Key words. *Brain dynamics. Consciousness. Large-scale neural synchrony. Metastability. Neural darwinism.* Qualia.

INTRODUCTION

To study the stomach without looking at its digestive function is counterintuitive. To study the brain, cognition, or the mind without looking at consciousness, would be the same [1]. Consciousness exists; moreover, it is essential to human beings. Cognitive neurosciences have not shied away from this affirmation over the last decades, since this discipline carries a unifying character [2]. The study of consciousness, which until recently was considered a nonexistent topic from materialistic approaches, or on the contrary, was separated from the scientific explanation on dualistic points of view, has become nowadays the most promising of cognitive sciences. Over the last 30 years more than 3,000 articles in neuroscience, psychology, philosophy and artificial intelligence have been published. Over the last 20 years, multiple neurobiological theories of consciousness have arisen [3-19]. Since these theories are in the developmental phase [20], the usual strategy consists of leaving the most difficult challenges on standby (ie. *Qualia*), and focusing on neuronal correlates [4, 21]

Nevertheless, one of the most prominent theories in this field seems to stand out from the rest in regards to *Qualia*. *Qualia* is a philosophical term that defines the subjective qualities of mental experiences, for example, the redness of red, or the painfulness of pain. Normally, neurobiological theories of consciousness avoid taking ownership of these subjective properties (known as the hard problem of consciousness) and approach more empirical and observable aspects of it (i.e., awareness, correlates of conscious activity). Nevertheless, neural darwinism intends to take on *Qualia*. Proposed initially as a broad ranging cerebral activity theory [22-25], it evolved into a theory of consciousness [26-29]. Its main exponent, Gerald Edelman, defends a theory built on assumptions originating from the neo-Darwinian theory and complexity theories. His focus maintains that consciousness is a consequence of an interaction process between neuronal populations, which is coordinated spontaneously and continuously among themselves, with the body and the environment. The main domain of the study is consciousness as *Qualia* or subjective quality of experience. Edelman thus proposes a scientific theory of subjectivity, as a basis for understanding higher processes of human consciousness.

Given the high relevance of the consciousness naturalization project, developed within the cognitive neurosciences, and the radicalism of G. Edelman's proposal, the present text's objective is to carry out a revision of the theory of the dynamic core of consciousness:, present the basic characteristics of it, analyze the explanatory strategies and their empirical advances, and elaborate some critical considerations of the neuroscientific study of *Qualia*.

NEURAL DARWINISM'S CENTRAL COMPONENTS

Dynamic reentry

The hard core of the theory is based on identification of consciousness with the image of dynamic reentry. This concept is considered a sufficient condition for the study of consciousness [27]. Dynamic reentry is 'The ongoing recursive interchange of parallel signals among brain areas, which serves to coordinate the activities of different brain areas in space and time' [27] (p. 41). Dynamic reentry is a kind of dynamic system. This is a mathematical representation of a set of variables which describe the temporary evolution of a system. A dynamic system can be

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topologically represented by means of a spatiotemporal topology that defines the global properties of a system of variables. This reentry process defines a particular spatiotemporal distribution of the cerebral system, which is a result of the interaction of the brain, the body and the environment. According to the theory, the reentrant dynamic interactions between cortical circuits stimulated by signals originating in the body, the environment, and the ongoing activity in the brain, allow the integration of several processes of neuronal coordination between multiple distributed areas [26].

Dynamic reentry is a multidimensional spatiotemporal system instantiated in the neurons by means of integration and mutual segregation of neuronal assemblies. Integration and segregation are metastable properties of dynamic reentry [26,30]. Unlike simple coordination, metastability implies a conjugation between processes of local segregation and global integration. Metastability of a system consists of the coordination of two tendencies: the components' tendency to work independently (segregation) which coexists with the tendency to coordinate spontaneously with other components (integration). For example, pollination can be considered a metastable process, in which two independent and segregated components (the bee and the flower) interact in a metastable mode, in a global and changing dynamic that produces pollination.

Bimanual coordination is another good example of metastability. Consider the following phenomenon: You can move both of your hands symmetrically in a horizontal plane and in opposite directions, producing a homologous activation of the muscles in both hands. You can also move your hands inversely in the same direction, producing an antagonistic activation of the muscles of each hand. The first movement will be called 'in phase' whereas the second will be called 'anti-phase'. In phase movements tend to be more stable than anti-phase, and when the movements' oscillation frequency (Hz) is increased to a certain threshold, the anti-phase activity tends to become stabilized in an in phase motion. This is a metastable phenomenon in which two segregated components (the movement of each hand) are coordinated in a dynamically integrated, global metastable movement. This phenomenon can be understood by means of a nonlinear coupling function of a collective-variable:

$$V(\phi) = -a*\cos(\phi) - b*\cos(2\phi)$$

The in phase and anti-phase movements of both hands operating at a common frequency can be mapped in two attractors, = 0° (phase) and = 180° (anti-phase). The dynamics of a disordered regime's move to another metastable one, can be represented with a relative phase defined by a *V* function (that represents the coordination between both movements). When changing the ratio *b/a*, which is inversely related to the cyclical frequency, *V* can move from a bistable position (in-phase and anti-phase) to a metastable one (in phase). With the simple example of bimanual coordination, global dynamics of a coordinated system, defined by a collective variable, experience global changes in which each segregated activity of its components is coordinated globally.

With the same initial formula, certain metastable patterns of neuronal assemblies and many other phenomena may be understood. Until now we have briefly developed the metastability concept which is central to this text. Let us return now to Edelman's theory.

This theory's general statement is that neuronal systems related to consciousness are an evolutionary consequence that allows for integrating a high quantity of parallel perceptual-motor processes, along with the organism's memory of contextual and historical information [27]. The space-time coordination of the neuronal assemblies is considered a stage of delayed selection on the nervous system development; and it represents the process by means of which the brain self-organizes with its body, its environment and itself. This process of topological coordination is the key element in extending neural darwinism to the study of consciousness [31]. Since dynamic reentry is the general property of the nervous system (it has also been applied to explain perceptual categorization processes, learning and motor control [32,33]), it is brought up to date as the dynamic core in the scope of explaining consciousness.

Theoretical frame of neural darwinism

Ontological assumptions about the brain

For Edelman the brain is a nonlinear system, highly connected with the body and its environments, constantly impregnated by noise and not autonomous (with respect to its environments). How does the brain become this system? In 1978 Edelman laid down the foundation of his general theory, based on three stages of selection and experience:

- *Development and selection of neuronal primary repertoire:* this implies the neurogenesis of neuronal groups based on cell division and subsequent grouping into neuronal assemblies, which by means of cooperation and competition mutually extend or are eliminated.
- *Secondary repertoire:* refers to changes in synaptic connections mediated by learning and experience. This process determines that certain neuronal routes are favored.
- *Processes of reentry of the neuronal assemblies:* make spatiotemporal connection possible on a large scale in the brain. These processes thus imply global coordination of cerebral dynamics.

The primary and secondary repertoires and reentry will determine the nervous system's organization, which will be defined by processes of integration and segregation, constantly interplaying with local and global processes.

Ontological assumptions about consciousness

From this theory, two fundamental properties about consciousness are assumed. The reentrant interaction of neuronal assemblies related to action and memory is associated with primary consciousness that refers to the multimodal presence of perceptual and motor events. Primary consciousness relates to the processes of reentry between areas of perception and memory systems, which allow the organism to adapt based on its previous history [28]. This way, primary consciousness implies integration of conscious experience oriented by the organism's historical-evolutionary sense.

Secondary consciousness implies future plans, semantic knowledge, and self-consciousness. Secondary consciousness is based on the same reentry processes as primary consciousness, but in more delayed evolutionary stages, in which the reentrant circuits connect memory systems with linguistic and semantic systems [26]. There are then two consciousnesses in Edelman's theory (Fig. 1): a more basic process that consists of integrated experience of perception-action and memory, associated with

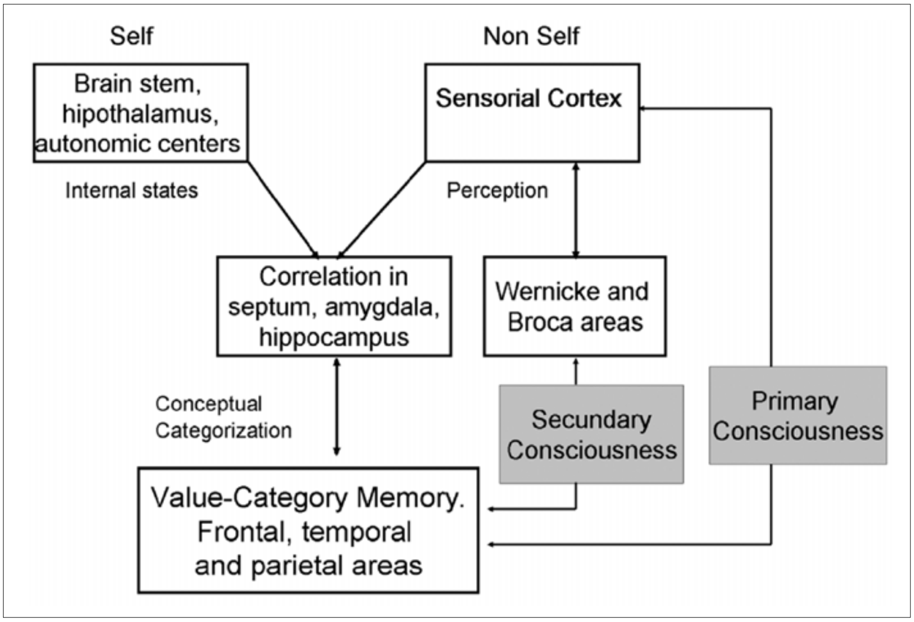

Figure 1. The two consciences. The reentrant connections between the internal signals (self) and the world (not self) are correlated and are constituted in the organism's memories. These are connected by reentries with perceptive processes, which cause primary consciousness to emerge. Higher order consciousness depends on later processes of reentry between memory and language categorization processes. Based on [28].

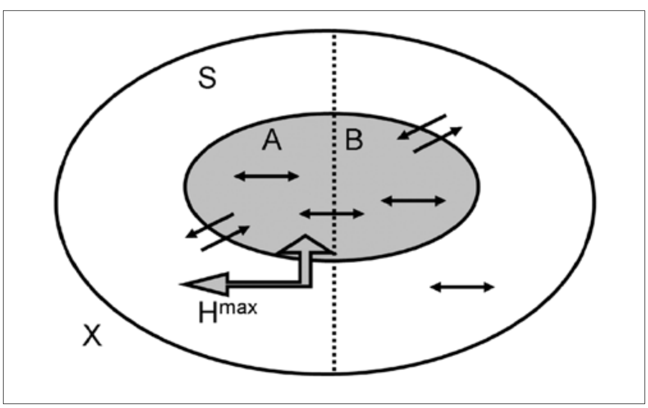

Figure 2. Effective Information. Subgroup S (gray ellipse) is comprised of a greater system X. S is separated in A and B (dotted line). Arrows indicate connections between subgroups. All the connections being present, effective information is measured introducing H^{max} (maximum entropy) in the external A connections. Then, the entropy of B states is measured. Note that A may directly affect B (via connections A-B) and indirectly (via X). Based on [38].

Qualia, and a secondary, of superior order, that is constructed on it. Both are precisely elicit by means of reentry. The consciousness phenomenon is conceptualized from a 'unified field approach' [1] based on the assumption of studying consciousness as a unified phenomenon (a theory opposed to this approach is supported by Bartels et al [34]). This is not about an atomization model of conscious phenomena but rather a unitary experience of consciousness as an essential phenomenon of it.

Restrictive assumptions

This concept refers to subsidiary elements of Edelman's theory based on mathematical measures of integration and segregation, which will be used to argue in favor of consciousness properties. Since consciousness depends on metastable process, the theory defines a set of tools to characterize the neuronal phenomena of integration and segregation. These tools are based on information theory and measures of complexity applied to cerebral activity [35-37].

Segregation of a local area will be defined mathematically as the relative statistical independence of a subgroup (a local area) in relation to the whole system. Integration will be established as a deviation of relative statistical independence of large subgroups [36]. Processes of integration and segregation will be conceptualized in terms of effective information: a measurement that encompasses all the possible interactions between the subgroups of a system (Fig. 2).

The statistical probability of these functions is defined by a multivariate process characterized by entropy and mutual information [29,38]. Consider a subgroup of *k* elements (X*k*j) taken from an isolated neuronal system (X), and its complement (X – Xkj). Interactions between the subgroup and the rest of the system introduce statistical dependencies between both. This is measured by its entropy (H) and mutual information (MI): MI (X*k*j, X – X*k*j) = H (X*k*j) + H (X – X*k*j) – H (X). It encompasses all the possibilities in which the entropy of X*k*j is explained by the entropy of X – X*k*j and vice versa [36].

A system will be considered metastable if it exhibits simultaneously high local segregation and high global integration. The degree of metastability will be evaluated by means of a measurement entitled 'complexity'. A system will be considered complex when its subgroups exhibit high statistical dependency internally and low statistical dependency with respect to the exterior of the subgroup; and simultaneously the dynamics of the system will tend to be highly integrated globally. In this way a complex system will be simultaneously segregated locally and integrated at a global level. The complexity measures will be low in systems that are highly isolated (non-integration) or if they are massively and homogenously connected (non-segregation). On the contrary, a system will have high measures of complexity if its elements are connected densely and in a specific way (which will imply both measures of integration and segregation). The complexity measurement will then be an average function of the mutual information between each subgroup and the rest of the system. A complex system will have heterogeneous subgroups that act quasi-independently at the local level, but will form large assemblies among one another, producing global functions of global coherence [26].

The application of these measures of integration-segregation and complexity will then be applied to consciousness in two ways [28]:

– A neuronal assembly will directly contribute to conscious experience if it comprises part of a functional cluster, which produces a process of global coordination in milliseconds

through reentrant interactions in the thalamus-cortical system.
– In order to be part of a conscious experience, it is essential that the previous functional cluster is also highly differentiated, observed by means of measures of high complexity.

Explanatory assumptions

This theory assumes that consciousness is conceived as an emergent property of neuronal reentries. Although these depend on the thalamus-cortical interaction, consciousness does not reside in a specific set of neurons. It is considered a global unitary phenomenon, non-attributable to a reduced set of neurons. Frequently, the dynamic core of consciousness is changing its neuronal configuration [29].

The emergent coordination of consciousness is a type of global to local causation (or 'downward causation'). This concept experienced remarkable development in the field of cognitive sciences, mainly with the development of dynamic approaches to cognition. The downward causation is dependent from the global properties of the system, which being emergent, are also 'submergent'; that is to say, they produce causal effects at the local level or from their basal properties. The dynamic core of consciousness is affected by causal sequences of the world, body and other cerebral processes in themselves, but simultaneously the core activity affects neuronal phenomena and future actions (Fig. 3).

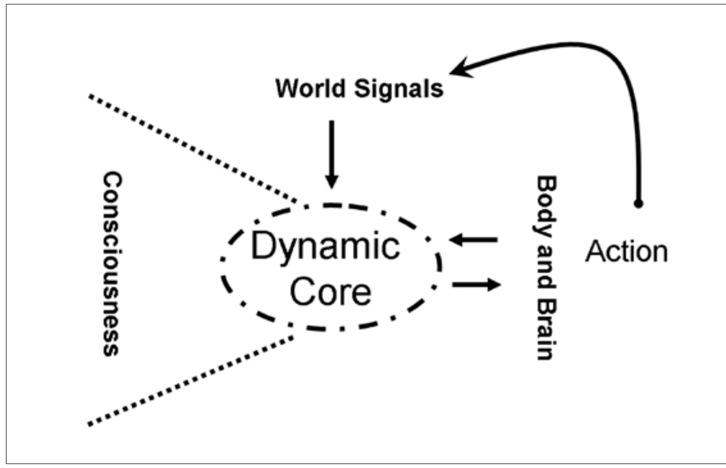

Figure 3. Causal circularity of reentrant dynamic core. The causal chains between the world, the body, and the brain affect the reentrant dynamic core. Conscious activity of the core also affects future neuronal events and actions. Core boundaries are continuously changing (dotted circle). Modified from [26].

According to the theory, neuronal systems that lie behind consciousness allow the emergence of higher order discriminations in a multidimensional space, and *Qualia* consists of those discriminations [26,27]. In other words, subjective consciousness would correspond to a particular temporary coordination between neuronal assemblies which would change simultaneously with the change of subjective states of consciousness. This is what converts the dynamic core theory into one of the most radical and controversial proposals. Explicitly, it proposes one analogy between phenomenological properties and properties of a dynamic cerebral system. Phenomenology (of the Greek φαινομαι, 'to show up' or 'to appear', and λογοζ, 'reason' or 'explanation') refers to experiences or subjective states. Phenomenological states are considered a property of consciousness since they refer to the subjective act of knowledge. *Qualia* (the subjective sensation of something, for example, the redness of red) are examples of it. Edelman's theory establishes a condition of identity between *Qualia* and spatiotemporal dynamics or nervous system topology. It refers to an identity relationship between spatiotemporal topology and consciousness, as an implementation of Fechner's identity postulate [39]. The image of spatiotemporal patterns of the brain is mapped directly with *Qualia*/subjectivity, by means of isomorphism between properties of integration and segregation of consciousness (as phenomenological properties) and reentrant dynamic core (as statistical measures). Note that in the mathematical definition, segregation and integration refer to 'connectivity'. This is unlike the segregation and integration of consciousness, which make reference to phenomenology: the unitary experience of consciousness and the continuous change of states in it.

Relevance and promise of neural darwinism

How does consciousness emerge? What are its neuronal correlates? Is the existence of *Qualia* possible at a neuronal level? These are the main questions that this theory promises to answer. The project of consciousness naturalization must be read simultaneously as mathematization, neurobiologization and subjectivization of consciousness. This project is based on the metaphor of a dynamic system applied to cerebral activity and conscious phenomena. Unlike other consciousness naturalization projects this one's promise is centered on the notion of *Qualia* and subjectivity as unitary consciousness phenomenon. In this sense, it shows the promise of subjective naturalization based on an objective theory, being able to 'measure' (by means of the metastability measures) consciousness (as *Qualia* or subjectivity) at the neuronal level. For that reason, the central promise of the theory consists of acceding to the study of consciousness by means of dynamic tools, offering specific means to identify that neuronal activity which 'is' *Qualia* [26].

ADDITIONAL COMPONENTS OF NEURAL DARWINISM

Knowledge domain: appeal to the phenomenology of consciousness and neuronal correlates

Knowledge domain will be understood as the accumulated knowledge in a research area that constitutes factors that are not contemplated by the central components of a theory, but that redefine the global properties of it. Edelman assumes two consciousness properties relevant to the theory: integration and differentiation based on analogies with metastable properties. For neural Darwinism, integration is a property shared by each conscious experience. Each conscious state implies a singular scenario that cannot be separated into independent parts [26]. Integration can be observed by the inability to carry out multiple tasks separately, except when these tasks are automatic and do not require consciousness. In conjunction to considering consciousness as an integrated whole, the extraordinary differentiation or complexity of experience stands out. The number of conscious states that can be discussed in a short period of time is very high [38]. The perception of a red square is a unified experience: we perceive the redness of red and the 'squareness' of square in only one way, as a unique event. The experience of the red square can be equally perceived against a constant change in any other stimulus of any type (auditory, visual, kinesthetic, olfactory, and somatosensory).

In the field of neuroscience the knowledge domain that is used by the theory can be outlined in three main points:

- *It is assumed that consciousness has a correlate of fast neuronal oscillations at low amplitude:* it has been well known since Berger [40] that conscious activity is usually correlated with oscillatory activity of 20-70 Hz [41]. On the other hand, a number of unconscious states (deep sleep, vegetative state, anesthesia, and epileptic convulsions) show a predominance of slow activity (less than 4 Hz) at high amplitude [42].
- *Thalamus-cortical interactions:* conscious activity in mammals is widely associated with interaction between the thalamus and the cortex; and when this interaction is interrupted (for example, by means of injuries), diverse degrees of loss of consciousness are denoted [43].
- *Prefrontal, medial temporal and parietal distributed activity:* dozens of studies demonstrate that conscious activity is correlated with widespread distribution in brain regions; and on the contrary, the study of unconscious phenomena demonstrates local activation of cerebral areas [44]. Subsequently, distribution of conscious activity is usually related to global coordination of cerebral activity [45,46], mainly through large-scale neural coordination (although evidence to the contrary also exists, that is to say, conscious activity in terms of a small group of local neurons has been shown [47]). Large-scale neuronal synchrony has been studied in humans and animals, through sensorimotor and perceptual-motor tasks [48]; visual discrimination [49-51]; perception of human faces [52]; binocular rivalry [46]; multimodal integration [53]; learning and attention [54,55]; and working memory [56]. Finally, it has been proposed as a neural correlate of consciousness [16-17,57].

The prototype of neural darwinism: dynamic core as specification of the consciousness hypothesis

It has already been affirmed that neural Darwinism is a general theory about the nervous system and its evolution with the body and its environments. The reentry notion is the conceptual nucleus that allows the general nervous system theory to become a theory of consciousness. The reentrant circuits are conceptualized as a 'dynamic core', a specific reentrant system able to explain consciousness. It assumes the general properties of reentrant systems, specified however in such a way that it can hold knowledge domain about consciousness and its cerebral correlates. It simultaneously allows their mathematical measurement. Edelman and his collaborators define it as a neuronal grouping process that in a temporal scale of milliseconds constitutes a metastable coordination of high complexity (simultaneously integrated and segregated) [29].

Dynamic core is always related to neural activity between 20-70 Hz in the thalamus-cortical system [26,29]. Nevertheless, consciousness is not a consequence of some specific cerebral area activity. On the contrary, a subjective state is determined by the entire dynamic core. A conscious event may be associated with a simple point in a multidimensional space (N) where N represents the number of neuronal groups that are part of a dynamic core at a given time. 'Conscious sensation' is then linked to a dynamic organization of the topological system [31]. The landscape of the dynamic core is always changing its topology, according to metastability processes. This core is then considered a process, not a thing or a particular location. The concept of dynamic core implies then a macroscopic state of cerebral activity defined by previous dynamics, sensorimotor activity and contextual information. At this point, dynamic core approaches other theoretical perspectives elaborated with different mathematical and neurophysiologic developments [58,59].

This specific reentrant process entitled dynamic core was initially proposed to explain the phenomena of perceptual binding, the process that wholly integrates the different aspects from an event, like its shape, color, movement, etc.; in a perception with sense [4]. It is conscious property that has mostly been assessed by neuroscience [16,25,60-62]. Initially the metastable properties (by means of measurements of integration-segregation) of the neuronal networks that accomplish the integration of multiple percepts were studied.

Later, the dynamic core hypothesis was studied in schizophrenic subjects, in whom a reduction of metastable measures of complexity obtained from a registry of conscious cognitive PET activities was observed [63]. It supposes, according to the authors, that dynamic core is reduced in patients with schizophrenia, assuming that conscious activity in them is found to be reduced or, at least, altered. Also, metastability measurements were applied to cerebral areas not associated with conscious activity, like the cerebellum. In light of a reduction in complexity measures, it is assumed that these areas are not essential for dynamic core.

The authors affirm the possibility of testing the dynamic core hypothesis of consciousness by applying measures of neuronal integration and complexity, together with extensive analysis of neurological data [29].

Empirical extensions

The empirical study of dynamic core is highly dependent on the development of more sophisticated methods of measurement that allow measuring cortical-thalamic activity in humans, as well as methods for simultaneous measurement in different cerebral regions [26]. Progress in mathematical methods most in accordance with metastable cerebral dynamics, particularly not-linear methods, is also required to advance the theory [30].

The use of computational simulations [30,64-66] has demonstrated that patterns associated with integration processes have high indices of complexity with locally dense connections and large-scale connections that provide global integration. Additional simulations have demonstrated that complex dynamics of neuronal networks can reproduce the same results from different network sub-partitions, which supports the dynamic aspects of reentrant core [37]. Such results are also found in neuronal networks that control agent activity [66].

Synchronous neuronal activity has been used as an indirect measure of dynamic core metastable activity (for example, in studies of binocular rivalry that indicate increase in synchronous neocortical activity associated with perceived stimulus [46]). Studies of synchronous activity have been interpreted as indirect measures of dynamic core metastable activity [26,27].

Although at the moment it is not possible to obtain direct evidence in human brains about dynamic core, there is indirect evidence in comparative studies between sleep and wakefulness, and in intralaminar nuclei injuries of the thalamus associated with loss of consciousness [31,67].

Nathan et al [68], compared, by means of structural equation modeling, measures of integration, complexity and effective information in PET data of conscious and unconscious subjects. Their results show that the unconscious state induces increases of massive network integration, with decreases in complexity measures.

Finally, brain-based devices [32,69-72] in the robotic area have proven the power of perceptual binding, metastability and evolution of neuronal dynamics. An advanced prototype of these models is Darwin VIII which consists of a multisensorial movable robot neurally organized (with a cerebral simulation of 19,556 neurons, 18 neuronal areas and 450,000 synaptic connections, without algorithmic rules of representation or symbol manipulation). This device achieves perceptual binding and categorization (with variations according to history of learning and events) and conditioned learning, both explained in terms of the history of interaction of the robot with its environment.

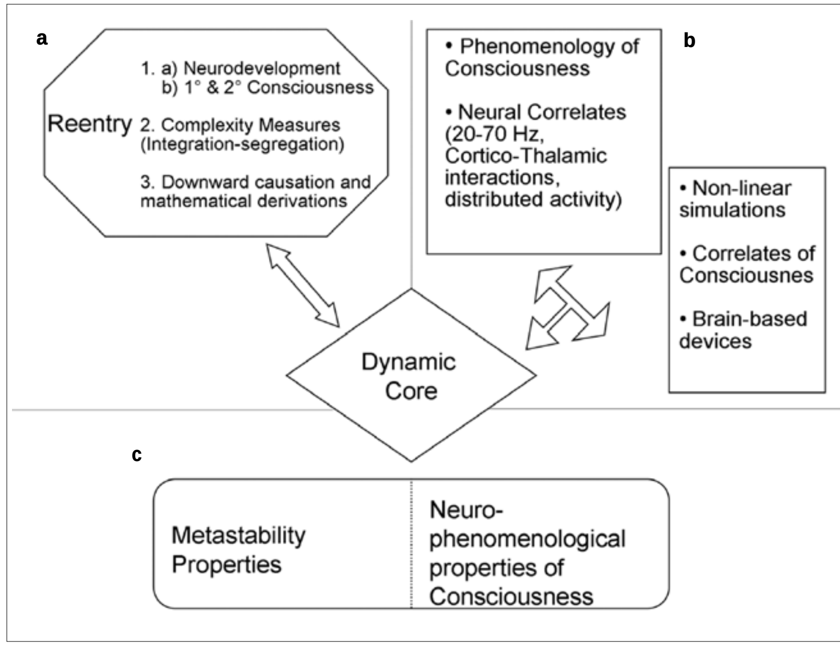

Figure 4. Theoretical components of neural darwinism. a) Central components: core and ontological assumptions (1), restrictive (2) and explanatory (3); b) Additional components: knowledge domain (upper left picture) and empirical advances (right picture). The prototype (dynamic core) entails both, the reentrant systems' properties and consciousness properties; c) Isomorphism relations between explanatory tools (left) and consciousness phenomenon (right).

DISCUSSION

The neural darwinism theory of consciousness is based on an isomorphism relation between consciousness properties and the theory's main components. The notion of dynamic reentry as topological system implies the conjugation of different level concepts, that is to say: consciousness properties, topological tools and information complexity measures [73]. This central core is supported by basic assumptions (evolution of primary, secondary and reentry repertoire; and consciousness assumed as a unitary property based on two evolutionary steps); methodological tools (the use of information measures: effective information, segregation, integration and complexity) and explanatory strategies (downward causation and mathematical derivations). The argumentative relevance of the theory is based on the emergent explanation of subjective consciousness and, later, on secondary consciousness as a dynamic process [74]. Depending on the dynamic core prototype, isomorphism between the central components (metastability and dynamic core) and the subjective properties of consciousness are established when linking the complexity measures with conscious events (Fig. 4).

In this theory, the establishment of isomorphism between consciousness properties (neuronal and phenomenological) and properties of mathematical measures (segregation and simultaneous integration) is explicitly carried out by its authors [26, 29]. The development of the inferences and empirical derivations is based on an analogy of concepts that share partial meanings. For example, mathematical segregation as informational measure and segregation of conscious experience, referring to constant and fast change of subjective events. Or, on the contrary, information integration (as measurement of the relative statistical independence of two sets of information) on one hand, and the integration of a conscious subjective experience that is unitary, in the sense of perceptual binding, on the other hand. Since the 'integration' and 'segregation' concepts are assumed to be isomorphic in mathematical and phenomenological domains, they can be used to test the hypothesis of dynamic core of consciousness. This same conceptual mapping allows for maintaining computational simulations of complexity measures and metastability as evidence in favor of dynamic core no longer in simulation but in living organisms' conscious activity.

One type of explanation used is emergentist (downward causation), since dynamic core implies emergent properties that are a consequence of the influence of the body, brain and environment, and simultaneously, dynamic core redefines the relations with the body, the world and the brain itself [75-77]. Also, since *Qualia* is caused by dynamic core and there is an identity relation between both, it is possible to derive an explanation by means of mathematical laws, since dynamic core begins to be considered a mathematically defined phenomenon.

Criticism of neural darwinism applied to consciousness

Until now, the dynamic core theory of consciousness has been put forward without raising any criticism, so as to present the theoretical components and empirical extensions of it. In this section the most critical aspects of this theory are synthesized.

Firstly, all the validity of the theory rests on the conceptual isomorphism between phenomenological consciousness properties (integration and segregation), and dynamic core properties (integration and segregation). Although these properties of integration and segregation are *conceptually* analogous (at a 'conceptual analogies' level between phenomenological states and mathematical properties), it could well be that in fact they are not. In other words, nothing guarantees that phenomenological conscious activity (described as integration and segregation of conscious experience), necessarily has a metastable neuronal mechanism (which implies an integrated and segregated functional connectivity). Integration and segregation as phenomenological properties of consciousness do not imply *ipso facto* a relation of formal identity with mathematical properties of integration and metastable segregation. For that reason, this isomorphism is not demonstrable *a priori*, but only *a posteriori*, that is to say, if causal evidence (and not merely correlative) that phenomenological properties of consciousness are metastable (in its mathematical sense) exists.

Secondly, it is possible to emphasize that to a great extent, these studies tend to offer indirect information and of a correlative nature (non-causal) about the hypothesis of the dynamic core. The synchronous activity is not necessarily evidence of metastability in its mathematical sense. Although it is certain that large-scale synchronous activity always indicates the interplay of global areas interacting with local areas, the synchrony *per se* is not a measurement of metastability in its mathematical sense. It is a measure of neuronal co-activation (in terms of coherence) or phase (in terms of neuronal phase synchrony). Computational simulations used by Edelman are just a partial version of real cerebral dynamics, and they do not assume all its restrictions. Studies of sensorial integration and learning of brain-based devices, although they imply sensorial integration, are not examples of the study of phenomenological properties of consciousness. Since the theory assumes the study of *Qualia*, it can only cite as evidence computational simulation and robotics if it supposes that both have subjective activity. Or otherwise, only indirect information will be given. In this same sense, extracting measures of metastability of data matrices collected in neurophysiologic records does not necessarily imply that the brain uses metastability mechanisms to generate conscious activity.

Finally, the theory does not seem to be able to argue against certain empirical evidence which suggests that conscious activity, at least in some conditions, depends exclusively on local areas. Also, some properties attributed by the theory to consciousness and the dynamic core (ie. dynamic sensitivity to the context) do not necessarily require conscious activity [78].

CONCLUSIONS

Certainly the theory of dynamic core of consciousness moves away from the most orthodox lines of consciousness naturalization [4,21], when affirming that it deals with the study of *Qualia* from the neurosciences. On the other hand, this theory is inserted within the frame of a global theory of cerebral activity [79]. Given the high relevance of the naturalization project of consciousness developed in the cognitive neurosciences, and the radicalism of G. Edelman's proposal, the present text presented a revision of the consciousness dynamic core theory, describing the basic characteristics of it, analyzing the explanatory strategies and their empirical advances, and elaborating some critical considerations concerning neuroscientific study of *Qualia*. Neurobiological study of consciousness as *Qualia* is a boundary that few dare to trespass with the present scientific tools. As long as the hypothesis of dynamic core confronts the inherent difficulties presented in the previous section, it will be able to sustain that it has passed the boundary self-imposed by most consciousness naturalization theories, or it will be framed within the territory of the so called 'easy problem' of consciousness and its correlates.

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EL NÚCLEO NEURODINÁMICO DE LA CONSCIENCIA Y EL DARWINISMO NEURONAL

Resumen. Introducción. *En las últimas décadas, el proyecto de naturalización de la consciencia en el ámbito de las neurociencias cognitivas puede considerarse uno de los desafíos más grandes de la ciencia contemporánea. La teoría del núcleo dinámico de la consciencia de Gerald Edelman es uno de los enfoques más promisorios y controvertidos. Esta teoría se distingue por el abordaje de tópicos obviados por otras teorías neurocientíficas de la consciencia, como el caso de la explicación neurofisiológica de la experiencia subjetiva consciente (*qualia*).* Objetivo. *Realizar una revisión de la teoría del núcleo dinámico de la consciencia, presentando sus características principales, analizando las estrategias de explicación y sus avances empíricos, y elaborando algunas consideraciones críticas acerca de la posibilidad del estudio neurocientífico del qualia.* Desarrollo. *Se analizan los componentes de la teoría del núcleo dinámico de la consciencia, destacando sus supuestos ontológicos, restrictivos y explicativos, las propiedades de los fenómenos conscientes y sus correlatos cerebrales abordados por la teoría, sus experimentos principales y sus expansiones empíricas. También se abordan las estrategias explicativas de la teoría basadas en isomorfismos conceptuales entre las propiedades fenomenológicas y las medidas neurofisiológicas y matemáticas. Se analizan críticamente algunas limitaciones de la teoría para dar cuenta del denominado 'problema duro' de la consciencia o* qualia. *[REV NEUROL 2007; 45: 547-55]*

Palabras clave. *Consciencia. Darwinismo neuronal. Dinámica cerebral. Metaestabilidad.* Qualia. *Sincronía de gran escala.*