A matter of mind: reductionism and emergentism as frameworks for understanding consciousness

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Abstract

According to materialists, mental processes are a product of the brain. In the context of neural properties such as complexity and consciousness, new frameworks for understanding the brain have raised philosophical issues on how to interpret neural activity and if the underlying structure is sufficient to explain consciousness. Reductionists argue that macro-phenomena such as consciousness can be fully explained by description of the corresponding underlying micro-phenomenon (e.g., molecules and neuron interactions). This approach constitutes the core of contemporary neuroscience and has been used in many different fields, ranging from cognitive to system neuroscience. However, it underestimates the role of all macro-level properties (emergent). An integrative framework called emergentism that tries to explain the relationship between macro and micro-mechanisms has allowed to study the brain from a network-centered perspective, showing that phenomena such as consciousness are better understood by quantifying and addressing the interactions of the elements. Emergentism should then be adopted as a framework to study properties that cannot be explained by studying each of the elements of the system separately and at the same time, reductionism should be carefully used to trace the elements. Both frameworks are mutually inclusive and a better understanding of consciousness is achieved if they are used in conjunction.

Keywords

Reductionism, emergentism, brain complexity, consciousness.

1.0 *Reductionism and emergentism: Primers for understanding consciousness*

Since the 19th century, we have tried to empirically explain the origin of subjective (conscious) experience and its relation to the brain. Different frameworks have been applied to address this relation. One of them is known as the *reductionist-atomistic* approach in which the priority is to describe the parts or the components of the system. According to this approach, it is possible to unify psychology with traditional physical sciences as the chemical basis of the brain suffices to explain the components of conscious experience (Watson, 1913). A second framework (opposite of an atomistic approach) is known as *holism*, in which humans are considered as irreducible wholes (Sawyer, 2002). Given the incapacity to reduce any phenomena, *holism* rejects reductionism and many holists from the beginning of the 20th century even rejected materialism (only physical matter exists) grounding their believes on *vitalism* and implying that humans have a vital substance different from any physical known matter which constitutes our conscious perception (Sawyer, 2002). Because dualistic approaches such as vitalism and holism reject materialism, empirical measurements of conscious experience are impossible to achieve and thus are considered unscientific.

A concept called *emergence* that was originally coined by George Lewes (1875) has received attention again in the quest on understanding consciousness. He mentioned the emergence 'arises out of combined agencies'[1] (vol.2, p. 412). Interestingly, emergence is a type of non-reductionism that in contrast to vitalism or holism accepts materialism (Sawyer, 2002). Emergent explanations of a given phenomenon try to tackle the problem not by addressing the parts nor the sum of

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[1] According to Lewes (1875) emergence 'arises out of the combined agencies, but in a form which does not display the agents in action.' (vol.2, p. 412). It is then safe to say that *agencies* can be interpreted as the elements of a system.

the parts (reductionist), but the interactions of the system that give rise to new properties (see Table 1). Emergence also accept supervenience, which in Sawyer words (2002) means that:

> if a collection of lower-level components with a given set of relations causes higher-level property *E* to emerge at time *t*, then on every other occasion when that same collection of components in that same set of relations occurs, *E* will again emerge. (p.4).

This working definition, as will be discussed later on, is fundamental to understand how brain complexity (Sporns, 2013) and other emergent phenomena work. The concept of *emergence*, urges the necessity to acknowledge that our understanding of higher brain functions cannot be reduced to a microlevel only. Furthermore, in contrast with holism (in Sawyer (2002) terms), microlevel phenomena do matter. This means that our limited technology for measuring brain activity forces us to acknowledge emergence as real as long as we don't have the tools to trace all microlevel interactions that can cause a higher-level phenomenon such as consciousness. Starting always from bottom to top is idealistic.

By using reductionism and emergentism as two primary frameworks I will discuss how consciousness has increased our understanding about the brain. In addition, brain complexity and its relation to consciousness will also be discussed. I will finally argue why reductionism and emergentism are mutually inclusive and complementary and not counterparts and using them together leads to better approximations of what we know about our brains.

1.2 *Reductionism*

The search for a neural explanation on consciousness needs a neuroscientific approach. The Modern Synthesis (Huxley, 1942) in the 1940's marked the beginning of the modern reductionist program in which behavior, evolution and general features of an organism could be traced to its genetic foundation. By the late 70's the blooming field of genetics was at a pick in which Richard Dawkins (1976) called living organisms 'lumbering robots' controlled by its genes. Neurophysiological studies were also flourishing with techniques like patch-clamp (Hamill, Marty, Neher, Sakmann, & Sigworth, 1981; Neher, Sakmann, & Steinbach, 1978) in which for the first time, electrical ion current of neurons where recorded *in vivo*. Around the same dates, single-unit recordings with electrodes were being applied with exiting new ways of mapping and localizing neural activity (Hubel & Wiesel, 1968; Schmidt, McIntosh, Durelli, & Bak, 1978) as well as creating an architectural backbone of the brain (Godschalk, Lemon, Kuypers, & Ronday, 1984).

Analogous to the original paper by Francis Crick (1970) that defined a 'central dogma of molecular biology', a similar dogmatic approach towards the brain currently permeates molecular and more recently, cognitive neuroscience (Bickle, 2006). Although emergentism has become increasingly popular over the last years, especially in network analysis (Sporns, 2013) and cognition (Gazzaniga, 2010), the reductionistic approach is still the most commonly used framework in which genes, ion currents and action potentials represent the core and the center of attention for extracting useful information in neuroscience. Note from Figure 1 that any higher-level organization of the brain such as consciousness can be reduced to the underling lower-level organization. Many studies have shown that indeed cognitive functions such as long-term memory are actively regulated by molecules (Abel et al., 1997; Garcia, Lasiter, Bermudez-Rattoni, & Deems, 1985; Kogan, Frankland, & Silva, 2000). For example, a specific type of protein kinase directly enhances memory consolidation in rats (Shema et al., 2011) while disruption of cAMP-responsive element-binding protein (CREB) causes deficiencies in long-term memory consolidation in mice (Bourtchuladze et al., 1994). Probably this is why the reductionist program has received such an approval among neuroscientist. It is possible to intervene at a cellular level to achieve changes in behavior in controlled experimental conditions. Another methodological example to illustrate how complex phenomena can be traced at (reduced to) a cellular level is optogenetics. Here, transgenic mice that have neurons that depolarize and generate action potentials after a light stimulus are used to directly stimulate target neurons. A direct manipulation of the underlying structure (neurons) again creates a controlled behavioral response (Diesseroth, 2011), which implies that lower-level properties cause changes in cognition and behavior directly. Although a reductionist framework accepts that a step-by-step description of the system (Figure 1) is required to understand each of the organizational levels, a molecular biology of cognition should be achieved. In

Bickle’s words (2007):

> *The behavioral data is fully explained by the dynamics of interactions at the lowest level at which we can intervene directly at any given time to generate behavioral effects, along with the known anatomical connectivities throughout neural circuits leading ultimately to effects on muscle tissue attached to skeletal frames.* (p. 429)

Like so, a reductionist would say: ‘if you understand the molecular foundation of memory, you understand memory itself’. But then: What is then the lowest level we can get? If memory can be reduced to molecules, does this also hold for subjective (conscious) experience? Molecules can in fact be reduced so, atom interactions should explain any behavioral response. Hameroff and Penrose (1996) even mention that conscious experiences arise at quantum-level interactions in the microtubules of neurons. Although theoretically plausible, we still don’t have the tools or the knowledge to critically test such approximations (Gazzaniga, 2010; Pigliucci, 2013). Furthermore, there are other issues that arise from quantum mechanics perspective. Heisenberg’s uncertainty principle states that by successfully predicting the momentum of a particle we are completely uncertain about the location of it (Oppenheim & Wehner, 2010). Simply interacting with a system causes information loss and creating a theory on consciousness that deals with quantum phenomena should have this into account. Moreover, it is well recognized that neurons are always embedded on a context and do not operate as isolated systems (Harris, 2011) so the argument about creating controlled experimental conditions can be misleading. For example, information about space is coded in special neurons called place cells (Moser, Kropff & Moser, 2008) and their neural map can only be understood if studied as a collective. Recording of activity of a single place cell wouldn’t be of much help.

With this in mind, if we want to describe a system by its most fundamental description possible, where should we start? If we can always trace the molecular basis of higher order processes such as cognition, why are we interested in such processes in the first place? Can we always perform a step-by-step reduction of the system, from higher to lower levels in a predictable way? The most straightforward answers to this question is that 1) We cannot trace all higher order phenomena such as consciousness to molecules yet and 2) At least at some extend, there seams to be a reason why higher order processes have real and tangible properties that cannot be explained directly by molecules.

1.3 *Emergentism in human neuroscience:*

Consider the following example: the elements sodium and chloride have specific properties and together form a completely different compound called Sodium Chloride (common salt). Why? How can we explain why and how these two chemical elements form a completely new property? We could explain that all elements have special electron configurations that allow sharing mechanisms to achieve compound creation but this is not the matter under question. The fundamental question why salt *emerges* remains a mystery. The beauty of this simple example is that clarifies what continuously happens in the brain. Indeed, the brain can be reduced to quantum mechanics and an understanding of these interactions would give us the possibility to understand conscious perception completely but again, where to start if quantum mechanics are unpredictable? Also, if consciousness is a fraction of the whole, how can we get a grasp on the whole which consciousness is a small part of? With that said, let's focus on the brain.

We automatically y treat most of all higher order processes in the brain as an emergent properties. But we must be cautions as the meaning of words such as 'arises' or 'emerges' can be much powerful and dangerous to use than we might think. Emergence, if understood correctly, should also be used as a framework to understand the relation between brain function and consciousness. If we want to understand what we actually mean by emergent phenomena, this concept should not be confused with holism. As mentioned in previous paragraphs, although both acknowledge systems as complete wholes, holism states that any given system is irreducible and the elements that make up the system can be ignored (Sawyer, 2002; van Regenmortel, 2004a). This is probably why a ruthless reductionist (in terms of Bickle, 2006) might immediately reject the statement 'cognition emerges' from the brain, ignoring the fact that emergentism does accept lower-level causation for higher-level phenomena.

There are two branches of emergentism that are worth mentioning before continuing this discussion. These are *ontological emergentism* and *epistemological emergentism* (Pigliucci, 2013). Ontological emergentism is defined as emergentism that accepts the natural existence of emergent phenomena and thus, new laws arise after complex interactions of the parts. This type of emergentism is conceptually similar to holism as a given property emerges from the interaction of the elements and we cannot explain this property with the elements alone. The implication of this view is that studying the elements becomes irrelevant and so an empirical and scientific explanation is not possible. As Pigliucci (2013) noticed, the common agreement among scientist is to accept an ontological reductionism, but reject an ontological emergentism, as 'there are no true emergent phenomena, only phenomena that cannot currently be described or understand in terms of fundamental physics' (p. 4). In contrast to ontological emergentism, epistemological emergentism accepts that properties emerge not because they are ultimately real, but because that's the way we can currently perceive them (Piglucci, 2013). The measurement determines the behavior and knowledge we acquire from a system. Piglucci (2013) argues:

> *It is not just, for instance, that it would be too computationally cumbersome to develop a quantum mechanical theory of economics (the predictive issue), it is that one would not know where to start with the task of deploying the tools of quantum mechanics (indeterminacy principle, non-locality, etc.) to somehow account for the phenomena studied by economists (relation between supply and demand, boom-and-bust cycles, etc.). So, again, one does not need to be an ontological emergentist to firmly reject a greedy reductionist programme in biology or the social sciences.* (p. 3)

This is exactly why it is useful to study cognition, behavior, consciousness and brain complexity. It is not that there is not an ultimate physical or quantum explanation of cognition or behavior, it is just that we would not know where to start. Furthermore, the emergent framework has indeed increased our understanding on complexity (Sporns, 2013; Tononi, Sporns & Edelman, 1994) and consciousness (Dehaene & Naccache, 2001; Edelman, 2003; Tononi &

Edelman, 1998). Molecular neuroscience has definitely given hints that behavior can be traced molecularly. In addition to a molecular explanation of memory consolidation (Bickle, 2006), genome wide association studies (GWAS) have successfully linked genes to disease (Hirschhorn & Daly, 2005) just to give an example. Nevertheless, if we want to reconcile the idea that emergent properties and the elements of the system are both important, we need to find ways to measure the interaction between emergent properties and the underlying components, not just find correlations of causation. Linking genes to behavior or molecules to consciousness is not enough. Miner, Pickett & desJardins (2009) propose a logical method they call rule abstraction in which the idea is to find mathematical correlations between low-level rules (fundamental) and all abstract or emergent properties of a system. In a similar way Sauer, Heinemann & Zamboni (2007) mention in a review on system genetics that:

> *The reductionist approach has successfully identified most of the components and many interactions but, unfortunately, offers no convincing concepts and methods to comprehend how system properties emerge. To understand how and why cells function the way they do, comprehensive and quantitative data on component concentrations are required to quantify component interactions.* (p .550).

This approach was successfully applied by Ishii and colleagues (2007) who used a set of enzyme gene-specific disruptants to alter gene expression in *Escherichia coli.* Surprisingly, changes in messenger RNA were extremely small for most genes suggesting the existence of a metabolic network resilient to environmental perturbations. The central message is that we cannot solely rely on the reductionist program to understand a system, because a system is basically a set of interactions between its elements. But how can the emergent framework be used in brain sciences without devaluating or ignoring reductionism? The next sections will show by using brain complexity and consciousness that neuroscience largely benefits from a position in which tracing the parts and studying emergent (epistemological definition) properties gives a better description of brain function.

2 *Key features of the brain: complexity and consciousness*

2.1 *Brain complexity*

Complexity might be one of the hardest concepts to define and many different definitions arise depending on the field of study (Gell-Man,1995). Because the focus of the current study is not to differentiate all kinds of complexity and determine which one suits neuroscience best, I will use *brain complexity* as defined by Tononi, Sporns & Edelman (1994), as it exemplifies how emergent properties gives valuable information about a system. It might be difficult to grasp what this means in terms of brain function, but this definition illustrates how the brain process information and what can we say about it. It requires full understanding of the elements of the system and at the same time, gives valuable information about the system as a whole.

Before describing brain complexity, a short summary of network theory concepts needs to be described. A network is a set of nodes and links that can be depicted in a graph (Figure 2). In neuroscience, nodes represent neurons or regions while the links that connect such nodes represent the connections between the elements (van den Heuvel & Sporns, 2012). Because elements are interacting with each other through the links and are not isolated, graph theory analysis allows the identification of such interactions providing metrics about the topology of the network and about the type interactions the network facilitates. Many emergent phenomena have been described and measured in the brain (Rubinov & Sporns, 2010). It is the interaction of the elements (from structural to functionally synchronized interactions) then and not the elements alone that create different types of metrics, one of them being brain complexity.

Lets imagine two kinds of networks (Figure 2), one completely organized and the other completely disorganized (lack of predictability). In the first one all of the nodes are arrange in a simple and organized manner. Roughly this would be like zooming in to the molecular structure of a simple compound in which all of its molecules are organized. If assuming that this network presents this topology and only this topology, it is very simple to predict even by eye the position, the amount of connections and the amount of steps (move from one node to another if they are connected) required to move from a given node *i* to a node *j*. In this sense, this system is not complex. You can imagine an incredibly large graph like this, the result is the same: it is well *organized* and *predictable*. The second network is quite the opposite: all of the nodes and links are distributed in random order (Figure 2). Notice that although the amount of nodes is similar as in the organized network, the connections between the nodes are placed in completely random order. Here, we cannot predict anything from the system. To better understand this, imagine that each node is a closed room with no windows and links are halls that connect each room. Where would you start moving? We have absolutely no clue about it. We could just walk in any direction and we will be lost every step. Noteworthy, this network is *disorganized* and *unpredictable*.

Why to put so much emphasis on organized and disorganized systems? It is because the brain is a network that is both organized and disorganized, it is neither completely predictable and organized nor disorganized and unpredictable: it is complex. In one of their seminal papers about brain complexity, Tononi, Edelman & Sporns (1994) identified that a given system arranged in a random manner (this can be gas molecules) or completely regular (molecules inside a crystal) is not complex at all. The brain in contrast has a combination of randomness and homogeneity that makes it extremely difficult to measure. Complementing this idea, Bullmore and Sporns (2012) described that the architectural pattern of the brain represents a trade-off between information transfer capacity and wiring cost. Homogeneity of the system might represent efficient information transfer and although this is metabolically expensive, meaningful information is processed. A low wiring cost in turn might reflect local interactions that can be less organized. Interestingly, this type of organization is scale-free (Eguíluz, Chialvo, Cecchi, Baliki, & Apkarian, 2005; He, Zempel, Snyder, & Raichle, 2010) and hierarchical (Bassett et al., 2008; Meunier, Lambiotte, & Bullmore, 2010), meaning that regardless of the level studied (brain regions, nuclei or single neurons) the principles of complexity are the same, which also means that from higher to lower levels, complexity can be addressed using the same methodological tools.

Furthermore, the environment in which we are embedded is complex in the same way our own brains are. The environment represents a set of highly predictable and unpredictable variables. Weather forecasts for example can predict the transition from day to night and that rain is caused by clouds, but fail to predict with absolute certainty what will happen with the weather within just a few days. Leaving aside the principle of quantum mechanics in which unpredictability is an actual property of the physical world and not a lack of awareness of 'hidden' variables (Hawking, 1982), there are too many factors that we cannot (yet) control or predict. Our brains are wired this way. It is predictable and unpredictable at the same time, which suggests that the emergent architecture of the human brain might be a result of selective evolutionary pressure (Mantini, Corbetta, Romani, Orban, & Vanduffel, 2013).

From the first studies addressing emergent properties of biological networks (Bhalla & Iyengar, 1999; Hopfield, 1982), neuroscientists started to pay more attention as many of these properties might have been ignored by a pure reductionist approach. As a result, many other emergent phenomena present in complex (in Tononi, Edelman & Sporns 1994 words) systems described by network theory such as *small-worldness* and *community structure* have now been well documented in different fields of neuroscience, from neural (Watts & Strogatz, 1998) to structural (Hagmann et al., 2007, 2008) and functional (Lord, Horn, Breakspear, & Walter, 2012; Schwarz, Gozzi, & Bifone, 2008) large scale interactions. It is becoming increasingly clear that we can measure emergent properties if the proper tools and methodologies are applied and by acknowledging that measurements are approximations of interactions of the elements of the system. In fact, it is also possible to make comparative studies. A vast amount of information has been generated in the last two decades that compares emergent brain network properties across different psychiatric disorders (Bassett et al., 2008; Kennedy & Courchesne, 2008; Pollonini et al., 2010; Zhang & Raichle, 2010), developmental stages (Fair at al., 2008) and even altered states of consciousness (Achard et al., 2012; Boly et al., 2008; Mazoyer et al., 2001).

In sum, because many properties in the brain are better described as interactions, a reductionist approach doesn't seem enough to explain how these emerge and what can we do with them. Complexity represents one of these properties and an emergentist framework helps to clarify that indeed the brain *gives rise* to many phenomena that cannot be fully explained just by looking or tracing the elements of a system.

2.2 *Consciousness*

It is now clear that emergent properties of the brain, defined under an epistemological point of view, can be measured and studied. Complexity is just one of many examples that neuroscience is currently studying. It shouldn't come as a surprise that the study of resting state networks for example (Damoiseaux et al., 2006) represents a paradigm shift in system neuroscience where previously ignored background stochastic activity became the main phenomenon to look at (Raichle, 2009). Needless to say, even though we know a lot about the brain (Bickle, 2006), that does not mean we are even close to understand precisely how it functions completely. Could we artificially replicate the architecture of the brain and assume it works in the same way? How can 'I' be sure of it? These questions generate debate among philosophers and scientists alike and are usually centered on the fact that we, as living entities, are conscious. But then again, what is consciousness? I will not discuss and describe the many different theories on consciousness nor give a historical review of the many explanations about what it is (Blackmore, 2002; Chalmers, 1995; Dennett, 2001). I will use instead emergentist and reductionist approaches on consciousness to show that this concept requires much more than molecules or networks.

Similar to complexity, we should define consciousness first. Instead of addressing the question of self and the 'I am' concept, the current review is centered on the simple, but rather complicated idea of the subjective experience of what we perceive. This is also because what we would like to achieve as neuroscientists is to find the neural correlates of consciousness. It is not around 'third-person' explanations on consciousness (Velmans, 2009, p. 4). It is the subjective experience after engaging in a cognitive task that puzzles and matters here the most. Our eyes are capable of perceiving light and produce neural signals that eventually reach our visual cortex. This information is later processed and we react to that. But the apparent 'extra' phenomenon is the subjective experience of light. We do not only perceive color, we experience color. David Chalmers (1995) defined this as the 'hard question on consciousness' and it is the one that I will address here. What happens next? Our eyes decode information about light and our brains encode it back to information the brain can use. But, what next? How or where in the brain does consciousness 'arises'?

If consciousness really arises from the brain, then consciousness is an emergent phenomenon. It is again the interactions of the elements, from molecules to brain regions that give rise to a conscious perception. Giulio Tononi (2008) is one of the many scientists that have tried to explain consciousness under an emergentism framework. In Tononi's integrated information theory, information in human brains becomes consciously available because we are capable of reducing uncertainty (ambiguity) of a present stimulus and at the same time, this reduction of ambiguity is accompanied by integration of information of all elements that were active during the perception of the given stimulus. To clarify this idea he also gives an example about the difference between photodiodes in a camera and our brains. A camera photodiode can only differentiate (reduce uncertainty) with one bit of information. This means that it will perceive light in a binary manner: present or not present. Our brains don't do that. We perceive and recognize certain stimuli as driven by the incredibly large amount of information our brains have to disambiguate. An apple is only an apple among the other billions of things we know. In addition to reduce uncertainty, our brains also integrate information about the stimulus. All photodiodes in a camera perceive light but do not interact. They recreate an image by perceiving light separately and there is no information transfer between each of the photodiodes. In contrast, our brains integrate this information to make it meaningful within the context they are present. Using the previous example, 'green' and 'apple' are to different concepts but our brains are capable of integrating them into a 'green apple', which is a unique brain state. According to Tononi (2004), it is the capacity of a system to reduce uncertainty by integrating information from segregated processing units that give rise to subjective experience. Consciousness then ‘emerges’ only in systems with high information integration levels. It turns out that the human brain while consciously aware, presents higher information integration than during sleep (Tononi 2004, 2008) and while anesthetized (Alkire, Hudetz & Tononi, 2008).

Another theory that also tries to give an information-based explanation on conscious perception is the Global Workspace theory by Dehaene ant Naccache (2001). According to this theory, information is being processed all the time in an unconscious manner. However, when this information becomes available to a large variety of processes such as perceptual categorization, long-term memorization, evaluation and intentional action, the process itself becomes a conscious experience. In other words, the global availability of information throughout all these processes is ‘what we subjectively experience as a conscious state’ (Dehaene and Naccache, 2001, p.1). At first, it might seem that this theory is similar to Tononi’s integrated information theory as the required brain state is not localized but rather segregated through the brain and addresses the problem from an information flow approach. But there is one key difference between Global Workspace and integrated information theory: the first one states that consciousness *emerges* after integration while the second one states that consciousness *is* global accessibility and nothing more. Notice that here, there is no *what next* question, no hard problem (Chalmers, 1995) and no special emergent feature. As Dennett pointed out (2001):

> *In particular, theorists must resist the temptation to see global accessibility as the cause of consciousness (as if consciousness were some other, further condition); rather, it is consciousness.* (p. 221)

Recalling the previous section, a real emergent (ontological) phenomenon cannot be explained by its elements but rather by the interactions between them (segregation and integration of information in Tononi’s (2004) words). In a way, under this later framework, consciousness would be perceived as a new property of the universe. As mass is to matter, consciousness is to integrated information. It sounds attractive, but yields serious problems if looking for lower-level explanations for consciousness. Dennett's (2001) assumption allows the reduction of conscious perception to the elements of the system. Because information *is* consciousness, all the detailed architectural and organizational features of the brain also matter. Neurotransmitters, molecules, neurons and interactions matter because they make up a conscious-capable system. We just can't ignore the fact that our brains are made out of molecules. Similar to reducing mental processes to molecules, it has been suggested that consciousness can be explained solely by molecules and chemical reactions in the brain (van Regenmortel, 2004a; Bickle, 2006). In fact, Hameroff and Penrose (1996) stated that the unit for neural processing and so the place where we should look up for consciousness is not neurons, but in molecules inside the neurons as their quantum interactions are key features for neural communication. In short, they proposed a model in which consciousness cannot be produced by any classical computation occurring in the brain. Rather, it is the sum of collapsed quantum states of tubulin electrons inside neurons. Others have proposed that cognition cannot be compared to classical Turing-computation (van Gelder, 1995), but the extend to which consciousness could be explained by quantum processes remains uncertain and is beyond the scope of this paper.

Consciousness can be addressed from many levels and explaining it explains how the brain works. Either from higher or lower-level approaches, understanding how a conscious experience happens seems to give a lot of information about the brain. In addition, both reductionist and emergentist frameworks seem to be useful, although the general trend towards understanding consciousness, either from higher or lower-level perspectives, is to explain it as a set of interactions. Again, tracing the parts and describing their interactions (Miner, Pickett & desJardins, 2008) is still the best thing we can do with tools and technology we currently have.

3. Where to look at then?

Much of the ongoing discussion about what is the best way to describe a specific process or where should we start looking, comes from two contrasting ideas:

either emergent phenomena can indeed control our micro-world or it is only our micro-world that matters; the rest is just the illusion of having a complex manifestation of a system. The problem is that, even if there is a molecular or quantum explanation of a specific feeling in a specific moment, going from the microscopic level (atoms) to the macroscopic level (thoughts) seems impossible (Krakauer & de Zannotto, 2009). There is simply too much things going on that we cannot control and more importantly predict. As much of a hate this can cause to ruthless-reductionists, macroscopic events do seem to impact our microscopic world. Take a traumatic event for example. Post Traumatic Stress disorder is a well-known and well-recognized disorder that causes severe depression and anxiety problems (Yehuda, 2002). We are able to study and trace what caused it. Interestingly, it's manifested after a real-world event. In other words, it starts at a macroscopic level. Thomas Nagel (1974) mentioned that it should be common sense to believe that we have access to our specific subjective experiences and studying them is fundamental if we want to understand consciousness. Following this line of thought, Michael Gazzaniga (2010) also said that we have access to our macro properties only (think about anger, fear or happiness) and not to all lower-level, micro events that produce them. Using his own words: 'we are in no way separate from the machine, but are only able to understand ourselves at the macro-level.' (p. 292).

Another conceptual problem that a reductionist-only point of view causes is that all interactions and phenomena occurring at lower levels from what has been just reduced are immediately underestimated. In terms of Bickle (2006) we can explain cognition with molecules (Figure 1), but aren't molecules already complex interactions of atoms? Is enzyme function not an emergent property exclusive to each enzyme? We could always go one level down, so accepting and studying the brain as a set of complex interactions changes completely the landscape. By doing this, we should not ignore the fact that brain complexity has a fractal-like organization. Addressing complexity at any level gives us an idea of what we might encounter at other levels. For example, it has been shown that community structure of structural brain networks is highly hierarchical and nested organization of communities is present at various levels (Meunier, Lambiote &

Bullmore, 2010). This type of fractal organization has been observed by using electrocortical recordings as well. He, Zempel, Snyder & Raichle (2010) found by using spontaneous electrocorticography that the temporal power spectrum of arrhythmic brain oscillations viewed in the frequency domain is indeed nested, which is representative of fractal dynamics.

We don't have to talk about large brain network interactions to understand this concept. It is more than accepted that the unity of neural communication is an action potential, which is produced by neurons. If we were to model a brain simply by skipping what a neuron is and reduce it as a binary yes-or-no machine, we would immediately underestimate the power of what a neuron is. A neuron is what it is not because it sends information to other neurons only. It is an extremely complex system that, in addition to facilitate information through action potentials, interacts with its context in ways that we still don't understand entirely. Take glial cells as an example. It has been suggested that activity coordination across neural networks is facilitated through communication between glial cells carried through intracellular waves of calcium (Fields & Steven-Graham, 2002). So, to create an actual action potential, we need a neuron and its context, not a neuron model. This is what Daniel Dennet (2001) has called as a 'triumph for the lovers of detail' (p. 234) in modern neuroscience. In the same way, we need a brain to create network properties like complexity and consciousness and knowing how a single neuron functions is not sufficient.

Notwithstanding, it has already been discussed why we should not fall for the illusion of holism in which everything is connected, as it does not bring any real methodological alternative that could be empirically tested. (Sawyer, 2002; van Regenmortel, 2004b). If we want to address phenomena such as complexity and consciousness, we need the proper tools, methodologies and paradigms to study them. Another way of extending our understanding on complex brain interactions is by doing simulation studies (Gerstner, Sprekeler & Deco, 2012). Even that we still cannot understand all micro-interactions, these studies are able to control and artificially predict the functional outcome of a system (Berger, 1998). It is almost as a controlled experiment addressing emergent phenomena. Inevitably this raises a question: what's the evolutionary advantage of the structural architecture of the brain if its function is what truly matters? A functionalist will argue that ultimately, it is possible to simulate brain function artificially (even consciousness then could be achieved artificially). This seems improbable, at least in the near future. First, the way the brain performs computations is all but equal from how modern computes do it (Churchland, 2002). The first real artificial brain will probably won't function on an ordinary super computer. Second, our brains are embedded on a context. Even if we were able to simulate an artificial brain, we would need to make sure that context-dependent variables such as embodiment (Thompson & Varela, 2001) and interactions between the nervous system, body and environment (Chiel & Beer, 1997) are also artificially recognized and processed. Finally, structure does matter. Architectural features of the brain tell us everything about how the brain functions (Dennett, 2001) and we need to keep special attention to this (with a reductionist framework) in order to have better approximations of brain activity.

New avenues for understanding our brains also require paradigm shifts of the current frameworks in neuroscience. Take the Higgs boson for example. Recently, it was announced that the Higgs field is responsible of giving mas to matter (Dreiner, 2013). Should we ask why or should we simply accept that's the way it works? Is mass an emergent property then? In our brain, in order to understand complexity and higher order phenomena like behavior and consciousness (Figure 1), we are left with a similar choice: either we accept that there is no further questioning on the higher-level phenomena we observe and that a reductionist approach should explain in the end any illusionary emergent property or we acknowledge the fact that, as long as we don't understand completely how elemental physics work, emergent properties are, under an epistemological definition, real. Given the current information reviewed, I tend to embrace the latter. We should look up for the elements and continue studying them (Sauer, Heinemann & Zamboni, 2007), but their interactions are equally important.

Until we discover (or not) which lower-level interactions give rise to all higher-level phenomena, we are required to explain what we can observe, regardless of the level. Yes, if genome-wide association studies have identified schizophrenia-related loci (Purcell et al., 2009) it matters. But it also matters if this disease correlates with large-scale brain network alterations (Bassett et al., 2008; Bluhm et al., 2007). These are observations that we can't simply ignore. The Human Genome Project (Collins et al., 1998; Watson, 1990) originally promised much more that what has actually delivered. But thanks to it we know that gene function is much more complicated than that conceived by a central dogma of molecular biology (Crick, 1970). The same applies to the brain. The billion-euro Human Brain Project has exiting promises (Markram, 2012), but we must be prepared and realize that the actual findings might not surpass or even meet our expectations. We might just find that the brain is even more complicated than we think.

4. Conclusion

The aim of the present review was to show that our knowledge on consciousness is extended if both a reductionist and an emergentist framework are used. Although both frameworks hold a materialistic point of view, the emergentist approach differs from the reductionist approach as the former acknowledge that interactions of elements give rise to higher-level phenomena such as consciousness while the latter reduce them to the underlying elements. Given that our understanding of lower-level phenomena is still limited, it is practical to acknowledge emergent properties as epistemologically (how we perceive them) real. Methodological tools such as brain complexity largely expands our understanding on consciousness as it tries to give an explanation of the phenomenon at different description levels (neurons to brain regions). Additionally, tracing the elements by using reductionism and using emergentism to understand the relations between the elements seems to be the best approximation to what we currently think consciousness is.

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6. Figures

Reductionism	**Emergentism**
Focus on the elements of the system	Focus on the interactions of the elements
Acknowledges materialism	Acknowledges materialism
Deconstructs the system	Reconstructs the system
From higher to lower-level properties	From lower to higher-level properties

Table 1: Summary of assumptions made by reductionism and emergentism.

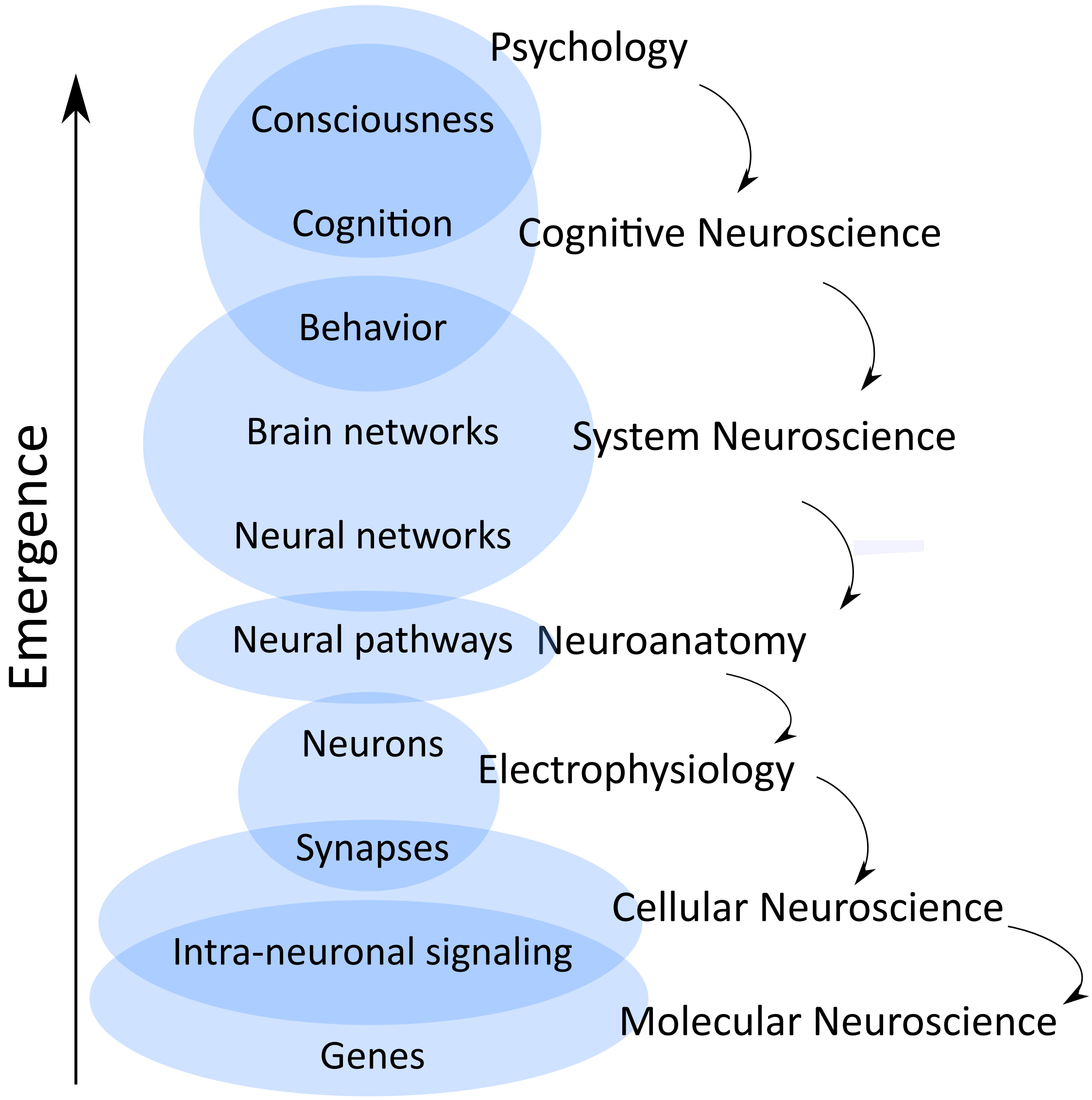

Figure 1: Schematic representation of the levels of organization in the nervous system with the corresponding disciplines. Levels of organization are inside pale-blue circles representing disciplines. Overlap of disciplines results in a darker blue. Arrows at the right side of each discipline represent a step-by-step reduction from the highest (consciousness) until the lowest (genes) level of organization. The arrow at the left side of the diagram represents the direction of emergence.

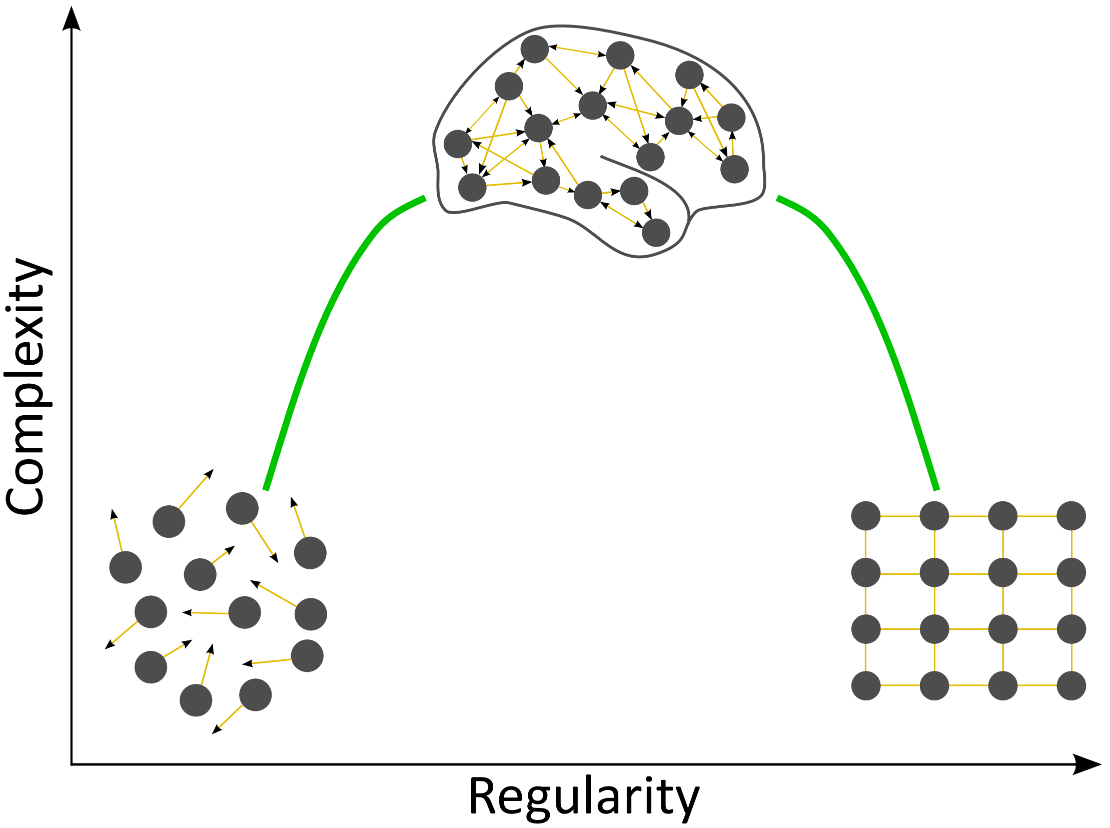

Figure 2: Plot representing the level of complexity as a function of regularity (green line). Lower left toy figure represents a random network in which all elements are segregated randomly resulting in low regularity and low complexity. Lower right figure represents a network in which all elements are equally organized. Here all connections (yellow lines) and spatial segregation of the elements (grey circles) are highly homogeneous resulting in high regularity but low complexity. The top figure represents the way brain networks are wired were the system is neither randomly organized nor completely regular. This level of regularity leads to high levels of complexity. Based on Tononi, Edelman & Sporns (1998).