

# The Binding Problem in the Light of Quantum Physics

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## Abstract

Inter-neuronal conduction is too slow to explain the quasi-instantaneous, long-range synchronization of neuronal discharges that seems to be required for the binding of information in the brain. This paper aims to evaluate to what extent the dissipative quantum model of the brain could bring a new light on this difficulty of classical neurobiology. This model extends Ricciardi's and Umezawa's proposition to represent the collective brain activity, and, in particular, the memorization process within the framework of quantum field theory. It explains the rapid formation of large patterns of synchronized oscillations of the electric dipoles carried by water molecules and macromolecules of the brain as a consequence of the spontaneous breaking of their rotational symmetry, as well as the superposition of these patterns of oscillation at different frequencies in the same area of the brain. However, it is argued that this model can really contribute to explain the temporal binding of information provided that it could establish a genuine correspondence between the description of the brain's dynamics it gives in terms of dipolar molecules field and spontaneous symmetry breaking and the usual, classical description of the brain's activity in terms of neurons, action potential, biomolecular architectures and specialized areas. Moreover, if the latter question regarding the *information* integration process could be overcome with further experimental and theoretical researches, it is explained that no convincing explanation of *conscious experience* can be given in such a model of the brain. Suggestions are made in order to overcome these difficulties.

**Key Words:** brain, quantum field theory, spontaneous breaking of symmetry, conscious experience

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## 1. Introduction: the binding problem

Visual information is collected by the retina and sent to a multitude of specialized brain areas that process its different aspects (i.e., information about the shape of the object, its color, its orientation, or its state of movement). Visual areas take up more than a quarter of the volume of the cortex and are

distributed along two different dorsal and ventral streams, beginning from the primary visual area V1 of the occipital lobe, respectively reaching the posterior parietal cortex and the inferotemporal cortex and ending in the prefrontal cortex. How can this distributed visual information give rise in the subject's mind to a unique conscious percept – for example, that of a red, square object moving in front of him/her?

This question becomes still more essential if one takes into account phenomena of subliminal perception that has been explored by Dehaene and colleagues (2001). Observations show that

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the brain areas that are activated in conscious visual perception (essentially, areas of the ventral stream) are also significantly activated in subliminal perception whereas conscious perception involves a wider response of the brain that requires the activation of regions remote from the ventral stream –like, for example, those dealing with spatiality and temporality (Block, 2003, p.7; Kawisher, 2001). Moreover, everyday perceptions not only require the integration of several types of sensorial information - like olfactive, visual, and auditive information - but also, as stressed by Lestienne (2008, chap. 1) or by Frith and Dolan (1997), the combination of sensorial information with prior information provided by our past experience and our a-priori knowledge – by what is called our working memory. The “binding problem” is the question to explain how this distributed information can be integrated to produce a *unified conscious perception* (Buser and Lestienne, 2001; Engel *et al.*, 1992; Koch, 2004).

The next section (section 2) will review some of the main attempts to explain the binding of information relative to conscious perception within the framework of classical neurobiology. Most of them appeal to the hypothesis of “temporal binding” initially formulated by Malsburg (1981) and according to which the binding of information would involve in an essential way the long-range synchronization of neuron discharges. As shown by several neuroscientists (Engel *et al.*, 1992; 1997; Singer and Gray, 1995), this hypothesis seems appropriate to explain the observed collective activity of the brain which is correlative to conscious perception and, more generally, to any cognitive or sensorimotor task. It could indeed explain the rapid formation and dissolution of extended domains of synchronized neuronal discharges within the specialized areas relative to this perception, between these specialized areas and even between the two cerebral hemispheres, as well as their great adaptability to stimuli and the possible co-existence in the same cortical area of patterns of oscillations at different frequency bands. This zero-lag long-range synchronization of neuronal discharges and its properties has been observed in several

species, such as the cat, the rabbit, or the monkey (Freeman and Vitiello, 2006; Roelfsema *et al.*, 1997; Soteropoulos and Baker, 2006), and even the human species (Rodriguez *et al.*, 1999). However, as will be explained, classical mechanisms of inter-neurons information transmission (essentially, the axodendritic synaptic conduction) are too slow to explain such a synchronization of neuronal discharges within a millisecond and on a distance that can be of several centimetres.

Section 3 will briefly present Ricciardi's and Umezawa's alternative approach (1967) to deal with the long-range oscillatory activity of the brain and, in particular, with memory processes within the quantum theory of condensed matter whose theoretical framework is quantum field theory. This physical approach of the brain activity has been developed by Stuart and by Jibu and Yasue (Jibu and Yasue, 1995; Stuart *et al.*, 1979), and extended more recently by Vitiello, Pessa, and the neurophysiologist Freeman by taking into account the dissipative dynamics governing the interaction between the brain and its environment (Freeman and Vitiello, 2006; 2008; Pessa and Vitiello, 2003; Vitiello, 1995;). It appeals in an essential way to the spontaneous symmetry breaking phenomenon which is considered in regard to the rotational symmetry of the dipolar molecules of the brain.

The final section (section 4) will examine to what extent the latter quantum model of the brain activity could bring a new light on the binding problem. It will be argued that this approach may prove very fruitful to explain the integration of information by the brain provided that it could either clearly explain the role played by the *molecular* dipole oscillations to which it refers in the observed *neuronal* collective activity of the brain or, as will be suggested, that the “brain variables” that are introduced to characterize the macroscopic state of the brain could be re-interpreted by referring to the properties of the *neuronal* dipole field of the brain.

If the latter question concerning the physiological substrates of consciousness could be overcome with further experimental and theoretical researches, it will be

explained that no convincing explanation of *conscious experience* can be given in such a materialist model of the *brain*. As will be explained, this question of the “explanatory gap” between the description of neurophysiological processes in the language of science, in the third person, and the subjective experience they give rise indeed requires a theory capable to deal with the *relationship* between the mental and material aspects of the psychosomatic unity of the individual.

## 2. Classical propositions to solve the binding problem

In spite of their diversity, classical approaches all assume that the binding of information in the brain could exclusively be explained in terms of “wiring” – indeed, they do not have other alternatives. Classical approaches of the binding problem, which are often presented as models of consciousness, rely on a great variety of hypothesis ranging from micro-local considerations (involving single neuron level), to considerations bearing on the collective activity of the brain. For example, in the so-called “convergence models” (Barlow, 1972), the binding of information would involve a convergent connection of the axons of cells dealing with partial information, at a primary processing level, to specialized “cardinal” cells of higher processing levels. However, the existence of such cells capable to integrate the distributed information transmitted by other neurons or groups of neurons faces several specific problems, like for example the combinatorial explosion problem (Engel *et al.*, 1992): the diversity and complexity of stimuli and, consequently, the great number of combinations of simpler features to encode would require far too many cells (and appropriate connections) than possible.

On a bigger scale, Koch (2006) or Logothetis and colleagues (Logothetis, 1998; Sheinberg and Logothetis, 1997) have suggested to understand the binding of visual information in the brain by focusing on the activity of some localized, interacting regions of the brain where visual stimuli are represented by the activity of *populations* of interconnected neurons and not by that of single cells. From experimental data about

binocular rivalry phenomena, these authors came to the conclusion that visual conscious perception essentially involves the high-level cortical areas of the ventral pathway of the visual system (and not the primary visual cortex or the areas of the dorsal pathway), assuming then that these specific areas are capable of integrating the distributed information processed in lower level areas to which they are connected and to make it conscious. As explained by Engel and his team (1992), consideration of assemblies of interconnected neurons can resolve some specific problems inherent to the previous micro-local approach, like its fragility regarding to the destruction of individual neurons or the combinatorial explosion of the number of neurons required to encode the great diversity of stimuli. However, both local and micro-local approaches cannot deal with the binding problem in a general way since, as mentioned in the previous section and as will be explained hereafter in more detail, the information process associated with conscious perception generally involves a *collective activity of the brain* which manifests by the synchronized firing of millions of neurons distributed in remote regions of the brain (Bach and Rita, 1995; 2005; Dehaene *et al.*, 2001; Freeman and Vitiello, 2005; Freeman 1991).

In contrast, global models appeal to the collective activity of the brain to explain the binding of information and consequently assume the existence of *long-range, rapid interconnections* between distant brain areas. In this class of models, one can mention Edelman’s re-entry model according to which the binding of information could be explained by the existence of strong and rapid re-entrant interconnections between the structured layers of neurons (called “cards”) that process the partial, distributed information relative to the perception of a stimulus (Edelman, 1989). The re-entry process, which is defined by Tononi and Edelman (1998) as “the ongoing, recursive, highly parallel signalling within and among brain areas,” would correctly interpret the observed short-term temporal interactions between groups of neurons that are involved in cognitive tasks. According to these authors, the re-entrant process would not only explain the integration of information

by the brain but also its access to consciousness. For example, conscious perception of the world (or “primary” consciousness), would rely on the existence of re-entrant interactions between posterior thalamo-cortical areas and anterior areas that are capable to link present perceptive categorizations to conceptual memory. Along this line of thought, Tononi has defined conscious experience as the brain’s ability to integrate information (Tononi 2007, p. 297).

In the same class of models, Dehaene and his colleagues have worked out the global workspace model, inspired from Baars’ cognitive theory of consciousness (Baars, 2007). In this model, a network of distributed, heavily interconnected neurons *with long-range* axons (the global workspace) would be capable to collect and to control the distributed, partial information processed by five categories of specialized modules, and to broadcast it very rapidly into the whole brain (Dehaene and Naccache, 2001). These modular systems are, respectively, devoted to perception, motivity, long-term memory, evaluation and attention, and their neural substrates are specified brain areas (like the primary visual cortex V1 which is involved in visual perception); whereas the workspace neurons would be distributed over the whole brain - and first in the specialized modular systems. According to Dehaene and Naccache, the existence of such a global network capable of long-range connections in a human’s brain is corroborated by some observations of the monkey’s brain showing the existence of long-range neural connections between prefrontal, parietal, temporal, and anterior cingulate cortex, and with other sub-cortical areas (Goldman-Rakic, 1988). The contribution of an area of the brain to the workspace would be determined by the proportion of pyramidal neurons of layers 2 and 3 it contains in as much as the latter neurons connect with other cortical areas and with the specialized processors via neurons of layer 5 and the thalamic nuclei – which argues in favor of a great contribution of the prefrontal cortex and the anterior cingulate cortex. According to this approach, information becomes conscious if it is rapidly broadcast (by the long-distance axons of the workspace neurons) in a sufficiently large part of the brain, making it

available to a variety of processes including the five categories of specialized processors mentioned above. This global availability of information through the workspace is indeed interpreted as subjective experience (Dehaene and Naccache, 2001).

However, if these models can roughly account for the global activity of the brain relative to conscious perception and to more complex cognitive tasks, one can ask how exactly information is exchanged so rapidly between remote parts of the brain in order to ensure the required long-range synchronization underlying this global activity. To answer to this question, Edelman and Tononi have mentioned the synchronous firing of groups of neurons that, according to them, would in fact rely on re-entry processes. Dehaene and his colleagues have also suggested that the long-range synchronization of the brain that takes place in the global workspace and gives rise to consciousness is realized “by the spontaneous and coherent firing” of neurons of the workspace (Gisiger *et al.*, 2000; p. 256). These models thus appeal to the hypothesis of temporal correlations of neuronal discharges to explain the binding of information. This notion of “temporal binding” initially formulated by Malsburg (1981), relies on a very precise (within a millisecond) synchronized firing of the neurons that encode information on the same object or the same event (which indeed characterizes the notion of “neuronal assembly”), and not of the neurons representing different objects or different events. Engel and colleagues (1992) have indeed mentioned decisive arguments in favor of the temporal binding hypothesis. In addition to robustness and parsimony, which are inherent to all assembly representations, and to resistance to amplitude fluctuations (since synchrony essentially involves phase coherence), temporal binding can explain: a) the synchronization of information processing of distributed neuronal populations that respond to features of the same object, b) the rapid adaptability of neuron assemblies to stimuli, since neurons can “rapidly switch between assemblies by subtly changing the temporal relationships of their firing patterns,” and c) the capability of the brain to simultaneously process information relative to superimposed stimuli

or to different aspects of a unique stimulus, since several assemblies can co-exist in the same region of cortex by the fact that the neurons of each assembly are tagged by their synchronous firing (p.220).

Singer and Gray (1995) had partially confirmed the temporal binding hypothesis by showing that the binding of information relative to conscious perception of an object relies on the phase coherence, especially in the gamma band ranging from 30 to 70 Hertz, of the membrane oscillations of the neurons that are involved in this perception. More generally, as shown in several species by multi-electrodes recordings and correlation analysis, any conscious perception involves the rapid formation of patterns of synchronized neuronal discharges on distances that can be of a few centimetres (i) within the specialized areas relative to this perception, but also (ii) between these specialized areas and even (iii) between the two cerebral hemispheres. The dynamical formation of zero-lag long-range patterns of oscillations relative to conscious perception have been observed for the cat, the rabbit, the monkey, and even the human (Eckorn *et al.*, 1988; Engel *et al.*, 1997; Gray and Singer, 1989; Rodriguez *et al.*, 1999; Roelfsema *et al.*, 1997; Singer and Gray, 1995; Soteropoulos and Baker, 2006). Moreover, Freeman and Vitiello (2006) have reported accurate observations of the primary sensorial areas and of the limbic system of cats and rabbits that show the rapid formation and dissolution over long distances of *co-existing* amplitude modulated patterns of synchronized oscillations (neuronal assemblies) in distinct frequency bands (in beta and gamma ranges 12-80 Hertz) correlated with the perception of different stimuli. At last, experimental studies have also shown that this synchronization of remote regions of the brain can be performed *within a millisecond*. This quasi-simultaneity has been, for example, observed for the cat visual cortex (Gray and Singer, 1987), for that of the macaque monkey (Buracas *et al.*, 1998) or for the auditory cortex of birds (Yu and Margoliash, 1996).

The problem is then to explain such a quasi-instantaneous synchronization in the firing of distant neurons. For, neuronal

interconnections between distant regions of the brain take time, principally because of the finite axonal conduction velocity. As shown by Swadlow and Waxman (1975), the axonal conduction time ranges from a few to tens of milliseconds, depending on many factors like the calibre or the myelination of the axons. For example, the delay associated with information transmission along an axon of average size connecting the temporal lobes of both hemispheres is of the order of 25 milliseconds (Ringo *et al.*, 1994). Moreover, synaptic delays ranging from 0,3 to 4 milliseconds (Katz and Miledi, 1965) and other smaller delays, like those due to the dendritic propagation, must be considered. Classical models based on wiring-type information transmission would thus impose important distant-dependent delays that are not observed on EEG recordings, which means that they are not a priori capable of explaining the very rapid (within a millisecond) synchronization on long distances (of the order of several centimetres) of neuronal discharges involved in conscious perception.

In order to overcome this difficulty, many directions of research have been explored within the framework of classical neurobiology. For example, from the observation of the synchronization of cortical and thalamo-cortical oscillations, Steriade and his team have shown how the oscillations generated by the thalamus can be synchronized by the cortex via cortico-thalamic loops (Amzica and Steriade, 1995; Steriade *et al.*, 1993). Computational simulations of the collective behaviour of interconnected populations of neurons have been performed (Destexhe and Contreras, 2006) and some authors have suggested that the synchronization of oscillations of two remote groups of neurons could be achieved through the coupling with a third group of neurons whose function would be to tune their respective frequency (Fisher *et al.*, 2006). However, if some of these works could certainly clarify particular features of the long-range neuronal synchrony, while others (as Fisher's approach) could provide a suitable mechanism to explain it on the basis of appropriate neuronal circuitries, the observed *global* oscillatory activity of the brain relative to conscious perception and cognitive tasks would certainly require a

more general explanation that does not rely on *particular configurations of the brain*, like the existence of specific circuitries.

More general explanations of the long-range synchronization of neuronal discharges have been proposed, as those that appeal to the existence of electromagnetic fields generated by the neurons activity or to the non-synaptic chemical diffusion; however, as explained by Freeman and Vitiello (2008), experimental data show that the former are too weak whereas the latter is too slow. The role of electrical synapses which, by contrast with chemical synapses, are not affected by transmission delays has also been mentioned (Bennet and Zukin, 2004) - which however cannot solve the problem since, as explained above, the main cause of the delays in wiring-type models comes from the axonal conduction. Consequently, it seems that classical neurobiology faces some difficulties for explaining in a general way the long-range synchronization of the brain that seems to be required in the binding of information: 1) it cannot explain in a general way *the observed rapid formation and dissolution of large patterns of synchronized neuronal discharges* correlative to conscious perception and cognitive tasks; 2) no explanation of *the possible co-existence of several assemblies in the same region of the cortex* has been provided until now within the framework of classical neurobiology. The latter property, which has been observed in cross-correlation studies (Engel *et al.*, 1992), or in high temporal resolution of EEG signals (Friedman and Vitiello, 2006), is essential since it allows the parallel processing of information relative to superimposed stimuli or to different aspects of a unique stimulus which is required for the construction of a unified conscious perception.

### **3. A quantum approach to the collective brain dynamics**

As explained by Tarlaci (2010), quantum physics is required to deal with brain phenomena on the millisecond time scale and on a size smaller than dendrites and synapses, phenomena that cannot yet be directly investigated by existing experimental methods. Some physicists and neuroscientists have actually suggested that

the observed collective activity of the brain could be relevant to this quantum spatio-temporal level. These researchers have proposed an explanation of the collective dynamics of the brain correlative to conscious perception, cognition and memorization process within the *quantum theory of condensed matter* whose theoretical framework is quantum field theory (Freeman and Vitiello, 2005; Jibu and Yasue, 1995; Ricciardi and Umezawa, 1967; Vitiello, 1995). This section will present this quantum approach of the brain activity whose last developments take into account the dissipative dynamics governing its interaction with the environment.

Though Fröhlich (1968) did not explicitly use this theoretical framework, he can be considered as a precursor of this line of thought since he defended the idea according to which living matter should give rise to “condensation” phenomena (which manifests by long-range correlations) similar to those occurring with helium at very low temperatures (Bose-Einstein condensation). These condensation phenomena in living organisms, which have been observed by Duffield (1988), are explained as follows by Fröhlich: Living matter being made with dense structures of dipolar macromolecules (like proteins or nucleic acids), it can be modelled as a system of electrical oscillators at different frequencies embedded into electromagnetic fields. When this system of dipoles receives energy from the environment, this energy could be used to privilege a single oscillatory mode and then to maintain long-range phase correlations.

The latter approach has been explored more rigorously by Ricciardi and Umezawa within the framework of quantum field theory. In their foundational paper “Brain and physics of many-body problems” (1967), these physicists have suggested to explain the brain collective response to external stimuli and the recording of information as consequences of spontaneous symmetry-breaking phenomena. A “spontaneous” symmetry breaking occurs in a physical system when it goes into a particular state which is not invariant under the symmetry group governing the dynamical equations of this system –by contrast with an “explicit” symmetry

breaking for which the dynamical laws have been changed and are not any more invariant. Within the framework of quantum field theory, it can be the case for the fundamental (vacuum) state of minimum energy. The idea according to which the spontaneous breaking of symmetry in a physical system gives rise to the production of Nambu-Goldstone (NG) bosons<sup>2</sup> which propagate into the whole system and are thus capable to maintain it in a new, stable dynamical order is indeed a consequence of quantum field theory and has proved very fruitful in condensed matter physics (Itzykson and Zuber, 1980; Umezawa, 1993). For example, in ferromagnetic materials at low temperature, the rotational symmetry of the Hamiltonian describing the interaction of the magnetic dipoles of the atoms is spontaneously broken by a macroscopic magnetic order for which all the dipoles point in the same direction - the associated NG-bosons being spin waves called "magnons." It also occurs in a fluid of bosons where the lowering of temperature gives rise to a Bose condensate, which is a new dynamical order (collective behaviour of bosons) that does not respect any more the gauge symmetry  $U(1)$  of the fundamental equations governing this system.

In the quantum model of the brain, the dynamical variables that characterize the macroscopic state of the brain are neither identified with the binary variables describing the activity or the inactivity of the neurons (Ricciardi and Umezawa, 1969; p.45), nor with the properties of the neurons or of some other cells of the brain - which are not a priori considered as quantum objects (Jibu and Yasue, 1995; Vitiello, 1995). These dynamical variables, called "corticons," have been identified with those of the "cortical field" constituted by the *electrical dipoles* carried by water molecules or other macromolecules, dipoles which possess a rotational symmetry and are embedded into the electromagnetic field of the brain. The spontaneous symmetry breaking of this rotational symmetry is induced by an exterior stimulus and gives rise to the emergence of several possible collective modes (associated with NG-bosons called

"dipole wave quanta"). However, the resulting "condensate" in which the brain will be placed is internally selected among these different possible responses. Ricciardi and Umezawa interpret the rapid emergence of long-range patterns of oscillation in conscious perception and in cognitive tasks as a consequence of a spontaneous breakdown of rotational symmetry of dipolar molecules of the brain. According to this model, information coming from the environment is encoded into the whole brain through the condensation of dipole wave quanta, which would explain the alleged non-locality of brain functions - in agreement with Lashley's concept of mass action (Lashley, 1950), and, in particular, those of memory recording and recall process - in agreement with the idea supported by Pribram in his holographic model of the brain (Pribram, 1991). Moreover, the stability of long-term memory is explained by the stability of the condensate and short-term memory is interpreted in terms of meta-stable states of the brain (p. 46).

If Ricciardi's and Umezawa's quantum model of the brain suggests an explanation of the recording of an incoming information by the whole brain, it suffers from what Vitiello (1995) called the "overprinting problem:" this model cannot explain how other information coming into the brain can be encoded according to different condensation processes without erasing the previous one and changing then its state. To resolve this problem, Pessa and Vitiello (2003) have suggested taking into account the continual exchange of energy between the brain and its environment - extending thus the initial quantum model of the brain to a *dissipative* model. As a consequence of the energy balance between the brain and its environment, time-reversed copies of the collective modes of the brain can be *formally* attributed to the latter - which appears as its "Double" and, as will be explained below, would play an important role for explaining the emergence of consciousness (Vitiello, 1995; 2003; 2004). A first essential technical result of the dissipative quantum model of the brain is that the balance of energy fluxes at the brain-environment interface allows the co-existence of an infinite number of couplets of

<sup>2</sup> The NG-bosons are shown to be massless if the breaking of symmetry is totally spontaneous, that is, not also explicit.

specific values of the energy of the brain and of the environment, each one of them defining a physically different brain-environment ground state (Freeman and Vitiello, 2005; Vitiello, 1995). In this model each of the co-existing amplitude modulated patterns of synchronized neuronal oscillations that are observed is thus interpreted as one of these ground states, which would explain the co-existence in a same region of the brain of patterns of neuronal oscillations at different frequency bands correlated with stimuli. Moreover, the continuous energy exchange between the brain and its environment gives rise to energy non-conservation and irreversible time evolution for the collective modes of the brain. According to these authors, this non-unitary dynamics could explain the observed rapid and irreversible evolution of the extended patterns of synchronized neuronal discharges (see section 2).

Vitiello and Alfinito have also explored “parametric” dissipative models of the brain for which the frequency of the dipole wave quanta generated in the spontaneous symmetry breaking is dependent of time (Alfinito and Vitiello, 2000; Vitiello, 2003). These authors have established other important results, like the existence of a relationship between the capability in memorizing and the magnitude of the brain-environment exchange or the finite size of memory domains that makes possible transitions between ground states of the brain, and would then explain processes of association and/or confusion of memories. As remarked by Vitiello (2003), the finiteness of the domain size of coherent excitation implies that the mass of NG-bosons associated with the spontaneous symmetry breaking (noted as *dwq*) is not zero. This imposes that a threshold in the excitation energy of the *dwq* is required to trigger the recall process. A hierarchical organization of memories based on their lifetime can even be established within these models by considering the size of their corresponding memory domain.

Ricciardi’s and Umezawa’s quantum model of the brain has thus set the basis of a quantum explanation of the long-range oscillatory activity of the brain in terms of spontaneous symmetry breaking of the

dipolar rotational symmetry of molecules of the brain. Subsequently, this approach<sup>3</sup> has been complemented and extended to the dissipative quantum model of the brain which deals more accurately with the properties of the collective, oscillatory response of the brain to stimuli and by providing an explanation of the possible co-existence in a same region of the brain of patterns of dipolar molecules oscillations at different frequency bands. Could this model of the rapid formation of large patterns of synchronized dipolar *molecules* oscillations in the brain and of its properties shed a new light on the question to explain the synchronization of *neuronal* discharges that is required for the binding of information? It would seem that Vitiello (2004, section 4) has implicitly given an affirmative answer to this question in the following claim:

“...dissipation...seems to suggest a solution to the so called binding problem, namely the understanding of the unitary response and behaviour of apparently separated units and physiological structures of the brain.”

However, one will explain that in its present state of development the dissipative quantum model of the brain faces two important difficulties that must be overcome before being capable of dealing with the binding problem. These difficulties and their possible resolution are presented in the next section.

## 4. Limitations and prospects

### 4.1 The question of correspondence

To explain the long-range *neuronal* synchrony required for the binding of information, the dissipative quantum model of the brain should first establish a clear correspondence between, on one hand, the description of the brain activity it provides within the framework of quantum field theory, in terms of dipolar molecules oscillations, rotational symmetry breaking and dipole wave quanta and; on the other

<sup>3</sup> Indeed, as could show a survey of the main quantum approaches to consciousness that have been developed until now, it seems that the present approach developed within the framework of quantum field theory is the only one that explicitly tackles the question of the oscillatory, collective dynamics of the brain -see (Atmanspacher, 2006; Uzan, 2011, section B) for a review. In the following, one will then exclusively focus on this direction of research.



hand, the classical descriptions of the electrochemical brain activity in terms of neurons, action potential, glia, bimolecular architectures and specialized areas. This difficulty has been mentioned by the authors of this model but does not seem to presently find any clear answer (Freeman and Vitiello, 2008; Vitiello, 2003; 2005; Yasue, 1999). In order to account for the extent of the question, let us first report Yasue's illustrative claim in the third Tucson conference (Yasue, 1999; p. 321):

"Of course biologists see the brain as a structured mass of brain cells manifesting sophisticated but systematized biomolecular architectures. They see membranes, proteins, cytoskeletons, nuclei, organelles, water, ions, glia, and so on. Here I am saying the brain is a quantum electric dipole field and biologists are wondering: Where are biomolecular structures? Do not worry. They are in the quantum electric dipole field, represented by singularities, topological defects, local symmetries and localizations of the field. Biomolecular architecture provides geometric objects emerging in the quantum electric dipole field...."

This lack of correspondence between the dissipative quantum model of the brain and the classical description of the brain activity can be detailed as follows, as much at the neuronal level as at the macroscopic level of description (concerning areas of the brain).

Freeman and Vitiello claim that the dissipative quantum model of the brain could "account for the observed dynamical formation of spatially extended domains of neuronal synchronized oscillations and of their rapid sequencing" (Freeman and Vitiello, 2008; p.2). However, these patterns of neuronal oscillations are interpreted as condensates of *dwq* modes that are generated by the spontaneous breaking of the rotational symmetry of the *dipolar molecules of the brain* embedded in its electromagnetic field, which means that these patterns of oscillations involve long-range correlations between the oscillations of these *molecular* dipoles. Why should the synchrony of *dipolar molecules oscillations* be identified with that of *neurons firing*? What exactly is the relationship between

these two phenomena that are a priori distinct? Freeman and Vitiello (2005; p. 5) have arisen this question relative to the "bridge between microscopic, atomic and molecular, units and the macroscopic neural activity as we observe it." Their answer appeals to Freeman's notion of "wave packet" (Freeman, 1975/2004) that would be "acting as a bridge from quantum dynamics at the atomic level through *the microscopic pulse trains of neurons* to the macroscopic properties of large populations of neurons." However, as mentioned in the latter sentence (in the part that has been italicized by us) and as explained by Freeman himself (1975/2004, chap. 7), the notion of wave packet in question relies on the observed cooperative oscillatory activity of *neurons* and cannot then be mentioned for genuinely explaining the relationship between this synchronized neuronal activity of the brain and that of its dipolar molecules. Building this bridge indeed requires a theory that links *both* phenomena, namely the synchrony of neurons discharges *and* the synchrony of their dipolar molecules oscillations – a theory that does not yet exist. Let us also remark that in the case these two phenomena are considered as distinct, one could ask about the exact *function* of the synchrony of dipolar molecules of the brain for the binding of information - and even wonder if the latter phenomenon (that regards dipolar molecules) could be a mere epiphenomenon of the long-range synchronization of neuronal oscillations that is required in the information integration process.

An idea to overcome this difficulty could be to define differently the "brain variables" on which field theory applied, for example by considering the *neuronal* dipole field that can be associated with the circulation of ionic current in neurons. As explained by Nunez (1981), an excitatory synaptic contact gives rise to a current flow from the dendrites (which play the role of source) to the soma of the neuron (the sink) which can thus be described as an electrical dipole. On the other hand, pyramidal neurons of the cortex, which are indeed predominant in the neocortex, the last-formed part of the cortex specifically involved in higher human mental functions, have their dendrites in the same direction

and normal to the cortical surface. Consequently, due to the parallelism of their spatial orientation<sup>4</sup>, the synchronization of their discharge will give rise to a significant summation of their respective dipole fields which is detectable by EEG – contrary to the case of star neurons that have no preferential orientation (Pernier and Bertrand, 1977). This suggests that the “brain variables” could be defined by the properties of the *classical* field formed by the *neuronal* dipoles, namely their intensity, their frequency and their phase that can take infinity of possible values (which consequently defines a system with infinite degrees of freedom). In absence of some external stimulus, one can assume that the global field of the cortical region whose activity is generally observed to be correlated with it is zero, which finds expression in the global symmetry of the phases of the neuronal dipolar oscillations for each possible frequency. The external stimulus will spontaneously break this symmetry and give rise to a macroscopic state compatible with the internal brain constraints and where all neuronal discharges are synchronized at a particular frequency, whereas all other possible ones are ruled out. Moreover, by considering the dissipative dynamics of the brain/environment interaction, and following Vitiello’s suggestion, it could be possible to show the co-existence of patterns of *neuronal* oscillations at different frequency bands corresponding to different stimuli (or different aspects of a same stimulus) in this same region of the cortex. Such a redefinition of the “brain variables” could thus allow an explanation of the temporal binding of information and, correlatively, it would agree with the classical approaches about the specific role played by the neurons as the key sites of information exchange and storage.

However, even if a redefinition of the “brain variables” is provided in order to really explain the synchronization of *neuronal* discharges, the dissipative quantum model of the brain also faces this problem of correspondence on macroscopic levels. For example, it does not explain why some particular areas of the brain (regions of

the visual cortex, for example) can be more stimulated than others during conscious perception and, more generally, in higher cognitive functions that involve sensory-motors activity - what is actually observed. On the contrary, in this model all areas and all constituents of the brain seem to be *equally* involved in perceptions (being, moreover, conscious or not), and in cognitive acts. In particular, the “memorization” process is described as a global condensation process generated by the breakdown of rotational symmetry of the whole dipolar molecules of the brain. This means that no precise relationship is established between this *global* process of condensation and experimental data of classical neurobiology showing that *local* neuronal and molecular processes are importantly involved in learning and memorization. For example, on the basis of observations relative to the aplysia, Kandel (2006) has proposed an explanation of the memorization process in terms of strengthening of the synaptic connections between neurons, in agreement with Hebb’s proposal. In addition to the changes in synaptic connections, changes in white substance have also been observed in learning processes (which obviously involve memorization). Scholtz and colleagues (2009) have observed significant changes in the white-matter architecture of healthy human adult brains during training – namely, a thickening of myelin sheaths of axons. Has the “memorization” process described within the dissipative quantum model of the brain anything to do with the “memorization” process that is described by classical neurobiology? Are they complementary descriptions of the same process or do they refer to quite different processes? In the first case, how could these two different (quantum and classical) descriptions of the memorization process be reconciled, and in the second case how do these two different physical processes interact? Stuart and colleagues (1978) have suggested that “the brain should be considered as a mixed physical system in which a neuro-physiologically nonclassical cooperative dynamics is present in addition to, and capable of interacting with, the classical neuron system.” To justify this idea which has been recently re-affirmed by Tarlaci (2010, introduction), these authors

<sup>4</sup> The spatial orientation of the neuronal dipoles being invariable, there is no rotational symmetry.

focus on the “stability, nonlocal, and recording properties of memory” to claim, in agreement with Ricciardi and Umezawa (1969), that the latter should be “identified with a macroscopic ordered state created and maintained by quantum interactions.” However, it must be noticed that no precision of the hypothetical interaction between these two (quantum and classical) processes has yet been provided.

This lack of correspondence between the (dissipative) quantum model of the brain and the classical descriptions of the brain activity can also be mentioned for many important characteristics of memory. For example, the distinction between short-term and long-term memory is interpreted within the (dissipative) quantum model of the brain in terms of stability versus meta-stability of the condensate in which the brain seats (see above). However, from well-established experimental data, Kandel has explained this distinction in terms of functional versus anatomical modifications of the synapses: short-term memory relies on a functional, transitory strengthening of the synapse whereas long-term memory involves the synthesis of proteins in the nucleus and the growth of new synaptic connections, that is, an anatomical modification of neuronal interconnections (Kandel, 2006; chap. 16-18). How could these two interpretations be reconciled? On the other hand, the dissipative quantum model of the brain does not make any distinction between two very different concepts of memory which could a priori involve different regions of the brain: that of declarative memory, which refers to memories that can be consciously recalled, and that of procedural memory, which refers to an almost automatic retrieval of memories, without conscious processing, as is the case of riding a bike. By contrast, Weis and his team (2004) have shown that declarative memory correlates in the brain with some specific regions, like the medial temporal lobe, the left inferior prefrontal cortex and the left angular gyrus. How can the dissipative quantum model of the brain represent this fact?

In order to fruitfully use the spontaneous symmetry breaking phenomenon to understand the temporal binding of information, further theoretical

and experimental investigations are thus necessary, either to establish a genuine correspondence (or to explain the physical interaction) between the quantum description of the brain activity provided by the dissipative model of the brain and the classical, electrochemical one, or to re-interpret this phenomenon in terms of *neuronal* dipole field, that is, *classically*.<sup>5</sup> Of course, the amount of work required to clarify this situation should not be a reason for rejecting a priori this very promising approach of the brain that might contribute to the resolution of the binding problem - at least in its purely physiological aspect that regards the *information* integration process (see below). As emphasised by Kuhn (1962), the emergence of a new paradigm takes time.

#### 4.2. The question of the explanatory gap.

The second aspect of the binding problem is to explain how the (integrated) information processed by the brain can give rise to conscious, subjective experience. As will be explained hereafter, the authors of the dissipative quantum model of the brain or of its variants, generally think that conscious experience would be a mere consequence of the collective dynamics of the brain (or of the interaction between the brain and its environment), that these models describe within the framework of quantum field theory. Before presenting and discussing their arguments, let us first clarify this question.

The irreducibility of the phenomenal aspect of consciousness to neurophysiological processes which are described in the third person has been supported by many philosophers, like Chalmers in his book *The Conscious Mind* (Chalmers, 1996). Chalmers makes a clear distinction between the “easy” problem of consciousness which explains how the brain can deal with information and control motivity, a problem that will find (or already finds) a solution in terms of neurophysiological and computational processes; and the “hard” problem of consciousness which consists of explaining

<sup>5</sup> As shown in Strocchi’s book (2005), the spontaneous symmetry breaking phenomenon can be understood as well for classical systems with infinite degrees of freedom (classical fields).

the nature of subjective experience associated with this processing of information by the brain. There indeed exists an “explanatory gap” between subjective experience and the scientific description of its neuronal correlates at the third person: how could a description in the language of science, in the third person, of the brain activity (or of the correlative information process) involved in a subject’s experience of perception account for “what it is like” (Nagel, 1974) to live this experience for this particular subject? Can *individual, subjective experience* be “explained” objectively in the impersonal language of science, in terms of neural or informational processes? As emphasized by Noë and Thomson (2004), subjective experience is relative to what is experienced by a particular subject through an ensemble of personal characteristics, like his (or her) own sensibility, his/her beliefs, his/her desires, and his/her own rationality; whereas physiological processes, which are described in the language of science, are of sub-personal nature and do not consequently rely on personal characteristics. These two points of view, respectively expressed in the first and in the third person, seem to be incommensurable - hence the explanatory gap question.

Most of classical models of the brain merely ignore this question and reduce or identify subjective experience to its neuronal correlates, as shown for example by Changeux’s claim according to which our thoughts and our states of consciousness are nothing but the product of the biology of the brain (Changeux, 1983), or the explicit reduction of subjective experience to “integrated information” by Tononi (see section 2). This reduction of mental life to the brain activity (or to the associated informational process) finds its origin in the very materialist philosophy that underlies scientific research nowadays. According to materialism, any phenomenon of our world could be exclusively explained in terms of material processes; this entails in particular that, if not purely and simply denied (Denett, 1991), subjective experience should be *completely reducible to material (physiological) processes*. In other words, no place seems to be left for subjective

experience<sup>6</sup> in the materialist description of the world even though, as explained by Bitbol (2008) from arguments relevant to various fields, the latter is in fact *primary from a methodological and existential point of view*: for example, subjective experience plays an essential role at the very *beginning* of any construction of science and it is always *presupposed* to any ascription of existence.

Several strategies have been suggested in order to overcome this difficulty. According to the emergentist approach that has been defended by Searle (1997) among others, mental life would be an “emergent” property of the complex brain activity. However, this approach still pre-supposes matter and its objective laws as primary and cannot then account for the individual, subjective experience for the reason mentioned above. On the other hand, Chalmers (1996; chap. 8) appeals to a concept of information that would be interpreted in both objective and subjective domains and would then play a role of interface between them. Nagel (1974) has suggested the construction of an “objective phenomenology” capable of making intelligible, at least for the human being, the subjective character of experience. In a similar way, Bitbol (2008) has explored Varela’s idea of “neurophenomenology” (Varela, 1988) that takes into account the “mutual generative constraints” between the mental and physiological domains and would thus be capable of articulating the phenomenal dimension of consciousness with the underlying neurophysiological processes. Regarding now the dissipative quantum model of the brain, the question is thus: in which sense could this model of the *brain* activity developed within the framework of quantum field theory resolve the question of the explanatory gap more than other materialist approaches?

One can first remark that in most of the writings dealing with the quantum model of the brain or its extension, the dissipative quantum model of the brain, no clear distinction is established between, on one hand, brain states, neural processes or the

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<sup>6</sup> Following Kuhn’s analysis of the scientific revolutions (1962), one could say that subjective experience is an anomaly in the materialist paradigm.

associated informational processes and, on the other hand, mental states, mind, consciousness or its phenomenal aspect. Moreover, one could say that in this model both classes of processes seem often to be confused<sup>7</sup>, as shown, for example, by the title of Pessa's and Vitiello's paper (2003) which claims to deal with "mind/brain states." More specifically, one can read in Jibu's and Yasue's book (1995) the following sentence:

"With the help of quantum field theory, we have found that the creation and annihilation dynamics of corticons and photons in the QBD system<sup>8</sup> in the sub-microscopic world of the brain to be the entity that we call consciousness or mind."

This means that Jibu and Yasue quite simply *identify* "consciousness" or "mind" with a physical process; namely, the interaction between the electrical dipoles of the brain and the electromagnetic field generated by the neuronal network – with a particular emphasis on the role played by the dendrites, in agreement with Pribram's ideas. In a similar way, Stuart and colleagues (1979) claim that the activation of neural networks according to certain collective, oscillatory modes would make "conscious" the information they encode but do not provide us with any clarification of the expression "to be conscious" and, correlatively, on the nature of "consciousness" which is purely and simply identified with the brain activity.<sup>9</sup> Correlatively, the key concept of "memory" on which this model crucially relies does not refer to any mental or subjective content but only to an order parameter that also characterizes nothing more than the *physical organisation of the brain* (Vitiello, 1995).

<sup>7</sup> Note, however, that a clarification of this question has recently been provided Freeman's and Vitiello's paper (2008; p.3): "..., the dissipative model describes the brain, not mental states."

<sup>8</sup> QBD, for "quantum brain dynamics", denotes Jibu's and Yasue's version of the quantum model of the brain that integrates Pribram's holographic concept of memory (1991) according to which the information collected by the brain would be encoded on the membranes of the synapses by tiny changes of their electric sensibility.

<sup>9</sup> Note, however, that in another paper (Stuart *et al.*, 1978) these authors also claim that the brain "consciously feels" the pre-existing ordered pattern of oscillation in recall processes, which supposes that consciousness pre-exist to brain processes. The two points of view defended by these authors, namely that consciousness could be identified with brain processes and that consciousness pre-exist to brain processes, seem very difficult to reconcile.

One can find in Vitiello's work an interesting attempt to ground consciousness in the dynamical relation between the brain (noted as A) and its environment, called its *Sosia* or its *Double* (noted as  $\tilde{A}$ ), which is "permanently joined to it" (Vitiello, 2003): consciousness would emerge from the continuous interaction (or "dialogue") between the brain and its environment. According to this idea, consciousness would be "possible only if dissipation, openness onto the outside world is allowed," trivializing then the role of the subject inner activity. In other words, consciousness (and even the subjective "now") is here conceived of as resulting essentially from the dissipative dynamics governing the "dialogue" between the brain and its environment and would consequently be "diffused" in the great system composed of the brain and its environment - which, according to Vitiello, would put into question the traditional opposition between the objectivity of the external world and the subjectivity of conscious experience (Vitiello, 2004, p. 5).

However, as interesting and original as these developments can be, one can say that in this approach the phenomenal aspect of consciousness is still shrugged off. How can an impersonal, *physical* interaction between two systems (the brain and its environment) give rise to subjective experience, which is lived in a specific, personal context by a subject who perceives, thinks, or dreams? And, correlatively, why would the "dialogue" between the brain and its "Double", that is, the *physical interaction* between the brain and its environment, put into question the opposition between the subject and the external world? It seems that, contrary to Vitiello's claim, this "dialogue" only concerns *the frontier between two physical systems* and not between the external world and the subject, the latter being characterized by his/her personal sensibility, his/her beliefs, and his/her own rationality. One can thus consider that, as in all other materialist approaches, the explanatory gap between the description of brain processes in the language of neurobiology and subjective experience cannot be filled in this model: the phenomenal aspect of consciousness and

that of memory are still abusively reduced or identified with the brain activity.

Indeed, this question involves the *relationship* between the brain activity and the correlative subjective experience and therefore *exceeds the strict domain of sciences of matter, like physics or biology*. According to some authors, it could find some clarifications within the framework of quantum *theory* (and *not* quantum physics) where the latter is used, in its standard version or in weaker versions, for its key concepts of complementarity and entanglement. Quantum theory can indeed be used to represent a) the co-emergence of the material and the mental domains from an underlying level of reality that is “neutral” regarding to their distinction<sup>10</sup> - and can actually be considered as the psychophysical unity of the individual; and b) the psychophysical correlations, which can thus be considered as remnants of their common origin (Atmanspacher, 2003; Atmanspacher *et al.*, 2009; Primas, 2003). According to this direction of research, a model of the brain activity (like the dissipative quantum model presented above) can only be considered as a part of the physiological aspect or, formally speaking, of the physiological *interpretation* of a theory of the *psychosomatic unity of the individual* – a theory based on the idea that the whole psychic life (being conscious or not) is entangled with physiological processes, as well as with the metabolism, the endocrine and the immune processes *of the whole body* and not only of the brain (Uzan, 2011). Dealing with this question would thus require to leave the strict domain of physics - or, at least, to develop what Yasue (1999) has called a “frontier physics”, which goes beyond the initial goal of this paper that involves the capability of quantum *physics* to address the binding problem.

## Conclusion

One can say that the approach of the brain activity developed within the framework of quantum field theory, in the dissipative quantum model of the brain, may prove very fruitful to tackle the question of *information*

integration by the brain. However, as explained in section 4, it can really contribute to explain the observed synchronized oscillatory *neuronal* dynamics underlying the temporal binding of information provided that a genuine correspondence or a clear explanation of the physical interaction between the oscillatory activity of neurons and that of the *molecular* dipoles of the brain on which it focuses can be established, as well as a clear explanation of the exact *function* of the latter molecular oscillations phenomenon. By contrast, as suggested in section 4, a classical implementation of the spontaneous symmetry breaking phenomenon in terms of *neuronal dipolar field* could be of help to overcome this difficulty.

Regarding now the second aspect of the binding problem, namely the question to explain how neuronal (or informational) processes could give rise to subjective experience, I have explained that it cannot be tackled by a model that exclusively deals with the *brain* activity. This question indeed requires exploring other directions of research that is capable of dealing with the *psychophysical unity of the individual* – which necessarily involves consideration of the characteristics of the whole body and those of the whole mental life. In particular, quantum *theory* could be used for its key concepts of complementarity and entanglement to represent the observed psychophysical correlations.

<sup>10</sup> This means that, according to these authors, this question requires to leave the materialist conception of the world and to work within the framework of *neutral monism*.

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