

Quantum Noise, Entanglement and Chaos in the Quantum Field Theory of Mind/Brain States

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Abstract

We review the dissipative quantum model of the brain and present recent developments related to the role of entanglement, quantum noise and chaos in the model.

1. Introduction

The quantum model of the brain was originally formulated by Ricciardi and Umezawa (1967) and subsequently developed by Stuart, Takahashi, and Umezawa (1978, 1979), by Jibu and Yasue (1995), and by Jibu, Pribram and Yasue (1996). The model uses the formalism of quantum field theory (QFT). The extension of the model to dissipative dynamics has been worked out more recently (Vitiello 1995; see also Alfinito and Vitiello 2000, Pessa and Vitiello 1999), and a general account is given in the book *My Double Unveiled* (Vitiello 2001).

The motivations at the basis of the formulation of the quantum model of the brain by Ricciardi and Umezawa can be traced back to laboratory observations dating back to the 1940s, which led Lashley (1942) to remark that “nerve impulses are transmitted over definite, restricted paths in the sensory and motor nerves and in the central nervous system from cell to cell through definite inter-cellular connections. Yet all behavior seems to be determined by masses of excitations ... within general fields of activity, without regard to particular nerve cells. It is the pattern and not the element that counts” (cf. Pribram 1991).

In the mid 1960s, Karl Pribram, also motivated by experimental observations, started to formulate his holographic hypothesis. Indeed, information appears to be spatially uniform “in much the way that the information density is uniform in a hologram” (Freeman 1990, 2000). While the

activity of a single neuron is experimentally observed in the form of discrete and stochastic pulse trains and point processes, the “macroscopic” activity of large assemblies of neurons appears to be spatially coherent and highly structured in phase and amplitude (Freeman 1996, 2000).

Motivated by such an experimental situation, Ricciardi and Umezawa (1967) formulated the quantum model of the brain as a many-body physics problem, by using the formalism of QFT with a spontaneous breakdown of symmetry, successfully tested in condensed matter experiments. In fact, such a formalism provides the only available theoretical tool capable of describing long-range correlations in many-body systems.

In classical physics, long-range correlations are usually explained as the result of classical processes causally propagating along different pathways. However, such a view is not supported by many experimental observations in condensed matter physics. In contrast, such observations are fully described and predicted by quantum field theory (Itzykson and Zuber 1980, Umezawa 1993). The hypothesis by Ricciardi and Umezawa (1967) was, then, that the QFT approach could also be applied to describe the observation that the brain presents almost simultaneous responses in several regions to some external stimuli. As a matter of fact, the understanding of such correlations in terms of modern biochemical and electrochemical processes is still lacking, which suggests that these responses could not be explained in terms of single neuron activity (Pribram 1971, 1991).

In QFT the dynamics (i.e. the Lagrangian) is in general invariant under some group G of continuous transformations. This means that the dynamical evolution of the system is constrained by the conservation laws of some observables depending on G . For example, invariance under the time translation group implies energy conservation, and similarly one gets the conservation of momentum, of electric charge, etc. as consequences of the dynamical invariances under corresponding continuous transformation groups. The invariance of the dynamics, thus, characterizes physical states of the system by assigning conserved quantities to them.

Spontaneous breakdown of symmetry occurs when the minimum energy state (the ground state or vacuum) of the system is not invariant under the full group G , but under one of its subgroups. Then it can be shown (Itzykson and Zuber 1980, Umezawa 1993) that collective modes, the so-called Nambu-Goldstone (NG) boson modes, are dynamically generated. At this point, let us mention that particles may also be represented as wave excitations or modes. Referring to NG modes, thus, emphasizes wave-like behavior rather than particle-like behavior.

Propagating over the whole system, these modes are the carriers of the ordering information in terms of *long-range correlations*: order manifests itself as a global property dynamically generated. The long-range correlation modes are responsible for maintaining the ordered pattern: they are coherently *condensed* in the ground state. In the case of crystals, for

example, they keep the atoms trapped at their lattice sites. Long-range correlations thus form a sort of net, extending all over the system, which traps its components in an ordered pattern. This explains the macroscopic collective behavior of the system as a “whole”.

The macroscopic observable specifying the ordered state of a system is called the order parameter. For example, the density (or a quantity proportional to it) is the order parameter for a crystal, the magnetization for a ferromagnet, etc. Properties like the stiffness of a crystal, electrical conductivity, etc., depend on the value assumed by the order parameter under specific boundary conditions. Inducing changes in these properties by modifying the degree of order in the system state, e.g. by tuning a relevant parameter of the system, results in a change of the value of the order parameter. For example, one may melt a crystal or wash out the magnetic properties of a ferromagnet by raising the temperature above a particular threshold. Thus, the order parameter can be understood as the *code* specifying the order of the state. In QFT, the order parameter is a measure of the condensation of the NG modes in the ground state.

It should be noted that the spontaneous breakdown of symmetry is possible since in QFT there exist infinitely many ground states or vacua which are physically distinct (technically speaking, they are “unitarily inequivalent”). In standard quantum mechanics, on the contrary, all vacua are physically equivalent and, thus, a breakdown of symmetry does not occur.

In the following section we will see how these features of QFT can be applied to the activity of the brain. The paper is organized as follows: in Section 2 we briefly summarize the main aspects of the quantum brain model. In Section 3 we review its extension to dissipative dynamics and comment on brain-environment entanglement. In Sections 4 and 5 we present very recent developments concerning quantum noise and chaos, respectively. Section 6 is devoted to concluding remarks.

2. The Quantum Model of the Brain

In this section we present a brief summary of the model by Ricciardi and Umezawa, closely following the presentation by Vitiello (2001).

An essential, first requirement in the model is that stimuli arriving at the brain from the external world should be coded and their effects on the brain should persist after they have ceased. This means that stimuli should be able to change the state of the brain preceding the stimulation into another state in which the information is “printed” in a stable fashion. This implies that the state in which information is recorded under the action of the stimuli must be a ground state in order to realize the stability of the recorded information, and that some symmetry is broken in order

to allow the coding of the information. Recording of information is thus represented by a coherent condensation of the NG bosons implied by the symmetry breakdown. In the limit of infinite volume, the NG collective modes are massless bosons, and their condensation in the vacuum does not add energy to it. The vacuum state with condensed NG modes is, thus, an ordered state, namely the stable ground state of the system with lowest energy. In this way, the stability of the ordering and, therefore, of the registered information, is ensured. In realistic situations with finite volume, the NG modes may acquire a non-zero effective mass, which lifts the energy of the ordered state, thus affecting its stability as well. A finite lifetime of the state (memory) may then be the result.

The order parameter is specific to the kind of symmetry of the dynamics, and its value is considered to be the *code* specifying the information printed in that ordered vacuum. As mentioned in Sec. 1, NG mode condensation implies that the system components involved in the long-range correlations behave as a whole, as a collective system with “global properties” beyond the “local properties” of the individual components. As a matter of fact, some of the local properties may even become unobservable once the individual components are “trapped” in a long-range correlation: some of their degrees of freedom are frozen. A simple example is the drastically reduced mobility of individual atoms constituting a crystal and the corresponding appearance of macroscopic properties, which are not local. Lashley’s statement that “it is the pattern and not the element that counts” refers precisely to this situation. Such “non-local” properties, related to a code specifying the system state, are dynamical features of quantum origin. In this way, the stable, yet non-local character of memory is represented in the quantum model. It is derived as a dynamical feature rather than a property of specific neural nets (which would be critically damaged by local destructive actions).

It should be stressed that in classical many-body physics it is an impossible task to establish non-local (collective) properties by almost simultaneous correlations (ordering) over long distances in an almost stable fashion. The high level of stability and the high level of ordering are thermodynamically contradictory features inaccessible without the presence of a powerful external energy input. Observations of practically indefinitely long lived ordered states of matter, as crystals, ferromagnets, or superconductors, surviving in the absence of external energy supply, are only compatible with and predicted by QFT. In the quantum model of the brain, the laws of QFT describe long lived, ordered brain states corresponding to long lived, sharply defined memories. As yet, no classical model or simulation is available to account for such features of the brain.

The mechanism of recalling stored information is related to the possibility of exciting collective modes from the ground state. Suppose that an ordered pattern is printed in the brain by a condensation in the vacuum

induced by particular external stimuli. Though an order is stored, there can be no consciousness of this order as long as the brain is in its ground state. However, when a similar external stimulation occurs, it excites the massless boson associated with the long-range correlation. (In Sec. 5 we will clarify the notion of a “similar” stimulation, which was not explained in the original model, in more detail.)

Since the bosons are massless for an infinite volume, any small amount of energy can cause its excitation. (For a finite volume, NG bosons acquire non-zero mass, and the amount of energy to excite them is then raised beyond a particular threshold (see Vitiello 2001).) During the time of excitation, consciousness of the stored order arises (memory), thus explaining the mechanism of recollection (Ricciardi and Umezawa 1967). The excited modes have a finite lifetime and, thus, the recall mechanism is a temporary activity of the brain, as it is the case in our common experience. This also suggests that the capability to be “alert” or “aware” or to keep our “attention” focused on particular subjects for a short or a long time may have to do with the short or long lifetime of the modes excited from the ground state.

It may also happen that under the action of external stimuli the brain is put into a quasi-stationary excited state of greater energy than that of the ground state. Such an excited state carries collective modes in their non-minimum energy state. Thus, this state can support the recording of some information. However, due to its higher energy such a state and the collective modes are not stable and will sooner or later decay: short-term memory is then modeled by the condensation of long-range correlation modes in the excited states. Different types of short-term memory are represented by different excitation levels in the brain state. For a further analysis of short-term memory in terms of non-equilibrium phase transitions see also Sivakami and Srinivasan (1983).

The brain model should explain how memory remains stable and well protected within a highly excited system as the brain in fact is. Such a stability must be realized in spite of the permanent electrochemical activity and the continuous response to external stimulation. The electrochemical activity must also, of course, be coupled to the correlation modes which are triggered by external stimuli. It is indeed the electrochemical activity observed by neurophysiology that provides a first response to external stimuli (Stuart et al. 1978, 1979).

This suggests to model memory as a mechanism separate from the electrochemical processes of neuro-synaptic dynamics: the brain is then a “mixed” system involving different but interacting levels. The memory level is a quantum dynamical level, the electrochemical activity proceeds at a classical level. The interaction between the two is possible because the memory state is a *macroscopic quantum state* due to the *coherence* of the correlation modes, which is a result of the quantum dynamics.

The coupling between the quantum dynamical level and the classical electrochemical level is then reduced to the coupling of two macroscopic entities. Such a coupling is analogous to the coupling between classical acoustic waves and phonons in crystals. Acoustic waves are classical waves; phonons are quantum NG long-range modes. Nevertheless, their coupling is possible since the macroscopic behavior of the crystal “resides” in the phonon modes, so that the coupling between acoustic waves and phonons is equivalently expressed as the coupling between acoustic waves and crystals (which is a perfectly acceptable coupling from a classical point of view).

We remark that the quantum variables in the quantum model of the brain are basic field variables (the electric dipole field), and the brain as a whole is described as a macroscopic quantum system. Stuart et al. (1978) indeed stated that “it is difficult to consider neurons as quantum objects”, and they add: “we do not intend to consider necessarily the neurons as the fundamental units of the brain”.

The quantum model of the brain fits the neurophysiological observations of memory nonlocality and stability. However, several problems are left open. One is that of memory capacity, the *overprinting problem*: Suppose a specific code corresponding to specific information has been printed in the vacuum. The brain is then in that state, and successive recording of a new, distinct (i.e. differently coded) information, under the action of a subsequent external stimulus, is possible only through a new condensation process, corresponding to a new code. This condensation will superimpose itself on the former one (*overprinting*), thus destroying the first registered information.

It has been shown (Vitiello 1995) that taking into account the dissipative character of brain dynamics may solve the problem of memory capacity. Quantum dissipation also turns out to be crucial for the understanding of other functional features of the brain. In the next section we present a short summary of the dissipative quantum model of the brain.

3. The Dissipative Quantum Model of the Brain

In the quantum model of the brain the symmetry, which undergoes spontaneous breakdown under the action of the external stimuli, is the electric dipole rotational symmetry. Water and other biochemical molecules entering brain activity are, indeed, all characterized by a specific electric dipole which strongly constrains their chemical and physical behavior. Once the dipole rotational symmetry has been broken (and information has thus been recorded), then, as a consequence, time-reversal symmetry is also broken: *Before* the information recording process, the brain can in principle be in any one of the infinitely many (unitarily inequivalent)

vacua. *After* information has been recorded, the brain state is completely determined and the brain cannot be brought to the state configuration in which it was *before* the information printing occurred. This is the meaning of the well known warning *NOW you know!*, which tells you that since *now* you know, you are *another* person, not the same one as *before*. Once you get to know, you move forward in time.

Thus, “gathering information” introduces the *arrow of time* into brain dynamics – it introduces a partition in the time evolution, the *distinction* between the past and the future, which did not exist *before* the information recording. In other words, it introduces irreversibility due to dissipation. The brain is, thus, unavoidably an open system.

When the system under study is not an isolated system, it is customary in quantum theory to incorporate in its description other systems (constituting its *environment*) to which the original system is coupled. The full set of systems then behaves as a single isolated (closed) one. At the end of the required computations, one extracts the information regarding the evolution of the original open system by neglecting the changes in the remaining systems.

In many cases, the specific details of the coupling of a system with its environment may be very intricate and changeable, so that they are difficult to be measured and known. One possible strategy is to average the effects of the coupling and represent them, at some degree of accuracy, by means of some “effective” interaction. Another possibility is to take into account the environmental influence on the system by a suitable *choice* of the vacuum state (the minimum energy state or ground state). The chosen vacuum thus carries the *signature* of the reciprocal system-environment influence at a given time under given boundary conditions. A change in the system-environment coupling corresponds to a change in the choice of the system vacuum: the evolution of the ground state of the system, or its “story”, is the story of the trade-off of the system with its environment. The theory should then provide the equations describing the system evolution “through the vacua”, each vacuum corresponding to the ground state of the system at each time of its history.

In order to describe open quantum systems, first of all one needs to use QFT with many “inequivalent” vacua. Then one needs to use the time variable as a label for the set of ground states of the system (Celeghini et al. 1990): as time (the label value) changes, the system moves to a “new”, physically inequivalent ground state (assuming continuous changes in the boundary conditions determining the system-environment coupling). Here, “physically inequivalent” means that the system observables, such as the energy, assume different values in different inequivalent vacua, as is expected in the case of open systems.

In this way, one gets a description for open systems which is similar to a collection of photograms: each photogram represents the “picture”

of the system at a given instant (a specific time label value). Putting together these photograms in “temporal order” one gets a movie, i.e. the story (the evolution) of the system, which includes system-environment interaction effects.

The mathematical representation of the environment must explicitly satisfy the requirement that the energy lost by the system matches the energy gained by the environment, and *vice versa*. All other details of the system-environment interaction may be taken into account by the vacuum structure of the system, in the sense explained above. Then the environment may be represented in the simplest way one likes, provided the energy flux balance is preserved. One possible choice is to represent the environment as the “time-reversed copy” of the system: time must be reversed since the energy “dissipated” by the system is “gained” by environment (and *vice versa*). In this sense, the environment may be mathematically represented as the *time-reversed image* of the system, i.e. as the system “double”.

Let A_κ denote the dipole wave quantum (DWQ) mode, i.e. the NG mode associated with the spontaneous breakdown of rotational electric dipole symmetry. (See Sec. 1 for the use of the term “mode” alternatively to that of the term “particle”.) Then \tilde{A}_κ , its “doubled mode”, is the “time-reversed mirror image” of A representing the environment. Let \mathcal{N}_{A_κ} and $\mathcal{N}_{\tilde{A}_\kappa}$ denote the number of A_κ and \tilde{A}_κ modes, respectively. The suffix κ here generically indicates kinematical variables (e.g. spatial momentum) or intrinsic field variables fully specifying the degrees of freedom of the fields.

Notice that the “tilde”, or doubled, mode is not just a mathematical fiction. It corresponds to a real excitation mode (a quasiparticle) of the system as an effect of its interaction with the environment: the couples $A_k\tilde{A}_k$ represent the correlation modes dynamically created in the system as a response to the system-environment reciprocal influence. It is the interaction between tilde and non-tilde modes that controls the time evolution of the system. The collective modes $A_k\tilde{A}_k$ are confined *within* the system. They vanish as soon as the links between the system and the environment are cut. In the following Sec. 4 we will see how these doubled modes may be understood in terms of Wigner functions and how they are related to quantum noise (Srivastava et al. 1995).

Taking into account dissipation requires (Vitiello 1995) that the memory state, identified with the vacuum $|0\rangle_{\mathcal{N}}$, is a condensate of an *equal number* of A_κ and \tilde{A}_κ modes for any κ : such a requirement ensures that energy exchange between the system and the environment is balanced. Thus, the difference between the number of tilde and non-tilde modes must be zero: $\mathcal{N}_{A_\kappa} - \mathcal{N}_{\tilde{A}_\kappa} = 0$, for any κ . (The label \mathcal{N} in the vacuum symbol $|0\rangle_{\mathcal{N}}$ specifies the set of integers $\{\mathcal{N}_{A_\kappa}$, for any $\kappa\}$ which indeed

defines the “initial value” of the condensate, namely the *code* associated to the information recorded at time $t_0 = 0$.)

The requirement $\mathcal{N}_{A_\kappa} - \mathcal{N}_{\tilde{A}_\kappa} = 0$, for any κ , does not uniquely fix the set $\{\mathcal{N}_{A_\kappa}, \text{ for any } \kappa\}$. With $\mathcal{N}' \equiv \{\mathcal{N}'_{A_\kappa}; \mathcal{N}'_{A_\kappa} - \mathcal{N}'_{\tilde{A}_\kappa} = 0, \text{ for any } \kappa\}$, $|0\rangle_{\mathcal{N}'}$ obeys the energy flow balance and, therefore, is an available memory state. It does, however, correspond to a different code \mathcal{N}' and, therefore, to information different from that coded by \mathcal{N} . The conclusion is that the condition $\mathcal{N}_{A_\kappa} - \mathcal{N}_{\tilde{A}_\kappa} = 0$, for any κ , leaves completely open the choice for the value of the code \mathcal{N} .

Thus, infinitely many memory (vacuum) states, each of them corresponding to a different code \mathcal{N} , may exist: A huge number of sequentially recorded information data may *coexist* without destructive interference since infinitely many vacua $|0\rangle_{\mathcal{N}}$, for all \mathcal{N} , are *independently* accessible in the sequential recording process. The recorded information coded by \mathcal{N}' does not necessarily lead to the destruction of previously printed information coded by $\mathcal{N} \neq \mathcal{N}'$, contrary to the non-dissipative case. In the dissipative case the “brain (ground) state” may be represented as the collection (or the superposition) of the full set of memory states $|0\rangle_{\mathcal{N}}$, for all \mathcal{N} . In the non-dissipative case the “ \mathcal{N} -freedom” is missing and consecutive information printing produces overprinting.

The memory state is known (Vitiello 1995) to be a two-mode coherent state (a generalized $SU(1, 1)$ coherent state) and is given, at finite volume V , by

$$|0\rangle_{\mathcal{N}} = \prod_k \frac{1}{\cosh \theta_k} \exp \left(- \tanh \theta_k A_k^\dagger \tilde{A}_k^\dagger \right) |0\rangle_0, \quad (1)$$

and, for all \mathcal{N} , states are normalized such that ${}_{\mathcal{N}}\langle 0|0\rangle_{\mathcal{N}} = 1$.

$|0\rangle_{\mathcal{N}}$ is an entangled state, which cannot be factorized into two single-mode states (one of which refers to the system and the other one to its environment). Indeed, $|0\rangle_{\mathcal{N}}$ can be written as

$$|0\rangle_{\mathcal{N}} = \prod_k \frac{1}{\cosh \theta_k} \left(|0\rangle_0 \otimes |\tilde{0}\rangle_0 - \sum_k \tanh \theta_k \left(|A_k\rangle \otimes |\tilde{A}_k\rangle \right) + \dots \right), \quad (2)$$

where we have explicitly expressed the tensor product between the tilde and non-tilde sector and dots stand for higher order terms. Clearly, the second factor on the right hand side of Eq. (2) cannot be reduced to the product of two single-mode components.

We remark that the entanglement is expressed by the unitary inequivalence relation with the vacuum $|0\rangle_0 \equiv |0\rangle_0 \otimes |\tilde{0}\rangle_0$:

$${}_{\mathcal{N}}\langle 0|0\rangle_0 \xrightarrow{V \rightarrow \infty} 0 \quad \forall \mathcal{N} \neq 0, \quad (3)$$

which is verified only in the infinite volume limit. At finite volume, a unitary transformation could disentangle the tilde and non-tilde sectors:

for a finite number of components their tensor product would be different from the entangled state. However, this is not the case in the infinite volume limit, where the summation extends to an infinite number of components. In such a limit the entanglement of brain and environment is permanent. It cannot be washed out: The entanglement mathematically represents the impossibility of cutting the links between the brain and the external world (a closed, i.e. fully isolated, brain is indeed a dead brain in the sense of physiology).

Notice that memory states corresponding to different codes $\mathcal{N} \neq \mathcal{N}'$, $|0\rangle_{\mathcal{N}}$ and $|0\rangle_{\mathcal{N}'}$, are unitarily inequivalent to one another in the infinite volume limit:

$$\mathcal{N} \langle 0|0\rangle_{\mathcal{N}'} \xrightarrow{V \rightarrow \infty} 0 \quad \forall \mathcal{N} \neq \mathcal{N}' . \quad (4)$$

This means that in the infinite volume limit no unitary transformation exists which may transform a vacuum of code \mathcal{N} into another one of code \mathcal{N}' . This fact, which is a typical feature of QFT, guarantees that the corresponding printed information data are indeed *different* or *distinguishable* (\mathcal{N} is a *good* code) and that each information printing is also *protected* against interference from other information printing (absence of *confusion* among information data).

The average number \mathcal{N}_{A_κ} is given by

$$\mathcal{N}_{A_\kappa} = \mathcal{N} \langle 0|A_\kappa^\dagger A_\kappa|0\rangle_{\mathcal{N}} = \sinh^2 \theta_\kappa , \quad (5)$$

and relates the \mathcal{N} -set $\mathcal{N} \equiv \{\mathcal{N}_{A_\kappa} = \mathcal{N}_{\bar{A}_\kappa}, \forall \kappa, \text{ at } t_0 = 0\}$ to the θ -set $\theta \equiv \{\theta_\kappa, \forall \kappa, \text{ at } t_0 = 0\}$. We also use the notation $\mathcal{N}_{A_\kappa}(\theta) \equiv \mathcal{N}_{A_\kappa}$ and $|0(\theta)\rangle \equiv |0\rangle_{\mathcal{N}}$. In general we may refer to \mathcal{N} or, alternatively and equivalently, to the corresponding θ .

A finite (realistic) size of the system may spoil the above mentioned unitary inequivalence. In the case of open systems, in fact, transitions among “almost” unitarily inequivalent vacua may occur (phase transitions) for large but finite volume, due to coupling with the external environment. The inclusion of dissipation leads, thus, to a picture of the system “living over many ground states” (continuously undergoing phase transitions). Note that even very weak perturbations (above a particular threshold) may drive the system through its macroscopic configurations. In this way, occasional (random) weak perturbations are recognized to play an important role in the complex behavior of the brain.

The possibility of transitions among differently coded vacua is an attractive feature of the model: smoothing out the exact unitary inequivalence among memory states has the advantage of allowing the familiar phenomenon of the “association” of memories: once transitions among different memory states are “slightly” allowed, the possibility of associations (“following a path of memories”) becomes possible. Of course, these “transitions” should only be allowed up to a certain degree in order to

avoid memory “confusion” and difficulties in the process of storing “distinct” informational inputs (Vitiello 1995, Alfinito and Vitiello 2000). It is interesting to observe that Freeman, on the basis of experimental observations, showed that noisy fluctuations at a microscopic level may have a stabilizing effect on brain activity. Noise prevents capture by collapse into some unwanted state (attractor) and is an essential ingredient for the neural chaotic perceptual apparatus (Freeman 1990, 1996, 2000). In this regard, we will consider the role of quantum noise in Sec. 4.

Moreover, the evolution of the \mathcal{N} -coded memory can be represented as the trajectory of a given initial condition running over time-dependent states $|0(t)\rangle_{\mathcal{N}}$, each one minimizing the free energy functional. Recent results (Pessa and Vitiello 2003, Vitiello 2003) show that such trajectories may be chaotic. We will discuss this in Sec. 5.

The DWQ may acquire an effective non-zero mass due to the effects of the finite system size (Vitiello 1995; Alfinito and Vitiello 2000). Such an effective mass will act as a threshold for the excitation energy of DWQ so that, in order to trigger the recall process, an energy supply equal to or greater than such a threshold is required. When the energy supply is lower than the required threshold, a “difficulty in recalling” may be experienced. On the other hand, however, the threshold may positively act as a “protection” against unwanted perturbations (including thermalization) and contributes to the stability of the memory state. In the case of zero threshold any replication signal could excite the recalling and the brain would fall into a “continuous flow of memories” (Vitiello 1995).

Summarizing, the brain system may be viewed as a complex system with (infinitely) many macroscopic configurations (the memory states). Dissipation, which is intrinsic to the brain dynamics, is recognized to be the root of its huge memory capacity.

Of course, the brain has several structural and dynamical levels (the basic level of coherent condensation of DWQ, the cellular cytoskeleton level, the neuronal dendritic level, and so on) which coexist, interact among themselves and influence each other’s functioning. Dissipation introduces the rich variety of the replicas or degenerate vacua at the basic quantum level. The crucial point is that the different levels of organization are not simply structural features of the brain. Their reciprocal interaction and their evolution is intrinsically related to the basic quantum dissipative dynamics.

The brain’s functional stability is ensured by the system’s “coherent response” to the multiplicity of external stimuli. Thus, dissipation also suggests a solution to the so-called *binding problem* in terms of the unitary response and behavior of apparently separated units and physiological structures of the brain.

When considering DWQ with time-dependent frequency, modes with longer lifetime are found to be those with higher momentum. Since the

momentum is inversely proportional to the distance over which the mode can propagate, modes with a shorter range of propagation will survive longer. On the contrary, modes with a longer range of propagation will decay sooner. The scenario becomes then particularly interesting since this mechanism may produce the formation of ordered domains of different finite sizes with different degrees of stability: smaller domains would be the more stable ones. Remembering that the regions over which the DWQ propagate are the domains where ordering (i.e. symmetry breakdown) is produced, we arrive at the dynamic formation of a hierarchy of domains, ordered according to their lifetime or, equivalently, their sizes (Alfinito and Vitiello 2000).

4. Quantum Noise

In this section, we resort to previous results on dissipative quantum systems (Srivastava et al. 1995, Blasone et al. 1998) and show that the doubled variables account for quantum noise effects in the fluctuating random force in the system-environment coupling. This opens a new perspective in the quantum model of the brain and fits well with some experimental observations of brain behavior (Freeman 1990, 1996, 2000). Our discussion will also show how the doubling of the degrees of freedom is related to the Wigner function and to the density matrix formalism.

Before considering dissipation, let us address the case of zero mechanical resistance. The Hamiltonian for an isolated particle is

$$H = -\frac{\hbar^2}{2m} \left(\frac{\partial}{\partial x} \right)^2 + V(x) , \quad (6)$$

and the expression for the Wigner function is (Feynman 1972, Haken 1984)

$$W(p, x, t) = \frac{1}{2\pi\hbar} \int \psi^* \left(x + \frac{1}{2}y, t \right) \psi \left(x - \frac{1}{2}y, t \right) e^{-i\frac{py}{\hbar}} dy . \quad (7)$$

The associated density matrix function is

$$W(x, y, t) = \langle x + \frac{1}{2}y | \rho(t) | x - \frac{1}{2}y \rangle = \psi^* \left(x + \frac{1}{2}y, t \right) \psi \left(x - \frac{1}{2}y, t \right) , \quad (8)$$

where the equation of motion is given by

$$i\hbar \frac{d\rho}{dt} = [H, \rho] . \quad (9)$$

Introducing the notation

$$x_{\pm} = x \pm \frac{1}{2}y , \quad (10)$$

Eq. (9) is written in the coordinate representation as

$$i\hbar \frac{\partial}{\partial t} \langle x_+ | \rho(t) | x_- \rangle = \left\{ -\frac{\hbar^2}{2m} \left[\left(\frac{\partial}{\partial x_+} \right)^2 - \left(\frac{\partial}{\partial x_-} \right)^2 \right] + [V(x_+) - V(x_-)] \right\} \langle x_+ | \rho(t) | x_- \rangle, \quad (11)$$

namely, in terms of x and y , we have

$$i\hbar \frac{\partial}{\partial t} W(x, y, t) = \mathcal{H}_o W(x, y, t), \quad (12)$$

$$\mathcal{H}_o = \frac{1}{m} p_x p_y + V \left(x + \frac{1}{2} y \right) - V \left(x - \frac{1}{2} y \right), \quad (13)$$

with $p_x = -i\hbar \frac{\partial}{\partial x}$, $p_y = -i\hbar \frac{\partial}{\partial y}$. The Hamiltonian (13) may be constructed from the Lagrangian

$$\mathcal{L}_o = m\dot{x}\dot{y} - V \left(x + \frac{1}{2} y \right) + V \left(x - \frac{1}{2} y \right). \quad (14)$$

We see, thus, that both the density matrix formalism and the Wigner function formalism require the introduction of a “doubled” set of coordinates, x_{\pm} or, alternatively, x and y .

In the case of a particle interacting with a thermal bath at temperature T , the interaction Hamiltonian between the bath and the particle is taken as

$$H_{int} = -fx, \quad (15)$$

where f is a random force on the particle at position x due to the bath.

In the Feynman-Vernon formalism, it can be shown (Srivastava et al. 1995) that the effective action for the particle has the form

$$\mathcal{A}[x, y] = \int_{t_i}^{t_f} dt \mathcal{L}_o(\dot{x}, \dot{y}, x, y) + \mathcal{I}[x, y], \quad (16)$$

where \mathcal{L}_o is defined in Eq. (14) and

$$\begin{aligned} \mathcal{I}[x, y] &= \frac{1}{2} \int_{t_i}^{t_f} dt [x(t) F_y^{ret}(t) + y(t) F_x^{adv}(t)] \\ &+ \frac{i}{2\hbar} \int_{t_i}^{t_f} \int_{t_i}^{t_f} dt ds N(t-s) y(t) y(s), \end{aligned} \quad (17)$$

where the retarded force on y and the advanced force on x are given in terms of the retarded and advanced Green functions and $N(t-s)$ denotes the quantum noise in the fluctuating random force given by

$$N(t-s) = \frac{1}{2} \langle f(t)f(s) + f(s)f(t) \rangle. \quad (18)$$

The bracket $\langle \dots \rangle$ denotes the average with respect to the thermal bath. One can then show (see Srivastava et al. 1995 for details) that the real and the imaginary part of the action due to Eq. (16) are given by

$$\mathcal{R}e \mathcal{A}[x, y] = \int_{t_i}^{t_f} dt \mathcal{L}, \quad (19)$$

$$\mathcal{L} = m\dot{x}\dot{y} - \left[V(x + \frac{1}{2}y) - V(x - \frac{1}{2}y) \right] + \frac{1}{2} [xF_y^{ret} + yF_x^{adv}], \quad (20)$$

and

$$\mathcal{I}m \mathcal{A}[x, y] = \frac{1}{2\hbar} \int_{t_i}^{t_f} \int_{t_i}^{t_f} dt ds N(t-s) y(t) y(s), \quad (21)$$

respectively. These results, Eqs. (19), (20), and (21), are rigorously exact for linear passive damping due to the bath. They show that, in the classical limit “ $\hbar \rightarrow 0$ ”, non-zero y yields an “unlikely process” due to the large imaginary part of the action implicit in Eq. (21). (If $y \neq 0$, the resulting non-zero part of the action may lead to a negative real exponent in the evolution operator yielding, in the limit $\hbar \rightarrow 0$, a negligible contribution in the probability amplitude.) On the contrary, at the quantum level non-zero y accounts for quantum noise effects in the fluctuating random force in the system-environment coupling, arising from the imaginary part of the action (Srivastava et al. 1995).

If one approximates Eq. (20) with $F_y^{ret} = \gamma\dot{y}$ and $F_x^{adv} = -\gamma\dot{x}$, and puts $V(x \pm \frac{1}{2}y) = \frac{1}{2}\kappa(x \pm \frac{1}{2}y)^2$, then the damped harmonic oscillator for the x variable and the complementary equation for the y coordinate can be derived:

$$m\ddot{x} + \gamma\dot{x} + \kappa x = 0, \quad (22)$$

$$m\ddot{y} - \gamma\dot{y} + \kappa y = 0. \quad (23)$$

The y -oscillator is thus recognized to be the time-reversed image of the x -oscillator. Of course, from the manifold of solutions to Eqs. (22) and (23) we could choose those for which the y coordinate is constrained to be zero. Then we obtain the classical damped oscillator equation from a Lagrangian theory at the expense of introducing an “extra” coordinate y , later constrained to vanish.

It should be stressed, however, that *the role of the “doubled” y coordinate is absolutely crucial in the quantum regime where it accounts for the quantum noise in the fluctuating random force in the system-environment coupling*, as shown above. Reverting from the classical level to the quantum level, the loss of information occurring at the classical level due to dissipation manifests itself in terms of “quantum” noise effects arising from the imaginary part of the action, for which the y contribution is indeed crucial.

In the dissipative quantum model of the brain, the classical equations for x , Eq. (22), and its time-reversed image y , Eq. (23), are associated in the canonical quantization procedure with the quantum operators A and \tilde{A} (Vitiello 1995), respectively. In the framework of quantum field theory, A and \tilde{A} are labeled by the (continuously varying) suffix κ , and for each κ value we have a couple of equations of the type (22) and (23) for the field amplitudes (Celeghini et al. 1992).

In conclusion, we have seen that the doubling of the degrees of freedom discussed in the previous sections accounts for the quantum noise in the fluctuating random force coupling the system with the environment (the bath). On the other hand, we have also recognized the entanglement between the tilde and the non-tilde modes. Thus, we conclude that brain processes are intrinsically and inextricably dependent on the quantum noise in the fluctuating random force in the brain-environment coupling. It is interesting to mention, in this respect, the role of noise in neurodynamics which has been observed by Freeman (1990, 1996, 2000).

In the following section we discuss another intrinsic feature of the dissipative quantum model: the chaotic behavior of the trajectories in the space of memory states.

5. Chaos and Memory States

We denote by $|0(t)\rangle_{\mathcal{N}}$ the memory state at time t and refer to the space of memory states, for all \mathcal{N} and at any time t , to the “memory space”. In this space the memory state $|0(t)\rangle_{\mathcal{N}}$ may be thought of as a “point” labeled by a given \mathcal{N} -set (or θ -set) and by a given value of t . Points corresponding to different \mathcal{N} - (or θ -) sets and different t are distinct points (i.e., they do not overlap, cf. Eqs. (4) and (27) below). As mentioned, the memory states can be understood as the vacuum states of corresponding Hilbert spaces. In QFT, these Hilbert spaces are denoted as the representations of the canonical commutation relations for the operators A and \tilde{A} , which in the infinite volume limit are unitarily inequivalent. So, the memory space may also be denoted as the “space of (unitarily inequivalent) representations”, where each representation is represented by a “point”.

We show that trajectories in memory space (the representation space) may be chaotic trajectories. The requirements for chaotic behavior in non-linear dynamics can be formulated as follows (Hilborn 1994):

- (i) The trajectories are bounded and no trajectory intersects itself (trajectories are not periodic).
- (ii) There are no intersections between trajectories specified by different initial conditions.

- (iii) Trajectories of different initial conditions diverge with respect to one another.

At finite volume V , the memory state $|0(t)\rangle_{\mathcal{N}}$, to which the memory state $|0\rangle_{\mathcal{N}}$ evolves from $t_0 = 0$, say, is given by (Vitiello 1995)

$$|0(t)\rangle_{\mathcal{N}} = \prod_{\kappa} \frac{1}{\cosh(\Gamma_{\kappa} t - \theta_{\kappa})} \exp\left(\tanh(\Gamma_{\kappa} t - \theta_{\kappa}) A_{\kappa}^{\dagger} \tilde{A}_{\kappa}^{\dagger}\right) |0\rangle_0, \quad (24)$$

which is an entangled, $SU(1, 1)$ generalized coherent state. The damping constant Γ_{κ} is implied by dissipation (Vitiello 1995). Note that for any t :

$$\mathcal{N}\langle 0(t)|0(t)\rangle_{\mathcal{N}} = 1. \quad (25)$$

In the limit of infinite volume we have (for $\int d^3\kappa \Gamma_{\kappa}$ finite and positive)

$$\mathcal{N}\langle 0(t)|0\rangle_{\mathcal{N}} \xrightarrow{V \rightarrow \infty} 0 \quad \forall t, \quad (26)$$

$$\mathcal{N}\langle 0(t)|0(t')\rangle_{\mathcal{N}} \xrightarrow{V \rightarrow \infty} 0 \quad \forall t, t', \quad t \neq t'. \quad (27)$$

States $|0(t)\rangle_{\mathcal{N}}$ (and the associated Hilbert spaces $\{|0(t)\rangle_{\mathcal{N}}\}$) at different times $t \neq t'$ are, thus, unitarily inequivalent in the limit of infinite volume.

The time evolution of the memory state $|0\rangle_{\mathcal{N}}$ is, thus, represented as the (continuous) transition through the representations $\{|0(t)\rangle_{\mathcal{N}}\}$ at different t (same \mathcal{N}), i.e. by the “trajectory” through the “points” $\{|0(t)\rangle_{\mathcal{N}}\}$ in the space of the representations. The initial condition of the trajectory at $t_0 = 0$ is specified by the \mathcal{N} -set. It is known (Manka et al. 1986, Del Giudice et al. 1988, Vitiello 2003) that trajectories of this kind are classical trajectories: in the limit of infinite volume, a transition between two inequivalent representations is strictly forbidden in quantum dynamics.

We now observe that the trajectories are *bounded* in the sense of Eq. (25), which shows that the “length” of the “position vectors” (the state vectors at time t) in the representation space is finite (and equal to one) for each t . (Resorting to the properties of the $SU(1, 1)$ group, one can show that the set of points representing the coherent states $|0(t)\rangle_{\mathcal{N}}$ for any t is isomorphic to the union of circles of radius $r_{\kappa}^2 = \tanh^2(\Gamma_{\kappa} t - \theta_{\kappa})$ for any κ (Perelomov 1986, Pessa and Vitiello 2003).)

We also note that Eqs. (26) and (27) express the fact that the trajectory does not cross itself as time evolves (it is not a periodic trajectory): the “points” $|0(t)\rangle_{\mathcal{N}}$ and $|0(t')\rangle_{\mathcal{N}}$ through which the trajectory goes, for any t and t' , with $t \neq t'$, after the initial time $t_0 = 0$, never coincide. Requirement (i) is, thus, satisfied.

In the limit of infinite volume, Eqs. (26) and (27) also hold for $\mathcal{N} \neq \mathcal{N}'$, i.e. we have

$$\mathcal{N}\langle 0(t)|0\rangle_{\mathcal{N}'} \xrightarrow{V \rightarrow \infty} 0 \quad \forall t, \quad \forall \mathcal{N} \neq \mathcal{N}' \quad (28)$$

$$\mathcal{N}\langle 0(t)|0(t')\rangle_{\mathcal{N}'} \xrightarrow{V \rightarrow \infty} 0 \quad \forall t, t', \quad \forall \mathcal{N} \neq \mathcal{N}'. \quad (29)$$

The derivation of Eqs. (28) and (29) rests on the fact that in the continuum limit, for given t and t' and for $\mathcal{N} \neq \mathcal{N}'$, $\cosh(\Gamma_\kappa t - \theta_\kappa + \theta'_{\kappa'})$ and $\cosh(\Gamma_\kappa(t - t') - \theta_\kappa + \theta'_{\kappa'})$, respectively, are never identically equal to one for all κ . Notice that Eq. (29) is true also for $t = t'$ for any $\mathcal{N} \neq \mathcal{N}'$. Eqs. (28) and (29) thus tell us that trajectories specified by different initial conditions ($\mathcal{N} \neq \mathcal{N}'$) never cross each other. Hence, requirement (ii) is satisfied.

We remark that, in the limit of infinite volume, due to property (ii) no *confusion* (interference) arises among different memories, even as time evolves. In realistic situations of coherent domains with finite size, differently coded states may have a non-zero overlap (the finite size may spoil the strict unitary inequivalence of different representations, the inner products in Eqs. (28) and (29) may be non-zero). Due to this overlap, some *association of memories* becomes possible. In such a case, there may be a “crossing” point between two or more trajectories, enabling a transition from one of them to another one that it crosses. This transition may be experienced as a switch from one memorized information to another one.

The average number of modes of type A_κ at each t is given by

$$\mathcal{N}_{A_\kappa}(\theta, t) \equiv \mathcal{N} \langle 0(t) | A_\kappa^\dagger A_\kappa | 0(t) \rangle_{\mathcal{N}} = \sinh^2(\Gamma_\kappa t - \theta_\kappa) , \quad (30)$$

and similarly for modes of type \tilde{A}_κ . This number can be shown to satisfy the Bose distribution. Thus, it is actually a statistical average (Vitiello 1995). From Eq. (30) we see that at a time $t = \tau$, with τ the maximum of the values $t_\kappa \equiv \theta_\kappa / \Gamma_\kappa$, the memory state $|0\rangle_{\mathcal{N}}$ is reduced (decayed) to the “empty” vacuum $|0\rangle_0$: the information has been *forgotten*, the \mathcal{N} code has decayed. The time $t = \tau$ can be taken as the lifetime of the memory of code \mathcal{N} (for details on this point we refer to Alfinito and Vitiello (2000), where the lifetime of the κ -modes has been analyzed in detail). In this way, the time evolution of the memory state leads to the “empty” vacuum $|0\rangle_0$ which acts as a sort of attractor state. However, as time goes on, i.e. as t gets larger than τ , we have

$$\lim_{t \rightarrow \infty} \mathcal{N} \langle 0(t) | 0 \rangle_0 \propto \lim_{t \rightarrow \infty} \exp \left(-t \sum_{\kappa} \Gamma_\kappa \right) = 0 , \quad (31)$$

which tells us that the state $|0(t)\rangle_{\mathcal{N}}$ “diverges” away from the attractor state $|0\rangle_0$ exponentially (we always assume $\sum_{\kappa} \Gamma_\kappa > 0$).

It is interesting to observe that, in order to avoid entering the “empty” vacuum $|0\rangle_0$, i.e. in order to not forget a particular information, one needs to “restore” the \mathcal{N} code by refreshing the memory, *brushing up* on the subject (memory maintenance by external stimuli). This means to recover the whole \mathcal{N} -set (if the whole code is “corrupted”) or “pieces” of the

memory associated to those \mathcal{N}_κ , (for particular values of κ), which have been lost at $t_\kappa = \theta_\kappa/\Gamma_\kappa$. Restoring the code is a sort of “updating the register” of the memories since it amounts to resetting the memory code (and clock) to the (updated) initial time t_0 . We also observe that the code \mathcal{N} may be recovered even after the time τ has passed, provided that t is not much larger than τ (namely, as far as the approximation of $\cosh(\Gamma_\kappa t - \theta_\kappa) \approx \exp(-t \sum_\kappa \Gamma_\kappa)$ does not hold, cf. Eq. (31)).

We now consider the variation in time of the “distance” between trajectories in the memory space, i.e. the variation in time of the difference between two different codes, $\mathcal{N} \neq \mathcal{N}'$ ($\theta \neq \theta'$), corresponding to different initial conditions of two trajectories. At time t , each component $\mathcal{N}_{A_\kappa}(t)$ of the code $\mathcal{N} \equiv \{\mathcal{N}_{A_\kappa} = \mathcal{N}_{\tilde{A}_\kappa}, \forall \kappa, \text{ at } t_0 = 0\}$ is given by the expectation value of the number operator $A_\kappa^\dagger A_\kappa$ in the memory state. The difference is then (cf. Eq. (30)):

$$\begin{aligned} \Delta \mathcal{N}_{A_\kappa}(t) &\equiv \mathcal{N}'_{A_\kappa}(\theta', t) - \mathcal{N}_{A_\kappa}(\theta, t) \\ &= \sinh^2(\Gamma_\kappa t - \theta_\kappa + \delta\theta_\kappa) - \sinh^2(\Gamma_\kappa t - \theta_\kappa) \\ &\approx \sinh(2(\Gamma_\kappa t - \theta_\kappa))\delta\theta_\kappa, \end{aligned} \quad (32)$$

where $\delta\theta_\kappa \equiv \theta_\kappa - \theta'_\kappa$ (which, without loss of generality, may be assumed to be greater than zero), and the last equality holds for small $\delta\theta_\kappa$ (i.e. for a very small difference in the initial conditions of the two memory states). The time derivative then gives

$$\frac{\partial}{\partial t} \Delta \mathcal{N}_{A_\kappa}(t) = 2\Gamma_\kappa \cosh(2(\Gamma_\kappa t - \theta_\kappa))\delta\theta_\kappa, \quad (33)$$

which shows that the difference between originally only slightly different \mathcal{N}_{A_κ} 's grows as a function of time. For large enough t , the modulus of the difference $\Delta \mathcal{N}_{A_\kappa}(t)$ and its variation in time diverge as $\exp(2\Gamma_\kappa t)$ for all κ 's. For each κ , $2\Gamma_\kappa$ plays a role similar to that of the Lyapunov exponents in chaos. Thus, we conclude that trajectories in the memory space, differing by a small variation $\delta\theta$ in the initial conditions, diverge exponentially as time evolves.

As shown by Eq. (32), the difference between specific κ -components of the codes \mathcal{N} and \mathcal{N}' may become zero at a given time $t_\kappa = \theta_\kappa/\Gamma_\kappa$. However, this does not mean that the difference between the codes \mathcal{N} and \mathcal{N}' becomes zero. The codes are made up by a large number (infinite in the continuum limit) of components, and they are different even if a finite number of their components are equal. On the contrary, for $\delta\theta_\kappa \equiv \theta_\kappa - \theta'_\kappa$ very small, suppose that the time interval $\Delta t = \tau_{max} - \tau_{min}$, with τ_{min} and τ_{max} the minimum and the maximum, respectively, of the values $t_\kappa = \theta_\kappa/\Gamma_\kappa$, for all κ 's, be “very small”. Then the codes are “recognized” to be “almost” equal in such a Δt . In this case, Eq. (32) expresses the “recognition” (or recall) process and we see how it is possible that “slightly

different” \mathcal{N}_{A_κ} -patterns (or codes) are “identified” (recognized to be the “same code” even if corresponding to slightly different inputs). Roughly, Δt may be taken as a measure of the “recognition time”.

We finally recall that $\sum_\kappa E_\kappa \dot{\mathcal{N}}_{A_\kappa} dt = \beta^{-1} dS_A$ (see Vitiello 1995), where E_κ is the energy of the mode A_κ , $\beta = k_B T^{-1}$ is the inverse temperature with k_B as Boltzmann’s constant, dS_A is the entropy variation associated to the modes A , and $\dot{\mathcal{N}}_{A_\kappa}$ denotes the time derivative of \mathcal{N}_{A_κ} . Eq. (33) then leads to the relation between the differences in the variations of the entropy and the divergence of trajectories of different initial conditions:

$$\begin{aligned} \Delta \sum_\kappa E_\kappa \dot{\mathcal{N}}_{A_\kappa}(t) dt &= \sum_\kappa 2E_\kappa \Gamma_\kappa^2 \cosh(2(\Gamma_\kappa t - \theta_\kappa)) \delta\theta_\kappa dt \\ &= \frac{1}{\beta} (dS'_A - dS_A) . \end{aligned} \tag{34}$$

Therefore, requirement (iii) is satisfied as well.

We conclude that the trajectories in the memory space may exhibit chaotic behavior. This is a feature which may be related to experimental observations discussed by Freeman (1990, 1996, 2000), who indeed finds characteristic chaotic behavior in neural aggregates of the olfactory system of laboratory animals. The precise relation between Freeman’s findings and our results remains to be worked out in detail, though.

6. Concluding Remarks

We have presented a compact review of the dissipative quantum model of the brain, and we have shown that the doubling of the degrees of freedom of the system accounts for quantum noise in the fluctuating random force coupling the system with its environment. Due to the permanent entanglement of brain and environment, effects of quantum noise are intrinsically present in brain dynamics. Moreover, we have seen that time evolution in the memory space may exhibit chaotic behavior. This is interesting in view of the fact that laboratory observations show an important role of noise and chaos in brain dynamics (Freeman 1990, 1996, 2000). In the dissipative quantum model of the brain, noise and chaos turn out to be natural ingredients. In particular, the chaotic behavior of the trajectories in memory space may account for the high resolution in the recognition of perceptual inputs. Indeed, small differences in the codes associated to external inputs may lead to diverging differences in the corresponding memory paths. On the other hand, codes “almost” equal in all of their components may easily be taken to be the “same” code (code identification, or “code-pattern” recognition).

Further work on these subjects is in progress (Pessa and Vitiello 2003).

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