

Matter, mind and consciousness: from information to meaning

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This is a perspective on some theoretical studies obtained in the framework of the dissipative quantum model of brain. The formation of long range neuronal correlations is described in terms of quantum field theory mechanisms operating in systems with a huge number of degrees of freedom. Memory states are constructed through the condensation in the lowest energy state of quanta associated to the long range correlations. Many properties derived from such a modeling are discussed, also in relation with classical/quantum modeling interplay. The brain flexibility in responding to incoming inputs producing novel correlation patterns is attributed to the chaotic character of trajectories or paths through the memory states. A relevant role in the model is played by the fact that the brain is permanently open to its environment. The brain/mind activity is thus described in the formalism of dissipative systems, also accounting for the formation of the meanings of the information carried by the perceptual experiences. A recent novel description of criticality in brain activity during dreaming, meditation and non-ordinary brain states is briefly mentioned. In the model, it is proposed that consciousness finds its origin in the permanent dialog or interaction of the brain with its environment. Although a long way has been done, much work is still necessary to understand the extraordinary functional properties of brain.

Keywords

Dissipative quantum model of brain; neurodynamics; memory states; free energy; criticality; phase transition; quantum field theory

1. Introduction

In 1991 Walter Freeman was observing that his laboratory observations were showing that the study of the single neuron and the microscopic approach dominating the research in neuroscience could not fully account for the processes involved in perception and its elaboration by brain. Rather it was clear that such brain activities could be understood only provided that collective dynamical activity of a myriads of neuronal cells would be analyzed and such macroscopic contributions would be considered together with the microscopic results (Freeman, 1991). On the other hand, Ricciardi and Umezawa (1967), considering the state of the research in neuroscience and on the basis of the experimentally successful results obtained in the quantum field theory (QFT) of solid state and high energy physics were asking whether the behavior

of the single nervous cell would be really essential in determining the functional brain activity. Such a doubt, they were arguing, arises since if this would be the case, many pathological behaviors in brain functioning would be currently observed, which instead are not. As they were remarking, the observations of long-range correlations among many regions of the brain arising as simultaneous responses to external stimuli cannot be explained by classical physics models, which then suggests that adopting a quantum model, similar to those successfully used in many-body physics, could be useful in brain studies.

These statements by Freeman (1991), Umezawa and Ricciardi, and similar ones by Lashley (1942), and Pribram (1972) show how clear was their level of awareness of the crisis in neuroscience studies, notwithstanding the enormous progresses in the research of molecular biochemistry and cell specific properties obtained in those same years, and the reader is strongly advised to read the above mentioned statements in the original words by Freeman, and Ricciardi and Umezawa (1967), which therefore I report as footnotes^{1,2}.

¹ Freeman (1991): "My own group's studies, carried out over more than 30 years at the University of California at Berkeley, suggest that perception cannot be understood solely by examining properties of individual neurons, a microscopic approach that currently dominates neuroscience research. We have found that perception depends on the simultaneous, cooperative activity of millions of neurons spread throughout expanses of the cortex. Such global activity can be identified, measured and explained only if one adopts a macroscopic view alongside the microscopic one."

² Ricciardi and Umezawa (1967): "First of all, at which level should the brain be studied and described? In other words, is it essential to know the behavior in time of any single neuron in order to understand the behavior of natural brains? Probably the answer is negative. The behavior of any single neuron should not be significant for the functioning of the whole brain, otherwise higher and higher degree of malfunctioning should be observed...the activity of any single neuron is not significant, but rather the patterns of activity of clusters of them; what is important is only a quantity somehow related to the activity of the whole cluster, which does not change appreciably as function of the number of alive neurons belonging to that cluster...the existence of similar and almost simultaneous responses in several regions of the brain (a kind of long-range correlation) to a particular stimulation technique does not find any explanation in terms of activity of the single nerve cells: new non-classical mechanisms have to be looked for...it is strongly suggestive of a quantum model. In other terms, one can try to look for specific dynamical mechanisms (already known in physics of many degrees of freedom) which can satisfy the essential requirements of the observed functioning of the brain."

On the basis of these premises, considering that brain is in a permanent interaction with its surrounding world (the environment), in 1995, such a dissipative characteristics of the brain dynamics was formally described, which led to the dissipative quantum model of brain (DQMB) (Vitiello, 1995, 2001).

In the following Sections, by resorting to published results, I discuss few aspects of the DQMB. In Section 2, I review the Ricciardi and Umezawa (RU) model and the DQMB. The motivation for presenting the main features of these models is in the fact that it has been there that the dynamical formalism of QFT has been originally used for the study of brain activity and therefore the understanding of the subsequent discussion in the paper requires the knowledge of the conceptual and formal frame in which those models have been formulated. The "red thread" linking the various considered aspects is indeed the study of the dynamical cooperative activity of millions of neurons, as stressed by Freeman and above recalled, which must complement the study of the properties of individual neurons, by itself absolutely necessary but not sufficient for the comprehension of the complex functional behavior of brain. Within and consistently with such a dynamical vision, in Section 3, the concepts of coherence, phase transition, criticality, chaotic trajectories, the construction of "meanings" associated to perceptual experiences, will be discussed. Section 4 is devoted to conclusive remarks.

I will briefly comment on some aspects of the QFT formalism which might be not familiar to the QFT non-specialist reader. An useful introduction fully relying on qualitative presentation can be found in the references (Vitiello, 2001, 2018).

2. Brain-mind interplay in the dissipative quantum model of brain

Let me shortly present distinctive features of the RU model and DQMB useful for the better understanding of the following discussion. Then I will consider the interplay between brain and mind and the formation of meanings out of perceptual experiences through which the brain collects information about its surrounding environment.

As said in the Introduction, the unifying thread linking the various parts of this work finds its concrete realization in the QFT study of collective modes, the Nambu-Goldstone boson condensation and the associated long range correlation waves (see below). Therefore the different aspects and processes described in the following find their unitary origin in these genuine QFT dynamical features. This is not in contrast, but rather it complements the more widely followed approach focused on the properties of individual nervous cells.

2.1 The Ricciardi and Umezawa many-body model

The key mechanism in the RU model and in its extension to the dissipative model is the one of spontaneous breakdown of symmetry (SBS) in QFT.

Suppose that continuous transformations forming a group, say G , leave unchanged (invariant) the dynamics (in our case, the group G is the $SU(2)$ group of the spherical rotational symmetry of molecular electrical dipoles, see below). SBS occurs when the transformations of G are not symmetry transformations for the minimum energy state (the vacuum), although it may be symmetric under transformations of a subgroup of G . Then the dynam-

ics generates massless collective boson modes (Nambu-Goldstone (NG) quanta) (Blasone et al., 2011; Itzykson and Zuber, 1980; Umezawa, 1993). They are quanta of long range correlation waves, whose net is responsible for generating and maintaining ordered patterns in the systems. The vacuum is a *coherent condensate* of NG modes. Coherence, i.e. ordering, is a global property of the system induced by the mechanism of SBS. The system components in this way manifest themselves as a "whole" in the macroscopic collective behavior. This is characterized by the value of a field, the order parameter, which measures the density of the condensation of NG modes. Due to coherence property of the vacuum condensate, the order parameter is independent from quantum fluctuations thus behaving as a classical field.

The order parameter acts as a label for the infinite number of physically inequivalent spaces of states (unitarily inequivalent representations) existing in QFT (in contrast, the state spaces in quantum mechanics (QM) are physically (unitarily) equivalent). A transition through inequivalent state spaces is called a "phase transition". This is a *critical* process since different state spaces are, as said, unitarily inequivalent. Criticality thus characterizes phase transition processes.

In the RU model, the brain state is supposed to be shifted to a new one prompted by a newly coming external stimulus. This produces SBS and the "recording" process is achieved through coherent condensation of the NG modes. The order parameter represents the "code" (label) of the information carried by the stimulus. The effective mass of the NG modes due to boundary effects is very small (NG modes are quasi-massless), thus their associated long range correlation waves extend over large distances forming extended correlated patterns. This means that a huge number of neurons participate to memory recording resulting from such long range correlations, rather than a small number of nervous cells belonging to a quite small domain. This provides a protection of memories against local destructive actions on few individual neurons, as indeed observed.

The memory recollection mechanism is induced by a stimulus that can be not identical to the one causing recording, but similar to it. Such a similar stimulus may indeed excite the condensed NG modes (with a little expense of energy since these modes are quasi-massless) and the memory is "consciously" felt during the excitation time. The excited mode has finite life-time, and the recall activity is experienced as a flashing (temporary) activity, as indeed commonly experienced.

The model presents other interesting features fitting with observations. For example, it accounts for the memory stability in the presence of the brain intense ongoing electrochemical activity, the interaction of the memory state, which, due to coherence, is a *macroscopic quantum state*, with the classical level of biochemical activity, etc. For brevity, however, I do not report them here. See Ricciardi and Umezawa, 1967; Stuart et al., 1978, 1979; Vitiello, 2001 for a more complete presentation.

I finally recall that in the RU model and DQMB neurons and glia cells are described as classical systems. Jibu and Yasue (1995) and Vitiello (1995) identify the quantum variables with the vibrational modes of the water molecular electrical dipoles and the NG with the dipole correlation quanta, called dipole wave quanta (dwq). One important limitation of the RU model consists in

the very limited memory capacity. Once a memory has been recorded, any successive stimulus produces a new condensation process, *overprinting* on the previously recorded memory, which thus is lost. The solution of the overprinting problem is obtained in DQMB by considering dissipation (Vitiello, 1995).

2.2 The dissipative quantum model

As said, in the RU model and DQMB, the external stimulus causes the SBS of the water molecular electrical dipoles, which is the rotational spherical symmetry (the symmetry group G is the $SU(2)$ group), and this, through the condensation of the dwq (NG) modes, turns into the recording of the information carried by the input.

The brain state before the recording of the information is then *distinct* from the brain state after information has been recorded. Thus, time-reversal symmetry is broken and *the arrow of time* appears, i.e. irreversibility, typical of dissipative systems.

In QFT in order to study an open, dissipative system one needs to include also the thermal bath (environment) as to study the closed system {bath-system}. From a computational standpoint, besides the Hilbert space of the states of the system, also the Hilbert space of the states of the environment must be considered. This amounts to doubling the degrees of freedom of the system by selecting among the infinitely many inequivalent ground states, that specific one, denoted by $|0(t)\rangle_{\mathcal{N}}$, whose condensate structure, coded by \mathcal{N} , accounts for the system-environment interaction at time t . The notation here used for the state is the usual Dirac notation for vectors in the Hilbert space.

The memory state $|0(t)\rangle_{\mathcal{N}}$ evolves in time through "trajectories", which are shown to be classical chaotic trajectories (Vitiello, 2004). Free energy is minimized at each time t . Such an evolution describes the system-environment "trade".

Let the NG mode, i.e. the dipole wave quanta (dwq), be denoted by A_{κ} , with κ denoting, e.g., the momentum. The environment mode, i.e. the "doubled mode", is denoted by \tilde{A}_{κ} . The requirement of the balance of the in/out flows of energy between the system and its environment, requires that this last one acts as the copy or image "reversed in time" of the system. Consistently, \tilde{A} modes turn out to be the "holes", time-reversed copies of the A modes. The environment represents the system "Double".

One can show (Vitiello, 1995) that for any t the memory state $|0(t)\rangle_{\mathcal{N}}$ is an $SU(1, 1)$ squeezed coherent state (see Eqn. 2 below). It is an entangled state of condensate $\{A_{\kappa}, \tilde{A}_{\kappa}\}$ pairs. The balance of the energy flows implies that $\mathcal{N}_{A_{\kappa}} - \mathcal{N}_{\tilde{A}_{\kappa}} = 0$, for any κ in $|0(t)\rangle_{\mathcal{N}}$, where $\mathcal{N}_{A_{\kappa}}$ and $\mathcal{N}_{\tilde{A}_{\kappa}}$ denote the numbers of A_{κ} and \tilde{A}_{κ} modes.

The condensate at $t_0 = 0$ is defined by the set $\mathcal{N} = \{\mathcal{N}_{A_{\kappa}}, \forall \kappa\}$, which is the information code.

The set \mathcal{N} , however, is not uniquely defined by the constrain $\mathcal{N}_{A_{\kappa}} - \mathcal{N}_{\tilde{A}_{\kappa}} = 0$, for any κ . The balance of the flows of energy is guaranteed also by $\mathcal{N}'_{A_{\kappa}} - \mathcal{N}'_{\tilde{A}_{\kappa}} = 0$, for any κ . Thus, also $|0(t_0)\rangle_{\mathcal{N}'}$ may be a memory state, the one corresponding indeed to the \mathcal{N}' information.

In conclusion, we may have a huge number of distinct information, with distinct codes $\mathcal{N}, \mathcal{N}', \dots$, recorded each one in the unitarily inequivalent vacua $|0(t)\rangle_{\mathcal{N}}, |0(t)\rangle_{\mathcal{N}'}, \dots$, respectively. Unitary inequivalence insures indeed that for any t the states with different \mathcal{N} 's are orthogonal states in the infinite volume limit, which is

expressed by the relation

$$\mathcal{N}\langle 0(t)|0(t)\rangle_{\mathcal{N}'} \xrightarrow{V \rightarrow \infty} 0 \quad \forall \mathcal{N} \neq \mathcal{N}' . \quad (1)$$

This guarantees that printed information are protected against reciprocal interference (absence of confusion of memories).

Note that unitary inequivalence may be spoiled by the finiteness of the system size (Alfinito and Vitiello, 2000; Vitiello, 1995). We may have then possible transitions among differently coded vacua, producing "association" of memories, following a path of memories, a phenomenon commonly experienced (see also Section 3 on the association of memories). A recent novel discussion of the dynamic criticality in brain has been presented in (Re and Vitiello, 2020a,b). It has been indeed observed that the criticality of phase transitions is also enhanced in sleeping, meditation, under psychoactive substances, etc., whenever the openness of the brain is reduced. In such cases, a flow of images from memories may be experienced like in dreams and non-ordinary brain states (Re and Vitiello, 2020a,b). This is consistent with the proposal, within the DQMB, that the consciousness act lives in the dialog of the self with its Double (Vitiello, 1995, 2001). The physical grounds for the consciousness phenomenon are in the dissipative character of the brain dynamics and the coherent structure of the brain states. Partial or total lack of these conditions may lead to unconscious brain states.

Also note that the dwq effective mass, implied by the finiteness of the system size (boundary effects), introduces an excitation energy threshold, so that recall of memory requires energy equal or higher than the threshold one, and this may be then experienced as a "difficulty in recalling". On the other side, it also guarantees a memory protection and stability mechanism against energy fluctuations (Vitiello, 1995).

2.3 Brain activity and mind activity. Information and meanings

The ground state of the brain at a time t is in conclusion described as the manifold of the $|0(t)\rangle_{\mathcal{N}}$ states, for all \mathcal{N} . The brain thus appears as a complex system continuously undergoing phase transitions along trajectories through the states of memories.

In the DQMB, the observed formation of neuron assemblies in amplitude modulated (AM) synchronously oscillating patterns, in the beta and gamma frequency range, is described in terms of coherent condensation of dwq in the system ground state.

In this way the input associated ground state form an attractor and the landscape of the attractors (Abraham et al., 1978; Hilborn, 1994) constitutes the record of the brain perceptual experience. Any new perceptual stimulus either places the sensory system in an existing basin of attraction in the attractor landscape, selected by generalization (eliminating unnecessary details) and abstraction (association to a category), either, in the absence of the conveniently recognized attractor, generates a new attractor. This last one is not trivially added to the pre-existing attractor landscape; its introduction induces the general reorganization of the landscape.

In both cases, the perceptual experience acquires a *meaningful* value within the brain perceptual history. Knowledge is thus constructed as accretion of meanings, not just of bare information. Memory then appears to be memory of meanings, not of information. Observations suggest indeed that the brain combines through

the action-perception cycles perceptual inputs with its past experiences, within its own expectations and intentionality frame, thus making the perceptual stimulus *meaningful* to its own individual experience. As Freeman observes³, the same input, e.g. an olfactory input, may be associated to different meanings in different subjects.

In its effort aimed to its most harmonious to-be-in-the-world, which is the essence of the aesthetic experience according to Desideri (Desideri, 1998; Vitiello, 2015a), and is described, e.g., in the Merleau-Ponty phenomenology (Merleau-Ponty, 1945), brain acts into the world by testing hypotheses formulated in the action-perception cycle and projecting them backward in time in the attempt of matching them with past experiences. In the dissipative model, cerebral activity (matter) is responsible of actions in forward time, while their mirrored in time images come from and control perception (this is mind, awareness).

It is thus the Double (the mind) that produces hypotheses on the world by constructing images (Freeman and Vitiello, 2016). However, brain activity and mental activity are definitely, permanently entangled, without any possibility of separation or disentanglement. Brain-mind do not represent a dual manifestation of a basic entity. They *are* one single dynamical entity.

I close this Section by recalling that ECoG provides evidence in sensory cortices of phase modulated patterns in the form of phase cones with outward or inward cyclic pulsations with or without rotational gradients (vortices). One thus observes converging (imploding) and diverging (exploding) wave packets (Freeman, 1991; Freeman and Quiroga, 2013; Vitiello, 2015b), corresponding thus to forward and backward time evolution of phase cone as $\exp(\pm\Gamma t)$ (the converging and its time-reversed, diverging regime) (Freeman et al., 2012; Freeman and Vitiello, 2010). The DQMB predicts both these regimes. Conventional neurodynamics admits the exploding gradient; however, it does not explain the imploding gradient.

3. Chaotic trajectories and memory states

Let me now discuss the brain chaotic dynamics (Pessa and Vitiello, 2003, 2004) within the DQMB.

In brain functional activity, collections of millions of neurons (neuron assemblies) are observed to have chaotic behavior in their transitions from a synchronous oscillatory pattern to another one (Freeman, 1991). Since 1987 Walter Freeman and his collaborators have stressed that such a chaotic behavior is a characterizing feature of brain activity⁴ (Freeman, 1991; Skarda and Freeman, 1987)

³ “The result is a meaning-laden perception, a gestalt, that is unique to each individual. For a dog, the recognition of the scent of a fox may carry the memory of food and expectation of a meal. For a rabbit, the same scent may arouse memories of chase and fear of attack.” (Freeman, 1991)

⁴ In Freeman words “The brain transforms sensory messages into conscious perceptions almost instantly. Chaotic, collective activity involving millions of neurons seems essential for such rapid recognition.”...“Our studies have led us as well to the discovery in the brain of chaos-complex behavior that seems random but actually has some hidden order. The chaos is evident in the tendency of vast collections of neurons to shift abruptly and simultaneously from one complex activity pattern to another in response to the smallest of inputs...This changeability is a prime characteristic of many chaotic systems... In fact, we propose it is the very property that makes perception possible. We also speculate that chaos underlies the ability of the brain to respond flexibly

and their discovery has been subsequently confirmed and analyzed (Tsuda, 2001).

The set of states $\{|0(t)\rangle_{\mathcal{N}}; \forall \mathcal{N}, \forall t\}$ form the “memory space”. Eqn. 4-Eqn. 7 (see below) show that $|0(t)\rangle_{\mathcal{N}}$, considered like ‘points’ labeled by \mathcal{N} and t ’s in the memory space, do not overlap, they are distinct points. In QFT, the Hilbert spaces associated to each of the memory states are each other unitarily inequivalent (cf. Eqn. 1). See Fig. 1 for a schematic drawing. Trajectories over the memory space, whose “initial condition” at $t_0 = 0$ is specified by the set \mathcal{N} , are then found to be classical trajectories (Perelomov, 1986; Vitiello, 2004). They are also found to be chaotic trajectories (Hilborn, 1994; Vitiello, 2004), namely they are bounded, non-periodic, not self-intersecting trajectories. Moreover, trajectories with different initial conditions are non-intersecting, diverging trajectories. They represent “phase transitions” in the memory space. The following remarks show that these properties indeed hold.

Explicitly, the state $|0\rangle_{\mathcal{N}} \equiv |0(t_0)\rangle_{\mathcal{N}}$ evolves in time as (Vitiello, 1995)

$$|0(t)\rangle_{\mathcal{N}} = \prod_{\kappa} \frac{1}{\cosh(\Gamma_{\kappa} t - \theta_{\kappa})} \exp\left(\tanh(\Gamma_{\kappa} t - \theta_{\kappa}) A_{\kappa}^{\dagger} \tilde{A}_{\kappa}^{\dagger}\right) |0\rangle_0, \quad (2)$$

at finite volume V , where Γ_{κ} is the damping constant. We have⁵

$${}_{\mathcal{N}}\langle 0(t)|0(t)\rangle_{\mathcal{N}} = 1, \quad \forall t. \quad (3)$$

Provided that $\int d^3\kappa \Gamma_{\kappa} > 0$ and finite,

$${}_{\mathcal{N}}\langle 0(t)|0\rangle_{\mathcal{N}} \xrightarrow{V \rightarrow \infty} 0 \quad \forall t, \quad (4)$$

$${}_{\mathcal{N}}\langle 0(t)|0(t')\rangle_{\mathcal{N}} \xrightarrow{V \rightarrow \infty} 0 \quad \forall t, t', \quad t \neq t'. \quad (5)$$

These equations show that $|0(t)\rangle_{\mathcal{N}}$ (and their spaces $\{|0(t)\rangle_{\mathcal{N}}\}$) at each t are unitarily inequivalent for $V \rightarrow \infty$. Eqn. 3 shows that $|0(t)\rangle_{\mathcal{N}}$, the “position vector” on the trajectory at t , has finite norm. This confirms that the trajectories are *bounded* ones. On the other hand, Eqn. 4 and Eqn. 5 say that the “points” $|0(t)\rangle_{\mathcal{N}}$ and $|0(t')\rangle_{\mathcal{N}}$, never overlap, i.e. the trajectory never crosses itself (it is not periodic). Also (Pessa and Vitiello, 2003, 2004),

$${}_{\mathcal{N}}\langle 0(t)|0\rangle_{\mathcal{N}'} \xrightarrow{V \rightarrow \infty} 0 \quad \forall t, \quad \forall \mathcal{N} \neq \mathcal{N}' \quad (6)$$

$${}_{\mathcal{N}}\langle 0(t)|0(t')\rangle_{\mathcal{N}'} \xrightarrow{V \rightarrow \infty} 0 \quad \forall t, t', \quad \forall \mathcal{N} \neq \mathcal{N}', \quad (7)$$

i.e., trajectories with $\mathcal{N} \neq \mathcal{N}'$ (different initial conditions) are each other not crossing. The meaning of this is that in the infinite volume limit different memories do not get *confused* (they do not interfere) as time evolves. As already observed, “association” of memories becomes however possible in realistic cases of finite

to the outside world and to generate novel activity patterns, including those that are experienced as fresh ideas...” (Freeman, 1991).

⁵ For the non-specialist reader I note that in discussing the properties of chaotic trajectories, in the following I will use repeatedly the notation already used in Eqn. 1, namely the scalar product between two vectors $|a\rangle$ and $|b\rangle$ denoted by $\langle b|a\rangle$.

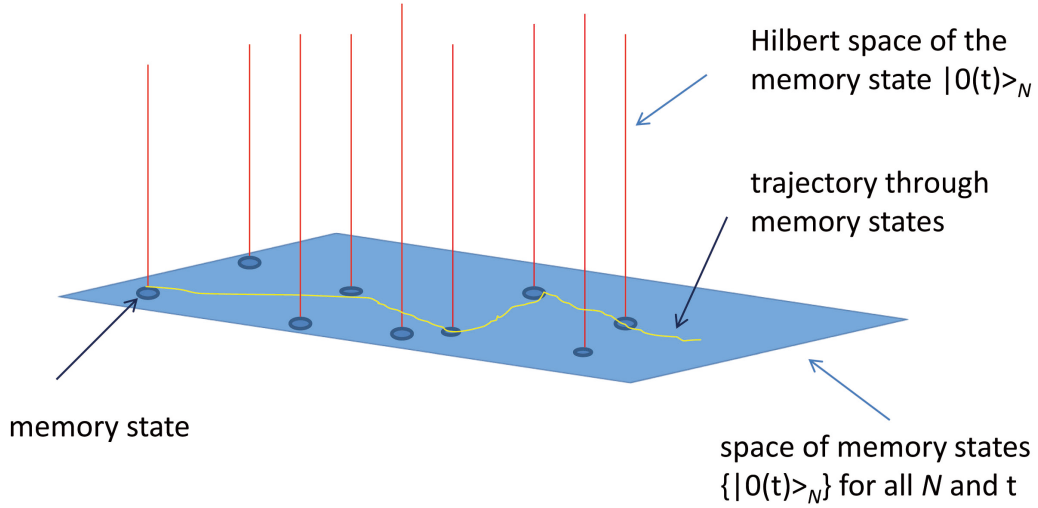


Fig. 1. Schematic view of the space of the representations (set of Hilbert spaces) whose lowest energy (vacuum) state is the memory state $|0(t)\rangle_{\mathcal{N}}$.

volume (boundary effects) since then Eqn. 6 and Eqn. 7 do not hold and a "crossing" (overlap) at some t may occur. We also have

$$\mathcal{N}_{A_\kappa}(\theta, t) \equiv \mathcal{N}\langle 0(t) | A_\kappa^\dagger A_\kappa | 0(t) \rangle_{\mathcal{N}} = \sinh^2(\Gamma_\kappa t - \theta_\kappa), \quad (8)$$

and a similar relation holds for \tilde{A}_κ . It can be shown that $\mathcal{N}_{A_\kappa}(\theta, t)$ satisfies the Bose distribution (Vitiello, 1995). Note that $|0(t)\rangle_{\mathcal{N}} \rightarrow |0\rangle_0$ for $t \rightarrow \tau$, with τ the largest of $t_\kappa \equiv \theta_\kappa/\Gamma_\kappa$: the information has been *forgotten* at τ , which represents its lifetime (see Alfinito and Vitiello, 2000 for details).

For $t \gg \tau$, one gets out of the attractor state $|0\rangle_0$ according to

$$\lim_{t \rightarrow \infty} \mathcal{N}\langle 0(t) | 0 \rangle_0 \propto \lim_{t \rightarrow \infty} \exp\left(-t \sum_{\kappa} \Gamma_\kappa\right) = 0, \quad (9)$$

with $\sum_{\kappa} \Gamma_\kappa > 0$. In order not to forget certain information (avoiding to fall in the attractor $|0\rangle_0$), "refreshing" or *brushing up* the memory is required, as to "restore" the memory \mathcal{N} code (Sivakami and Srinivasan, 1983). Sometimes the whole \mathcal{N} -set has to be recovered (if the whole code is "corrupted"), or one needs to recover "pieces" \mathcal{N}_κ , for certain κ 's, lost at $t_\kappa = \theta_\kappa/\Gamma_\kappa$.

The difference between the components $\mathcal{N}_{A_\kappa}(t)$ and $\mathcal{N}'_{A_\kappa}(t)$ of the sets \mathcal{N} and \mathcal{N}' , at t , (corresponding to two different trajectories) is given by:

$$\begin{aligned} \Delta \mathcal{N}_{A_\kappa}(t) &\equiv \mathcal{N}'_{A_\kappa}(\theta', t) - \mathcal{N}_{A_\kappa}(\theta, t) = \\ &= \sinh^2(\Gamma_\kappa t - \theta_\kappa + \delta\theta_\kappa) - \sinh^2(\Gamma_\kappa t - \theta_\kappa) \\ &\approx \sinh(2(\Gamma_\kappa t - \theta_\kappa)) \delta\theta_\kappa, \end{aligned} \quad (10)$$

for small $\delta\theta_\kappa \equiv \theta_\kappa - \theta'_\kappa$ (assuming without loss of generality $\delta\theta_\kappa > 0$), i.e. small differences in the initial conditions. We then obtain

$$\frac{\partial}{\partial t} \Delta \mathcal{N}_{A_\kappa}(t) = 2\Gamma_\kappa \cosh(2(\Gamma_\kappa t - \theta_\kappa)) \delta\theta_\kappa, \quad (11)$$

showing that $\Delta \mathcal{N}_{A_\kappa}$ is a growing function of time even for tiny different initial conditions, namely, as announced, trajectories are diverging trajectories. The divergence of (the modulus of) $\Delta \mathcal{N}_{A_\kappa}(t)$

and its time derivative goes for large t as $\exp(2\Gamma_\kappa t)$, $\forall \kappa$, with $2\Gamma_\kappa$ playing the rôle of the Lyapunov exponent. Eqn. 10 shows that $\Delta \mathcal{N}_{A_\kappa}(t_\kappa) = 0$ at $t_\kappa = \theta_\kappa/\Gamma_\kappa$.

Consider two sets \mathcal{N} and \mathcal{N}' , with $\mathcal{N} \neq \mathcal{N}'$. Since they are made by an infinite number of components in the continuum limit, even if a finite number of these are equal, it is still $\mathcal{N} \neq \mathcal{N}'$.

Suppose now that for small $\delta\theta_\kappa$, $\Delta t = \tau_{max} - \tau_{min}$, is "very small". Here τ_{min} and τ_{max} are the smallest and the largest of the $t_\kappa = \theta_\kappa/\Gamma_\kappa$, for all κ 's, respectively. Then, in such a Δt , "slightly different" \mathcal{N} and \mathcal{N}' are "recognized" to be "almost" equal. In this sense, Eqn. 10 may represent the "recognition" (or recall) process and Δt provides then an approximate measure of the "recognition time".

Note that $\sum_{\kappa} E_\kappa \dot{\mathcal{N}}_{A_\kappa} dt = (1/\beta) dS_A$, with $\beta = 1/(k_B T)$; E_κ and S_A denote the energy and the entropy of A_κ -modes, respectively. $\dot{\mathcal{N}}_{A_\kappa}$ is time derivative of \mathcal{N}_{A_κ} . Eqn. 11 relates divergence of trajectories with differences of entropy variations:

$$\begin{aligned} \Delta \left(\sum_{\kappa} E_\kappa \dot{\mathcal{N}}_{A_\kappa}(t) dt \right) &= \sum_{\kappa} 2E_\kappa \Gamma_\kappa \cosh(2(\Gamma_\kappa t - \theta_\kappa)) \delta\theta_\kappa dt \\ &= \frac{1}{\beta} (dS'_A - dS_A). \end{aligned} \quad (12)$$

By using $\tanh^2(\Gamma_\kappa t - \theta_\kappa) = \exp(-\beta E_\kappa)$, which is valid in the limit of stationary free energy (Vitiello, 2004), Eqn. 8 gives

$$\begin{aligned} \mathcal{N}_{A_\kappa}(\theta, t) &\equiv \mathcal{N}\langle 0(t) | A_\kappa^\dagger A_\kappa | 0(t) \rangle_{\mathcal{N}} \\ &= e^{-\beta E_\kappa} \cosh^2(\Gamma_\kappa t - \theta_\kappa). \end{aligned} \quad (13)$$

Since for A_κ and \tilde{A}_κ , $E_\kappa \approx \kappa$ and small κ -modes are short lived modes (Alfinito and Vitiello, 2000), from this equation we see that, for given β , the probability of recalling short-lived memories (reading out their code) is higher than for long-lived ones, and vice-versa (and the same holds for memory recording). This sheds some light on permanent memories on which, e.g., are based vital functions. In general, they cannot be recalled or (re-)written (changed) by some action or input from the outside. Thus the probability to read out or to change them (their memory codes) should

be near to zero. Eqn. 13 shows that they must be then associated to high values of κ , i.e. of E_κ , with vanishingly small Boltzmann factor for those processes.

4. Conclusions

We have seen that a central role in the RU model and DQMB is played by coherence. Memory states are indeed generalized $SU(1, 1)$ squeezed coherent states. The notion of coherence in quantum theories was in fact inspiring in the middle of the sixties Karl Pribram, who introduced his holographic picture of brain activity (Pribram, 1972) inspired by the observations that information appears to be spatially distributed in a uniform fashion in the brain, as it is in a hologram (Freeman, 1990, 2000).

Using field theory in brain studies was already suggested in the forties by Lashley (1942), who reporting his laboratory observations was noticing the dominant role of masses of excitations and field activity in brain, almost independently from the particular nerve cells. However, only in 1967, brain was modeled as a many-body (QFT) system in the RU field theory model, further developed by Stuart et al. (1978, 1979), Sivakami and Srinivasan (1983), Jibu and Yasue (1995), Jibu et al. (1996). Finally, in 1995 the RU model was extended into the DQMB by considering the brain dissipative dynamics (Vitiello, 1995). Further studies of the brain dissipative dynamics have been pursued in the following years (Alfinito and Vitiello, 2000; Capolupo et al., 2013, 2017; Freeman and Vitiello, 2006; Freeman et al., 2015; Pessa and Vitiello, 1999, 2003, 2004; Re and Vitiello, 2020a,b; Vitiello, 2001, 2015a,b) (for a review see Vitiello, 2017, 2018).

The relation between brain activity and mind activity has been discussed in the previous Sections and it has been stressed that brains construct "meanings" out of the perceptual inputs (information). Then, it has been shown that, in agreement with experimental observations (Freeman, 1990, 1996, 2000), trajectories in memory space exhibit chaotic behavior. Since tiny differences in the external inputs generate divergent, chaotic memory paths, high resolution in the perception of similar stimuli is obtained. Also, codes which are different only for some of their components forming a zero-measure set, may be recognized as being identical codes, which might turn to be useful, e.g., in pattern recognition in the presence of small perturbations or distortions.

Note that the stability of the entanglement between the A and \bar{A} modes in the $SU(1, 1)$ state is expressed by the orthogonality (unitary inequivalence) in the limit of infinite volume between $|0(t)\rangle_{\mathcal{N}}$, for any t , and $|0\rangle_0 \equiv |0\rangle_0 \otimes |\bar{0}\rangle_0$:

$$\mathcal{N}\langle 0|0\rangle_0 \xrightarrow{V \rightarrow \infty} 0 \quad \forall \mathcal{N} \neq 0, \quad (14)$$

it is remarkable that the entanglement does not disappear in such a limit, which describes the impossibility to fully isolate the brain from external stimuli. For a recent work on the entanglement in the DQMB see (Sabbadini and Vitiello, 2019). Reducing the links of the brain with the external world, as, e.g., during sleep, meditation, or induced by psychoactive drugs, etc., produces an enhancement of the dynamics criticality and may lead to dreaming activity or to non-ordinary brain states, as it has been recently discussed in (Re and Vitiello, 2020a,b). This brings us again to the proposed origin of the consciousness act (cf. Section 2), residing, according to the

DQMB, in the dialog of the brain with its surrounding world (the environment) (Vitiello, 1995, 2001). According to such a view, consciousness is a brain functional property which is impaired or lacking in a condition of separation (alienation, isolation) of the brain from its environment, as common experience shows.

As mentioned in Section 2, criticality plays indeed a relevant role in brain activity. It is interesting that criticality has been found to be a specific feature of cellular (self-)organization, to the point that critical dynamic processes describe the same cell life (Pietruszka and Olszewska, 2020). In the case of the DQMB, criticality is intrinsic to the brain dynamics since we have seen it continuously undergoes phase transitions described by chaotic classical trajectories. Moreover, coherent patterns of molecular dipole fields may be driven, perturbed or changed by, e.g., a change of temperature, or a fluctuation around the critical temperature T_C controlling the transition between different phases, or also by pressure due to mechanical action with consequent interaction with phonons (the quanta of displacement waves) (Pietruszka and Lipowczan, 2017).

In this connection, it is much interesting that a scale-free behavior (fractal self-similarity) has been observed in brain activity, e.g. obtaining log-log linear plots of PSD (Power Spectral Density) vs frequency, with fractal dimension depending on operational boundary conditions (Freeman and Vitiello, 2009; Freeman et al., 2008; Gireesh and Plenz, 2008). Similar signatures of fractal self-similarity with linear log-log PSD/frequency plots have been also observed in the study of ionic fluxes in living cell (specifically extracellular ionic fluxes for the ensemble of elongating pollen tubes of some plant cells), and have been related to criticality and coherent dynamics (Pietruszka and Olszewska, 2020). It is remarkable in fact that an isomorphism has been shown to exist between fractal structures and coherent states (Vitiello, 2012), so that the general feature of coherence in the DQMB finds a further consistent support in these observations of scale-free behaviors.

Finally, I observe that coherence plays in the dissipative quantum model the role of bridging two different approaches in brain studies: in the first approach, followed by the majority of researchers in neuroscience, a wide number of brain components are studied in their individual properties and theoretical and experimental data about each of them are accumulated. In the second approach the mathematical modeling tries to derive general macroscopic functional properties, usually out of reach of the first approach, from the microscopic dynamics of the brain system components. This second approach is complementary, not alternative to the first one. QFT investigates the basic dynamics underlying the rich phenomenology of the biochemical activity of neural cellular components.

There is then the question of whether a purely classical physics approach cannot do "the same trick" as QFT when it comes to the activity of clusters of neurons. The answer is that classical modeling so far has not provided the derivation of some macroscopic features of brain activity starting from the analysis at the microscopic level, such as, but not only, long range dynamical correlations waves spanning almost simultaneously large neuronal domains.

It is of course welcome any classical modeling able to reach such a task. However, commenting his experimental observations,

Lashley (1942) tells us that: "Here is the dilemma. Nerve impulses are transmitted (...) from cell to cell through defined cell connections. Yet all behavior seems to be determined by masses of excitations (...) within general fields of activity, without reference to particular nerve cells (...). What kind of nervous organization can ever account for patterns of excitations without well-defined and specialized channels of cellular communication? The problem is almost universal in the activity of the nervous system". About twentyfive years later, in 1967, the problem was still there. As already mentioned in the Introduction (cf. also the footnote 2), Ricciardi and Umezawa (1967) write: "...what is important is only a quantity somehow related to the activity of the whole cluster, which does not change appreciably as function of the number of alive neurons belonging to that cluster...the existence of similar and almost simultaneous responses in several regions of the brain (a kind of long-range correlation) to a particular stimulation technique does not find any explanation in terms of activity of the single nerve cells: new non-classical mechanisms have to be looked for...it is strongly suggestive of a quantum model. In other terms, one can try to look for specific dynamical mechanisms (already known in physics of many degrees of freedom) which can satisfy the essential requirements of the observed functioning of the brain". They thus say with the words of Physics what Lashley said as neuroscientist.

The problem is therefore the formulation of a model able to explain the dynamical formation of long range correlations acting as collective modes as to provide "almost simultaneous responses in several regions of the brain" to a stimulation technique, able to "satisfy the essential requirements of the observed functioning of the brain".

The available tools are the ones provided by many-body physics (QFT). They are the only ones we have when dealing with molecular charge distributions, such as electric dipole distributions characterizing all the molecules and bio-molecules involved in nervous cells. The quantum variables in the RU and the DQMB are in fact the vibrational modes of molecular electrical dipoles. In these models, as already remarked in Section 2, neurons and glia cells are indeed considered to be classical systems (Jibu and Yasue, 1995; Ricciardi and Umezawa, 1967; Vitiello, 1995). In this respect the RU model and the DQMB are drastically different from other quantum brain models proposed in the literature (for a general review see Atmanspacher (2020)).

As remarked in previous Sections, in QFT there exist infinitely many unitarily inequivalent state spaces (representations) and this fact offers the possibility of the SBS mechanism out of which long range correlation waves (and the associated NG quanta, the dwq) are dynamically generated. These are genuine QFT features, not existing in known classical models. Of course, since the aim is the understanding of the dynamical emergence of brain macroscopic activity out of its microscopic constituents, there is no competition between quantum and classical modeling. Any possible classical modeling able to provide the derivation, not just a description, of brain functional activity is mostly welcome. In the meantime, we adopt the tools which are today available and experimentally tested in a wide range of physical phenomena, including quantum behaviors in biological systems (Cao et al., 2020) and quantum matter-wave interference of large polypeptide bio-molecules recently ob-

served (Shayeghi et al., 2020).

Apart the mentioned long range correlation waves almost simultaneously spanning large regions of the brain, the huge memory capacity, the dynamical protection of memories against reciprocal interference, the chaotic classical nature of the trajectory in memory space, the protection of memories against local destructive actions on few individual neurons, the stability mechanism against energy fluctuations, already mentioned in previous Sections, I will not insist here in listing further published results of the dissipative model of brain in agreement with experimental observations, which the interested reader may find in the literature (see, e.g., Freeman and Vitiello, 2010; Vitiello, 2016).

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Conflict of Interest

The authors declare no conflict of interest.

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