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The Brain and its Mindful Double

Abstract: *In the past decade Walter Freeman has contributed to the development of the dissipative quantum model of the brain and its testing against laboratory observations. In this paper the model is briefly reviewed with particular reference to the brain–mind relation and its quantum gauge field structure which determines the macroscopic functional behaviour of the brain. Memory appears to be memory of meanings constructed by learning which results from intentional actions. The consciousness act finds its realization in the unavoidable adjustments (dialogues) in the brain/environment (brain/Double) relation, out of which the aesthetic experience is generated when the harmonious to-be-in-the-world is realized. Criticality, fractal self-similarity, chaoticity are manifestations of the coherent gauge field dynamics characterized by the free energy minimization condition.*

I met Walter Freeman for the first time in 2000, at a conference in the United States, where he gave a plenary lecture on mesoscopic brain dynamics. He presented his laboratory observations of the formation of domains of a large number of coherently oscillating neurons (Freeman, 1975/2004; 2000). His presentation induced me to think of the formation of ordered patterns in condensed matter and elementary particle physics — a subject on which I had a couple of papers. It reminded me also of Umezawa's writing, namely that 'memory is a printed pattern of order supported by long-range correlations' (Umezawa, 1995). Remarkably, in his talk Freeman was stressing the role played in brain activity by two ingredients, which are also present

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Journal of Consciousness Studies, **25**, No. 1–2, 2018, pp. 151–76

in the Ricciardi and Umezawa (1967) many-body model for the brain: the notion of field and the notion of coherence. In neuroscience both notions date back to two giants; the notion of field to Karl Lashley in the 1940s ('…Yet, all behavior seems to be determined by masses of excitation… within general fields of activity, without regard to particular nerve cells…' — Lashley, 1948), and the notion of coherence to Karl Pribram in the 1960s, inspiring his holographic picture of brain activity (Pribram, 1966; 1971; 1991; 2013). Although, of course, the notions of field and coherence are popular among physicists working in quantum field theory (QFT), they are still not so popular in biology and neuroscience, where the atomistic view of assembling little components together has been prevailing on the search of dynamical laws controlling the cooperative behaviour of myriad microscopic components (Freeman, 2014).

At once, thus I also realized that another giant in neuroscience was Walter Freeman, who, in the era of the paradigm of 'neural pulses', was daring to talk of dynamical widespread neuronal cooperation in terms of fields. Suddenly, it appeared obvious to me that the picture of the brain is not the one of a Christmas tree with little randomly flashing lights, as it might appear from studies focused on the individual firing of nervous cells, or in the use of computer analogies — a warning already put forward by John von Neumann in his *The Computer and the Brain*: '…the mathematical or logical language truly used by the central nervous system is characterized by less logical and arithmetical depth than what we are normally used to… We require exquisite numerical precision over many logical steps to achieve what brains accomplish in very few short steps…' (von Neumann, 1958).

I met Walter again in 2003, at a conference organized by Harald Atmanspacher in Germany (see his contribution in this issue). On this occasion, during the coffee break of the first morning of the conference, I tried to present to him *My Double Unveiled*, a small book of mine on the dissipative quantum model of brain (Vitiello, 2001). Walter was very kind, looked at the book cover, put it in his bag, said thank you, but also added that all that he was observing in his lab was classical, 'not quantum'. That was the end of our not-even-started discussion. However, I noticed that after my talk in one of the conference sessions, a light was shining in his eyes, which I felt was a little more friendly than his cold words of the first conference day.

One year later, he had to come to Rome for a conference and he wrote me asking to stop in Salerno for a couple of days to talk about 'My Double'. I do not remember if I was more happy or more surprised. In any case, at the end of our first meeting day in Salerno, I told him: ‘Very good, since I am a theorist, you will be my experimentalist.’ Of course, I was joking; we both knew that he was much more than that… However, it was true that without the attempts to fit the laboratory observations made by Walter and by other neuroscientists, the QFT dissipative model of the brain would simply remain a mathematical model, not a physical one.

The title of our first paper, rather than a title, was actually a research programme: ‘Nonlinear Brain Dynamics as Macroscopic Manifestation of Underlying Many-Body Dynamics’ (Freeman and Vitiello, 2006). We agreed to use ‘many-body dynamics’ instead of ‘quantum field dynamics’. Physicists know that they are equivalent words in QFT; Walter said that the use of ‘many-body’ would be less scary than using ‘quantum field’… For me it was a tribute to Ricciardi and Umezawa, whose paper had the title ‘Brain Physics and Many-Body Problems’ (Ricciardi and Umezawa, 1967). In the paper, after discussing the impossibility that electric and magnetic fields or electromagnetic ones, or ionic diffusion, might induce the synchronous neuronal oscillations observed over large distances in brains, we concluded that:

> …As a reasonable alternative we turn to the mathematical machinery of many-body field theory that enables us to describe phase transitions in distributed nonlinear media having innumerable coexisting and overlapping ground states, actual and potential. One might wonder about the necessity and the correctness of using many-body field theory in treating brain dynamics. The common belief is that, if physics has to be involved in the description of brain dynamics, classical tools such as non-linear dynamics and statistical mechanics should suffice. However, many-body field theory appears to us as the only existing theoretical tool capable to explain the *dynamic origin* of long-range correlations, their rapid and efficient formation and dissolution, their interim stability in ground states, the multiplicity of coexisting and possibly non-interfering ground states, their degree of ordering, and their rich textures relating to sensory and motor facets of behaviors. It is historical fact that many-body quantum field theory has been devised and constructed in past decades exactly to understand features like ordered pattern formation and phase transitions in condensed matter physics that could not be understood in classical physics, similar to those in the brain. (Freeman and Vitiello, 2006)

The research programme suggested by the title of the 2006 paper has been carried on until the 24 April 2016. Step by step, we have been considering many observations made, not only by Walter, in neuroscience labs, and have tried to describe them in the QFT dynamical frame of the dissipative quantum model.

During those same years, Walter had been continuing the exploration of the K-sets formalism (Kozma and Freeman, 2009) with Robert Kozma, writing papers with many of his former and new collaborators, opening new research directions such as, for example, in renormalization group theory with Cao (Freeman and Cao, 2008), writing books, travelling for conferences, etc. in an extremely dense activity, rich of new achievements and always open to listening and to studying what was going on in neuroscientific theoretical and experimental research; always with his peculiar ability of penetrating into the details without falling into the trap of *naturalism*, the pure collection of data, as in the enlightenment illusion of reducing knowledge to an encyclopaedia. Naturalism is of course *absolutely necessary* in order to undertake and follow the route towards knowledge. It is, however, *not a sufficient* condition for constructing knowledge. One needs to supplement the data collected in the encyclopaedia with the study of the dynamics, the forces, and the correlations linking together the data, giving them a *meaning*, going from the *syntactic* level to the *semantic* level. Only then does one make Science.

Such an exercise carried out by Walter, of going back and forth from data to their *comprehension*, has not seldom created difficulties and opposition to his work by those focusing their attention solely at the naturalistic stage, on specific aspects of nerve cells or on computer simulations of some computational aspects supposed, but not proved (von Neumann, 1958), to belong to natural brain activity. I was really amused by Walter's reply to a referee report on one of our papers: 'Thank you for your editorial efforts on our behalf. It appears that [your journal] is stony ground for our thesis. Your reviewers have helped to clarify for us how wide the gulf is between ourselves and the authors they have cited, all of whom are personal friends of mine as well as esteemed colleagues, but working in another garden.'

As a matter of fact, one strong link between me and Walter has been that we not only shared our own common garden, but we also and especially shared the freedom to move without boundaries with great curiosity in watching what was going on in neighbouring gardens. It is 'normal', for example, that in the reference lists of Freeman's papers are cited papers by authors that never cite Freeman's works. Science is of course a human activity, including also all the consequent defects and limitations of human behaviour. Sometimes, I received from some colleagues the complaint, also with a not small dose of intolerance, that Freeman was ‘much too open’ to different approaches and tools, which, according to them, is a waste of time and energy since a lot is already known about the brain, for example from computer simulations. These complaints give the measure of how deep the cultural gap is between these people closed in their gardens and Walter Freeman. He had been in fact a living example of the Galilean man, so well depicted by Gramsci in one of his *Quaderni del carcere*: in ‘a scientific discussion… the most “advanced” thinker is he who understands that his adversary may express a truth which should be incorporated in his own ideas, even if in a minor way. To understand and evaluate realistically the position and the reasons of one’s adversary (and sometimes the adversary is the entire thought of the past) means to have freed oneself from the prison of ideologies, in the sense of blind fanaticism’ (Gramsci, 1932/1977). At the 2007 conference in Berkeley, celebrating his 80th birthday, Walter ‘confessed’ that ‘…trying to understand brain function that way [by linear analysis] was like trying to cross an ocean in a dugout canoe… In the following 30 years I have explored the design of foundations for ocean crossings’ (Freeman, 2007).

Memory is not Memory of Information, it is Memory of Meanings

One particular aspect of the dissipative quantum model that attracted Walter’s interest is the possibility of linking the field concept to the continual interaction of the brain with its environment. The mathematical formalism requires that in order to study an open system, as the brain is, one must also consider what is outside the system, namely its environment, and the system–environment interaction. Such an interaction consists effectively in a permanent dialogue of the brain system with its environment, a sort of continual, reciprocal adjustment aimed to the most *harmonious being-in-the-world*. A feature, this last one, which actually relates much of Freeman’s thinking to the thought of phenomenologists such as Merleau-Ponty (1945/1962; Dreyfus, 1999). Here the brain system denotes the brain not solely in its physiological, anatomical characterization, but rather as a global effective body control system, including the plurality of perception channels and motion controlling apparatus. The world, including the internal world as seen, perceived by the brain, is its Double, its ‘portrait’; like the portrait of a photographer is offered by the collection of the photographs made by him. Actually, in the model formalism, the

Double is the time-reversed copy of the subject, since the energy fluxes out-going from the brain are in-going in the environment, and vice versa. The arrow of time (pointing forward) for the brain and the one for the environment are thus each other reversed, similar to the reversal of the image of an arrow in a mirror. The present mirror is, however, a 'time-mirror'. The openness, or dissipative character, of the brain implies indeed that an energy source in the brain finds an energy sink in the environment, and vice versa.

The Double is thus the brain's time-reversed copy, its image in the time-mirror. The consciousness act finds its realization in their dialogue, the permanent adjustment of the two (Vitiello, 1995; 2001). In the QFT formalism of the model, the search for the harmonious adjustment between the two is described by the gauge invariance property of the brain/Double system. It has indeed been shown that the doubling of the degrees of freedom which characterizes the QFT treatment of dissipative systems (Celeghini, Rasetti and Vitiello, 1992) is equivalent to the gauge theory structure of the theory (for the formal details of the derivation see Celeghini *et al.*, 1992; 1993). The 'dialogue' is thus formally described by gauge transformations and the continual search for harmonious adjustment finds its formalization in the gauge invariance of the model.

Summarizing, in the gauge theory paradigm of QFT, the Double is the brain's self-portrait, its image in the mirror in time. The continual balancing of the energy fluxes at the brain–environment interface formally describes the dynamical matching brain–Double and it allows the continual updating of the *meanings* of the flow of information reciprocally exchanged between the two. Walter Freeman has much stressed this crucial point in the brain's functional activity, namely the formation of *meanings* out of its perceptual experiences (Freeman, 2001; Freeman *et al.*, 2003a–c; Freeman and Rogers, 2003; Kay and Freeman, 1998). 'By repeated trial-and-error each brain constructs within itself an understanding of its surrounding, which constitutes its *knowledge* of its own world that we describe as its Double' (Freeman and Vitiello, 2008). What brains really do is to construct meanings: memory is not memory of information, it is memory of meanings.

Perception, Symmetry Breakdown, and Fractal Self-Similarity

In the dissipative model, the QFT formalism implies the formation of extended domains of coherently oscillating neurons (Vitiello, 1995; 2001; Alfinito and Vitiello, 2000). These are in fact the amplitude and phase modulated (AM and PM) assemblies of myriad neurons observed in the laboratory by Freeman and other neurophysiologists. As in the Ricciardi and Umezawa model, in the dissipative model the perceptual inputs produce in the brain the spontaneous breakdown of the symmetry (SBS) of the electric dipoles of biomolecules and water molecules (these represent more than 95% of the present molecules). These dipoles are the quantum variables of the system. In the model, neurons, glia cells, and their subcellular components are classical objects, not quantum objects. The symmetry which is broken is the dipole rotational symmetry (before the breakdown of symmetry the dipoles can point in any direction and their oscillations are not 'in phase oscillations') (see Appendix A).

In fact QFT predicts that the consequence of SBS is the dynamical formation of extended domains of long-range coherent correlations, called Nambu-Goldstone (NG) waves or quanta (see Appendix A). In the brain, this QFT coherent condensation process promotes the observed synchronously oscillating AM neuronal assemblies, their rapid onset, and their (irreversible) succession. The background of coherent condensation facilitates neuronal interaction and the establishing of dendritic and axonic connections, including interactions between spikeless neurons, gap junctions, ephapsis, etc. (Anastassiou *et al.*, 2011; Arvanitaki, 1942; Steriade and Amzica, 1994; Grundfest, 1959), not excluding pulses as carriers of neural information, so to produce the observed AM neuronal assemblies. In particular the model predicts, consistently with experimental observations, that an input of very low energy, in a proper range of phase values, is required to excite AM correlated neuronal patterns, that these have large diameters (with respect to the sizes of the component nervous cells), and that there is a lack of invariance of AM patterns with invariant stimuli. Moreover, predicted are the occurrence of (near-zero) null spikes in phase transitions, the insurgence of phase singularities, and a number of other features, such as e.g. the occurrence of phase gradients, the formation of vortices, the constancy of the phase field within the frames, and so on.

One further aspect which is relevant in Walter's observations and analysis is the self-similarity in background brain activity as suggested by power-law distributions of power spectral densities derived from ECoGs data. Self-similarity is the 'most important property' of fractal structures (Peytegen, Jürgens and Saupe, 1986). Self-similarity in brain activity, observed also by other research groups (Gireesh and Plenz, 2008), deserves particular attention since it is a common feature which appears in a large number of natural phenomena and systems, in biology and in physics in general. Remarkably, the occurrence of fractal self-similarity in so many different phenomena turns out to be related to the coherent state dynamics underlying them. In particular, one can show (Vitiello, 2009; 2012; 2014; Freeman *et al.*, 2015) that an isomorphism exists between fractal-like self-similarity and deformed coherent states (known to be squeezed coherent states in quantum optics). The dissipative quantum model which implies coherent brain dynamics at a basic level thus also implies self-similarity in brain functional activity (Vitiello, 2009).

Criticality, Free Energy, and Chaos

Above I have mentioned the doubling of the degrees of freedom required to set up the QFT formalism for an open system. Such a technique has indeed been developed to formulate thermal field theories in QFT (Umezawa, 1993). The dissipative model of the brain thus introduces temperature, entropy, and other thermodynamic features in brain studies in a very natural way since its basic foundation (Vitiello, 1995, 2015a,b; Freeman, 2015). The free energy functional (Vitiello, 1995) and its minimization in the brain states at time *t*, in the quasi-equilibrium approximation, turns out to be a constitutive aspect of the dissipative model. Free energy has been confirmed to play such a crucial role in brain modelling in all subsequent studies (Freeman and Vitiello, 2006; 2010; 2016, Freeman *et al.*, 2012; Capolupo, Freeman and Vitiello, 2013; Pessa and Vitiello, 2003; 2004; Vitiello, 2001; 2004b; 2008; 2009; 2015a; 2017), as confirmed also by other authors (e.g. Friston, 2010). Of course, this simply reflects the relevance of free energy in the evolution of thermal systems. In nonlinear dynamical systems (including brains) the free energy functional in the variational approach, given by the Bogoliubov inequality at the elementary component level (for formal details see Mańka, Kuczynski and Vitiello, 1986; Blasone, Jizba and Vitiello, 2011), turns out to be the effective Lagrangian, or the generalized Ginzburg-Landau functional at a classical level (see also Freeman *et al.*, 2012). It thus describes the system's macroscopic (classical) behaviour derived from the microscopic dynamics.

Metabolic energy is dissipated by brain at rates ten-fold greater rates than in any other organ. In brains there is constant perfusion with arterial blood and venous removal to dispose of substantial waste heat, keeping temperature nearly constant, which actually happens in mammalian brains. Indirect measures of the rates of dissipation (blood flow, oxygen depletion) are therefore an important resource in brain imaging (Freeman and Quian Quiroga, 2013). In the dissipative model, energy dissipation as heat manifests itself as disappearance/emergence of coherence. Dissipation in fact allows the forming of (infinitely) many different ground states, which guarantees high memory capacity (Appendix B). Memories are created and updated through phase transitions from a gas-like ground state to a liquid-like condensate. We see then how relevant in this respect the gauge structure of the model is and the role played by the minimization of free energy — F, $dF = 0$ — in the quasi-equilibrium approximation (Appendix B). In the continual interaction of the system (brain) with its environment, any perturbation taking it away from the free energy minimum produces the reshuffling of the entropy S and of (internal) energy E, according to $dF = dE - dS/\beta = 0$, with β the inverse temperature. This is achieved through repeated transfers, constrained by the minimization of free energy, of mesoscopic energy to microscopic energy and vice versa. As a result we have heat dissipation, $dQ = dS/\beta$, and, in turn, changes in the NG condensate, with effects on the neural dynamics (Freeman and Vitiello, 2010; Capolupo, Freeman and Vitiello, 2013; Raichle, 2006). The changes in the energy and in the entropy, constrained by the minimization of free energy, acts therefore as a regulatory process aimed at the optimization of ordering in the brain activity, namely in the appearance (disappearance) of the AM neuronal patterns.

In conclusion, free energy minimization, which amounts to nothing but action minimization in view of the equivalence of F with the generalized Ginzburg-Landau functional, relates the basic microscopic dynamics of the brain to the behavioural response of the system to the perceptual (macroscopic) experience. We also observe that the difference between the entropy of the system and the one of the Double is constant in time, expressing indeed the continual dynamical matching of the fluxes. These processes are actually taken in care by the doubled degrees of freedom, which play the same role of a gauge field freedom. In this way an intricate interrelation emerges among the QFT gauge structure of the reciprocal brain–Double nonlinear interaction and its thermodynamic properties (Vitiello, 1995).

In all this, one crucial aspect is criticality. The model implies that there is a permanent brain–environment entanglement. One consequence of this is that fluctuating random forces continuously enter the brain–environment coupling, producing observed continual perturbations involving all areas of the neocortex. These perturbations induce myriad local phase transitions, which are dynamically counteracted so as to maintain the cortex in a state of conditional stability (metastability; Bressler and Kelso, 2001; Freeman and Vitiello, 2008). In the processes of phase transitions, however, in a lapse of time before a new (quasi-)stable configuration is obtained, the dynamics shows criticality that manifests in the formation of non-homogeneous structures with topological non-trivial singularities (such as observed vortices, null spikes, phase cones (Freeman and Vitiello, 2008; 2010), hippocampal sharp wave-ripples (Buzsäki, 1986; 2006)).

Criticality is therefore a very important feature in brain neuronal dynamics. In the model, the process of phase transitions through different coherent condensate densities is described in terms of classical chaotic trajectories in the space of the coherent states (Vitiello, 2004a; Freeman and Vitiello, 2006; Pessa and Vitiello, 2003; 2004; Hilborn, 1994; Abraham and Marsden, 1978). Chaos plays a role at many levels in the cortical functional organization (Liljenström, 2016). In his famous paper published in *Scientific American* in 1991, Freeman was in fact stressing his discovery (Skarda and Freeman, 1987; Tsuda, 2001) of the role of chaoticity in brain functioning: 'Indeed, it may be the chief property that makes the brain different from an artificial-intelligence machine… One profound advantage chaos may confer on the brain is that chaotic systems continually produce novel activity patterns. We propose that such patterns are crucial to the development of nerve cell assemblies that differ from established assemblies' (Freeman, 1991).

The Classical Blanket and the Aesthetic Experience

Since the brain is a permanently open system, the flux of perceptions cannot be stopped: this produces an incessant renewal of the vision of the world with consequent temporary departure from the free energy minimization condition, $dF = 0$, due to the unbalancing of the matching with the Double. The dimension of the functioning of the brain is therefore one of surprise, of astonishment (Vitiello, 2004b) — ‘and suddenly, all at once, the veil is torn away, I have understood, I have seen’ (Sartre, 1948/2006) — and of the Now, the dimension of the present, the time that stops his course in the photographer *surprise*: ‘when at the precise instant an image suddenly stands out and the eye stops’ forcing ‘the time to stop his course’ (Prete, 2003; Vitiello, 2015a). In our trade-and-play with our Double this also allows us to re-establish, although never in a definitive way, the harmonious ‘to-be-in-the-world’, in which consists the aesthetic experience (Desideri, 1998), and to which we are constantly aimed. All of this happens at the macroscopic, classical level of the brain’s functional activity.

The important lesson is thus that the dissipative quantum model describes how the underlying quantum dynamics leads to classical phenomena of the cellular biochemical activity of neurons, synapses, and glia cells, as phenomenologically observed in laboratories. In this way, many kinds of topologically non-trivial solutions of classical field equations (e.g. vortex solutions, phase cones, etc.) are described in terms of microscopic boson condensates (for a detailed discussion see Freeman and Vitiello, 2008; 2010; Freeman *et al.*, 2012). Moreover, one can show in an explicit way how the gauge structure of the formalism manifests itself at the classical level (Vitiello, 1995; 2001; Freeman and Vitiello, 2006). As mentioned above, sequences of phase transitions are described in terms of classical trajectories in the space of the coherent states. Classicality appears thus as a *classical blanket* (Freeman and Vitiello, 2006; Vitiello, 2004a) covering the underlying quantum dynamics in brain activity. It is remarkable that the classical level is not reached by the so-called classical limit in quantum mechanics (the Planck constant $h \to 0$). Classicality in QFT is the macroscopic manifestation of the quantum coherent dynamics which is possible just because h is different from zero. Classically behaving *macroscopic quantum systems* are thus obtained, whose classical behaviour cannot be understood without recourse to the quantum dynamics (Umezawa, 1993; Vitiello, 1995; 2001; 2016; 2017; Blasone, Jizba and Vitiello, 2011) (see Appendix A).

Matter and Mind

In laboratory multichannel recordings of ECoG signals, Freeman observed the formation of imploding and exploding conical phase gradients and the occurrence of a sequence of null spikes (Freeman, 2004a,b; 2005a,b; 2006). Between null spikes the cortical dynamics is (nearly) stationary for intervals, called frames (like in a cinematographic display), of about *60–160 ms*. The location of the apex of the phase cone is fixed in a frame, but varies randomly from each frame to the next. The slope of the cone (phase gradient) also varies randomly between frames. Remarkably, the direction of the gradient is either negative (outward from maximum lead at the apex, explosion) or positive (inward from maximum lag at the apex, implosion), and often shows vortex rotation either clockwise or counterclockwise. The dissipative model describes such phase cones and their dynamical origin in the process of non-instantaneous phase transitions. The model predicts the existence of singularities associated with the apex of the phase cone. For details see Freeman and Vitiello (2010). The exploding gradient could be explained in neurodynamics, for example in terms of a pacemaker. However, in the conventional framework there is no explanation of the imploding gradient, nor of why both gradients, the positive and the negative one, occur, one or the other at random.

In the dissipative model, as already observed, we work with the $t > 0$ time direction, say the arrow of time pointing forward in time, and also with its time-reversed image (the Double). This corresponds to operating with retarded Green's functions, which allow us to describe what happens at a time t_0 (say the present) in terms of what happened at a past time $t < t_0$; or with advanced Green's functions describing the occurrences at t_0 in terms of events at a future time $t > t_0$. The imploding/exploding phase cones observed in the laboratory may be thus described adequately in the dissipative model.

We then postulate that 'the AM patterns in forward thermodynamic time implements action (matter), while the time-reversed copy (mirrored time) governs perception (mind, awareness). They are entangled dynamical modes that we distinguish by patterns of phase modulation that accompany the AM patterns in the electrocorticogram' (Freeman and Vitiello, 2016).

Our proposal of mind and mental activity generated by neural dynamics is therefore based on the observation that the neuropil can operate in both forward and reverse time (the Double), evolving 'along parallel time lines, one corresponding to reconstructing the past in remembering, the other forecasting environmental trends by extrapolation into the future in predicting' (Freeman and Vitiello, 2016; 2010). The scenario needs to include the dynamics of a continuous neural field in brains in addition to discrete neural firing of pulses (Freeman, 1991; 2015; Kozma and Freeman, 2016; Freeman and Quian Quiorga, 2013; Wright, 2009). As seen above, the classical behaviour of the system cannot be explained without recourse to the underlying many-body dynamics.

We know from observations that brains operate through the action–perception cycle, constructing knowledge ‘by acting into the environment to confirm or reject hypotheses imagined from memory’ (Freeman and Vitiello, 2016). This is the level where one realizes how crucial the formation of meanings out of perceived information is for brain activity. Meanings are formed from learning which results from intentional actions. The correctness and credibility of a meaning is then tested on the basis of the appropriateness of the action derived from it (behavioural changes, consequences), which is the content of the concept of pragmatic information (Atmanspacher and Scheingraber, 1990).

The action–perception cycle finds thus its realization within the brain dimension of ‘intentionality’. In this respect, Freeman was greatly inspired by Aquinas (Freeman, 2008) and it has been suggested that the action–perception cycle provides the realization in the neurosciences of the Merleau-Ponty intentional arc (Merleau-Ponty, 1945/1962; Dreyfus, 1999).

In order for brains to perform actions in the environment able to secure their survival, hypotheses are needed about the surrounding world and its evolved state in the future, when actions will be actually performed. The Double is the one able, by time-reversal, to ‘prefigure’ in the present what will be the future state of the environment. Such a state, however, is imagined (hypothesized) on the basis of (remembering) past actions and past perceptual experiences. The mirror copies of neural patterns (time-reversed phase cones observed in the laboratory) are thus dynamical systems, which the Double produces and uses to formulate its hypotheses and predictions. We experience them as perception of the world, and test these hypotheses and predictions with our actions. The Double is therefore ‘a massively coherent, highly textured brain activity pattern’ (Freeman and Vitiello, 2016) that by replaying the past can prefigure (predict) the future. Therefore ‘the Double is mind, yet it is completely entangled with brain matter that is shaped in the original AM pattern’ (*ibid.*). There is no possibility to separate mental activity and brain activity. The many-body model shows that they are dynamically entangled in the coherent states (Vitiello, 2001; Freeman and Vitiello, 2006). Brain–mind is not a dual-aspect representation or manifestation of some basic, mysterious, underlying reality. The brain–mind system is a physical undividable system.

In conclusion, I have presented a brief review of the results obtained in twelve years of collaboration with Walter Freeman. More details can be found in the works listed in the bibliography. There is a long way to go at the theoretical and experimental level. Scientific research never rests on the work of a single man, it is always a collective thinking adventure. The important point is that a direction for 'ocean crossing' has been pointed out.

References

Abraham, R. & Marsden, J. (1978) *Foundations of Classical Mechanics*, Reading, MA: Benjamin/Cummings.

Alfinito, E. & Vitiello, G. (2000) Formation and life-time of memory domains in the dissipative quantum model of brain, *Interntional Journal of Modern Physics*, **B14**, pp. 853–868.

Anastassiou, C.A., Perin, R., Markram, H. & Koch, C. (2011) Ephaptic coupling of cortical neurons, *Nature Neuroscience*, **14**, pp. 217–223.

Arvanitaki, A. (1942) Effects evoked in an axon by the activity of a contiguous one, *Journal of Neurophysiology*, **5** (2), pp. 89–108.

Atmanspacher, H. & Scheingraber, H. (1990) Pragmatic information and dynamical instabilities in multi-mode continuous-wave laser systems, *Canadian Journal of Physics*, **68**, pp. 728–737.

Blasone, M., Jizba, J. & Vitiello, G. (2011) *Quantum Field Theory and its Macroscopic Manifestations*, London: Imperial College Press.

Bressler, S.L. & Kelso, J.A.S. (2001) Cortical coordination dynamics and cognition, *Trends in Cognitive Sciences*, **5**, pp. 2–36.

Buzsäki, G. (1986) Hippocampal sharp waves: Their origin and significance, *Brain Research*, **398**, pp. 242–252.

Buzsäki, G. (2006) *Rhythms of the Brain*, New York: Oxford University Press.

Capolupo, A., Freeman, W.J. & Vitiello, G. (2013) Dissipation of 'dark energy' by cortex in knowledge retrieval, *Physics of Life Reviews*, **10** (1), pp. 85–94.

Celeghini, E., Rasetti, M. & Vitiello, G. (1992) Quantum dissipation, *Annals of Physics*, **215**, pp. 156–170.

Celeghini, E., Graziano, E., Nakamura, K. & Vitiello, G. (1992) Finite temperature quantum field theory and gauge field, *Physics Letters*, **B285**, pp. 98–102.

Celeghini, E., Graziano, E., Nakamura, K. & Vitiello, G. (1993) Dissipative and inhomogeneous systems and the gauge field, *Physics Letters*, **B304**, pp. 121–126.

Del Giudice, E., Doglia, S., Milani, M. & Vitiello, G. (1983) Spontaneous symmetry breakdown and boson condensation in biology, *Physics Letters*, **95A**, pp. 508–510.

Del Giudice, E., Doglia, S., Milani, M. & Vitiello, G. (1985) A quantum field theoretical approach to the collective behavior of biological systems, *Nuclear Physics*, **B251 (FS13)**, pp. 375–400.

Del Giudice, E., Doglia, S., Milani, M. & Vitiello, G. (1986) Electromagnetic field and spontaneous symmetry breakdown in biological matter, *Nuclear Physics*, **B275 (FS17)**, pp. 185–199.

Del Giudice, E., Preparata, G. & Vitiello, G. (1988a) Water as a free electron laser, *Physics Reviews Letters*, **61**, pp. 1085–1088.

Del Giudice, E., Mańka, R., Milani, M. & Vitiello, G. (1988b) Non-constant order parameter and vacuum evolution, *Physics Letters*, **B206** (4), pp. 661–664.

Del Giudice, E. & Vitiello, G. (2006) Role of the electromagnetic field in the formation of domains in the process of symmetry-breaking phase transitions, *Physics Reviews*, **A74**, 022105.

Desideri, F. (1998) *L'ascolto della coscienza. Una ricerca filosofica*, Milano: Feltrinelli.

Dreyfus, H.L. (1999) *What Computers Still Can't Do: A Critic of Artificial Reason*, Cambridge, MA: MIT Press.

Freeman, W.J. (1975/2004) *Mass Action in the Nervous System*, New York: Academic Press.

Freeman, W.J. (1991) The physiology of perception, *Scientific American*, **264** (2), pp. 78–85.

Freeman, W.J. (2000) *Neurodynamics: An Exploration of Mesoscopic Brain Dynamics*, London: Springer Verlag.

Freeman, W.J. (2001) *How Brains Make Up Their Minds*, New York: Columbia University Press.

Freeman, W.J. (2004a) Origin, structure, and role of background EEG activity. Part 1. Phase, *Clinical Neurophysiology*, **115**, pp. 2077–2088.

Freeman, W.J. (2004b) Origin, structure, and role of background EEG activity. Part 2. Amplitude, *Clinical Neurophysiology*, **115**, pp. 2089–2107.

Freeman, W.J. (2005a) Origin, structure, and role of background EEG activity. Part 3. Neural frame classification, *Clinical Neurophysiology*, **116**, pp. 1117–1129.

Freeman, W.J. (2005b) NDN, volume transmission, and self-organization in brain dynamics, *Journal of Integrative Neuroscience*, **4** (4), pp. 407–421.

Freeman, W.J. (2006) Origin, structure, and role of background EEG activity. Part 4. Neural frame simulation, *Clinical Neurophysiology*, **117**, pp. 572–589.

Freeman, W.J. (2007) My legacy: A launch pad for exploring neocortex, *Keynote Talk at the 2007 NSF Brain Network Dynamics Conference*, Berkeley, CA, 2007, [Online], https://archive.org%/details/brain_network_dynamics_2007-03_Walter_Freeman.

Freeman, W.J. (2008) Nonlinear brain dynamics and intention according to Aquinas, *Mind and Matter*, **6**, pp. 207–234.

Freeman, W.J. (2014) Review of the book: Karl H. Pribram (2013) *The Form Within: My Point of View*, Westport, CT: Prospecta Press.

Freeman, W.J. (2015) Mechanism and significance of global coherence in scalp EEG, *Current Opinion in Neurobiology*, **31**, pp. 199–205.

Freeman, W.J. & Rogers, L.J. (2003) A neurobiological theory of meaning in perception. Part 5. Multicortical patterns of phase modulation in gamma EEG, *International Journal of Bifurcation and Chaos*, **13**, pp. 2867–2887.

Freeman, W.J., Burke, B.C. & Holmes, M.D. (2003a) Aperiodic phase re-setting in scalp EEG of beta-gamma oscillations by state transitions at alpha-theta rates, *Human Brain Mapping*, **19** (4), pp. 248–272.

Freeman, W.J., Burke B.C., Holmes M.D. & Vanhatalo, S. (2003b) Spatial spectra of scalp EEG and EMG from awake humans, *Clinical Neurophysiology*, **114**, pp. 1055–1060.

Freeman, W.J., Gaál, G. & Jornten, R. (2003c) A neurobiological theory of meaning in perception: Multiple cortical areas synchronize without loss of local autonomy, *International Journal of Bifurcation and Chaos*, **13**, pp. 2845–2856.

Freeman, W.J., Capolupo, A., Kozma, R., Olivares del Campo, A. & Vitiello, G. (2015) Bessel functions in mass action modeling of memories and remembrances, *Physics Letters*, **A379**, pp. 2198–2208.

Freeman, W.J. & Vitiello, G. (2006) Nonlinear brain dynamics as macroscopic manifestation of underlying many-body dynamics, *Physics of Life Reviews*, **3**, pp. 93–117.

Freeman, W.J. & Cao, Y. (2008) Proposed renormalization group analysis of nonlinear brain dynamics at criticality, in Wang, R., *et al.* (eds.) *Advances in Cognitive Neurodynamics*, ICCN (2007), pp. 147–158, Heidelberg: Springer.

Freeman, W.J. & Vitiello, G. (2008) Dissipation, spontaneous breakdown of symmetry and brain dynamics, *Journal of Physics*, **A41**, pp. 304–042.

Freeman, W.J. & Vitiello, G. (2010) Vortices in brain waves, *International Journal of Modern Physics*, **B24**, pp. 3269–3295.

Freeman, W.J., Livi, R., Obinata, M. & Vitiello, G. (2012) Cortical phase transitions, non-equilibrium thermodynamics and the time-dependent Ginzburg-Landau equation, *International Journal of Modern Physics*, **B26** (6), 1250035.

Freeman, W.J. & Quian Quiroga, R. (2013) *Imaging Brain Function with EEG: Advanced Temporal and Spatial Imaging of Electroencephalographic Signals*, New York: Springer.

Freeman, W.J. & Vitiello, G. (2016) Matter and mind are entangled in two streams of images guiding behavior and informing the subject through awareness, *Mind and Matter*, **14**, pp. 7–24.

Friston, K. (2010) The free-energy principle: A unified brain theory?, *Nature Reviews Neuroscience*, **11**, pp. 127–138.

Fröhlich, H. (1968) Long range coherence and energy storage in biological systems, *International Journal of Quantum Chemistry*, **2**, pp. 641–649.

Gireesh, E.D. & Plenz, D. (2008) Neuronal avalanches organize as nested theta and beta/gamma-oscillations during development of cortical layer, *Proceedings of the Nationa Academy of Sciences*, **105** (21), pp. 7576–7581.

Goldstone, J., Salam, A. & Weinberg, S. (1962) Broken symmetries, *Physics Reviews*, **127**, pp. 965–970.

Gramsci, A. (1932/1977) *Quaderni del carcere*, Quad. N. 10, 1932–35, Gerratana, V. (ed.), Torino: Einaudi.

Grundfest, H. (1959) Synaptic and ephaptic transmission, in Fields, J. (ed.) *Handbook of Physiology*, **1**, 14798, p. 1902.

Hameroff, S. & Penrose, R. (2014) Consciousness in the universe: A review of the 'Orch OR' theory, *Physics of Life Reviews*, **11** (1), pp. 39–78.

Hilborn R. (1994) *Chaos and Nonlinear Dynamics*, Oxford: Oxford University Press.

Jibu, M. & Yasue, K. (1992) A physical picture of Umezawa's quantum brain dynamics, in Trappl, R. (ed.) *Cybernetics and System Research*, pp. 797–804, Singapore: World Scientific.

Jibu, M. & Yasue, K. (1995) *Quantum Brain Dynamics and Consciousness*, Amsterdam: John Benjamins.

Jibu, M., Pribram, K.H. & Yasue, K. (1996) From conscious experience to memory storage and retrival: The role of quantum brain dynamics and boson condensation of evanescent photons, *International Journal of Modern Physics*, **B10**, pp. 1735–1754.

Kay L.M. & Freeman W.J. (1998) Bidirectional processing in the olfactory-limbic axis during olfactory behavior, *Behavioral Neuroscience*, **112** (3), pp. 541–553.

Kozma, R. & Freeman, W.J. (2009) The KIV model of intentional dynamics and decision making, *Neural Networks*, **22** (3), pp. 277–285.

Kozma, R. & Freeman, W.J. (2016) *Cognitive Phase Transitions in the Cerebral Cortex: Enhancing the Neuron Doctrine by Modeling Neural Fields*, Berlin: Springer.

Lashley, K. (1948) *The Mechanism of Vision, XVIII, Effects of Destroying the Visual 'Associative Areas' of the Monkey*, Provincetown, MA: Journal Press.

Leleu, T. & Aikara, K. (2016) Overlapping and non-interfering waves of burst, in Kozma, R. & Freeman, W.J. (eds.) *Cognitive Phase Transitions in the Cerebral Cortex: Enhancing the Neuron Doctrine by Modeling Neural Fields*, pp. 233–237, Berlin: Springer.

Liljenström, H. (2016) Multi-scale causation in brain dynamics, in Kozma, R. & Freeman, W.J. (eds.) *Cognitive Phase Transitions in the Cerebral Cortex: Enhancing the Neuron Doctrine by Modeling Neural Fields*, pp. 177–186, Berlin: Springer.

Mańka, R., Kuczynski, J. & Vitiello, G. (1986) Vacuum structure and temperature effects, *Nuclear Physics*, **B276**, pp. 533–549.

Merleau-Ponty, M. (1945/1962) *Phenomenology of Perception*, Smith, C. (trans.), New York: Humanities Press.

Pessa, E. & Vitiello, G. (2003) Quantum noise, entanglement and chaos in the quantum field theory of mind/brain states, *Mind and Matter*, **1**, pp. 59–79.

Pessa, E. & Vitiello, G. (2004) Quantum noise induced entanglement and chaos in the dissipative quantum model of brain, *International Journal of Modern Physics*, **B18**, pp. 841–858.

Peytegen, H.O., Jürgens, H. & Saupe, D. (1986) *Chaos and Fractals: New Frontiers of Science*, Berlin: Springer.

Prete, N. (2003) Doubling image to face the obscenity of photography, in Globus, G., Pribram, K.H. & Vitiello, G. (eds.) *Brain and Being: At the Boundary Between Science, Philosophy, Language and Arts*, pp. 1–29, Amsterdam: John Benjamins.

Pribram, K.H. (1966) Some dimensions of remembering: Steps towards a neuropsychological model of memory, in Gaito, J. (ed.) *Macromolecules and Behavior*, New York: Academic Press.

Pribram, K.H. (1971) *Languages of the Brain*, Engelwood Cliffs, NJ: Prentice-Hall.

Pribram, K.H. (1991) *Brain and Perception*, Hillsdale, NJ: Lawrence Erlbaum.

Pribram, K.H. (2013) *The Form Within: My Point of View*, Westport, CT: Prospecta Press.

Raichle, M.E. (2006) The brain and dark energy, *Science*, **314**, pp. 1249–1250.

Ricciardi, L.M. & Umezawa, H. (1967) Brain and physics of many-body problems, *Kybernetik*, **4**, pp. 44–48. Reprinted in Globus, G., Pribram, K.H. & Vitiello, G. (eds.) (2004) *Brain and Being*, pp. 255–266, Amsterdam: John Benjamins.

Sartre, J.-P. (1948/2006) *La nausea*, Torino: Einaudi.

Schrödinger, E. (1944/1967) *What is Life*?, Cambridge: Cambridge University Press.

Skarda, C.A. & Freeman, W.J. (1987) How brains make chaos in order to make sense of the world, *Behavioral and Brain Sciences*, **10**, pp. 161–195.

Steriade, M. & Amzica, F. (1994) Dynamic coupling among neocortical neurons during evoked and spontaneous spike-wave seizure activity, *Journal of Neurophysiology*, **72** (5), pp. 2051–2069.

Stuart, C.I.J., Takahashi, Y. & Umezawa, H. (1978) On the stability and non-local properties of memory, *Journal of Theoretical Biology*, **71**, pp. 605–618.

Stuart, C.I.J., Takahashi, Y. & Umezawa, H. (1979) Mixed system brain dynamics: Neural memory as a macroscopic ordered state, *Foundations of Physics*, **9**, pp. 301–327.

Tsuda, I. (2001) Toward an interpretation of dynamics neural activity in terms of chaotic dynamical systems, *Behavioral & Brain Sciences*, **24**, pp. 793–847.

Umezawa, H. (1993) *Advanced Field Theory: Micro, Macro and Thermal Concepts*, New York: American Institute of Physics.

Umezawa, H. (1995) Developments in concepts in quantum field theory in half century, *Mathematica Japonica*, **41**, pp. 109–124.

Vitiello, G. (1995) Dissipation and memory capacity in the quantum brain model, *International Journal of Modern Physics*, **B9**, pp. 973–989.

Vitiello, G. (2001) *My Double Unveiled*, Amsterdam: John Benjamins.

Vitiello, G. (2004a) Classical chaotic trajectories in quantum field theory, *International Journal of Modern Physics*, **B18**, pp. 785–792.

Vitiello, G. (2004b) The dissipative brain, in Globus, G., Pribram, K.H. & Vitiello, G. (eds.) *Brain and Being: At the Boundary Between Science, Philosophy, Language and Arts*, pp. 315–334, Amsterdam: John Benjamins.

Vitiello, G. (2008) My Double and brain dynamics, *Chaos and Complexity Letters*, **4** (3), pp. 1–10.

Vitiello, G. (2009) Coherent states, fractals and brain waves, *New Mathematics and Natural Computing*, **5**, pp. 245–264.

Vitiello, G. (2012) Fractals, coherent states and self-similarity induced noncommutative geometry, *Physics Letters*, **A376**, pp. 2527–2532.

Vitiello, G. (2014) On the isomorphism between dissipative systems, fractal self-similarity and electrodynamics: Toward an integrated vision of nature, *Systems*, **2** (2), pp. 203–216.

Vitiello, G. (2015a) The aesthetic experience as a characteristic feature of brain dynamics, *Aisthesis*, **8** (1), pp. 71–89, [Online], http://www.fupress.net/index.php/aisthesis/article/view/16207/15156.

Vitiello, G. (2015b) The use of many-body physics and thermodynamics to describe the dynamics of rhythmic generators in sensory cortices engaged in memory and learning, *Current Opinion in Neurobiology*, **31**, pp. 7–12.

Vitiello, G. (2016) Filling the gap between neuronal activity and macroscopic functional brain behavior, in Kozma, R. & Freeman, W.J. (eds.) *Cognitive Phase Transitions in the Cerebral Cortex: Enhancing the Neuron Doctrine by Modeling Neural Fields*, pp. 239–249, Berlin: Springer.

Vitiello, G. (2017) The brain is like an orchestra: Better yet, it is like a jazz combo, which doesn't need a conductor, *Chaos and Complexity Letters*, **11**, pp. 163–178.

von Neumann, J. (1955) *Mathematical Foundations of Quantum Mechanics*, Princeton, NJ: Princeton University Press.

von Neumann, J. (1958) *The Computer and the Brain*, New Haven, CT: Yale University Press.

Wright, J.J. (2009) Cortical phase transitions: Properties demonstrated in continuum simulations at mesoscopic and macroscopic scales, *New Mathematics and Natural Computation*, **5** (1) pp. 159–183.

Wright, J.J. (2016) Electrocortical synchrony and the regulation of information flow in the cerebral cortex, in Kozma, R. & Freeman, W.J. (eds.) *Cognitive Phase Transitions in the Cerebral Cortex: Enhancing the Neuron Doctrine by Modeling Neural Fields*, pp. 163–175, Berlin: Springer.

Appendices

A. Macroscopic Quantum Systems

In the early 1960s it became clear among QFT physicists how ordered patterns could be *dynamically* generated in condensed matter physics (e.g. in superconductors, crystals, ferromagnets). ‘Dynamically’ means that, for example in a crystal, atoms are not ordered by fixing them in their lattice positions by short range forces (arising between neighbouring atoms). The possibility was discovered, instead, that in the (disordered) collection of atoms there could arise long-range correlations, or waves, as the system’s reaction to an external, even *weak* but ‘in phase’, input. These long-range correlations among the atoms are responsible for their ordering in the crystal pattern. The transition from the *symmetric*, or disordered, gas-like, collection of atoms to the ordered crystal pattern can be then described: *order* is lack of symmetry. The external input produces thus the spontaneous symmetry breakdown (SBS). The term ‘spontaneous’ refers to the fact that the system autonomously, i.e. under the action of its own internal dynamics, reacts to the input, entering the ordered (non-symmetric) phase. The quanta associated with the long-range correlations are called Nambu-Goldstone (NG) modes or quanta (Goldstone, Salam and Weinberg, 1962). They are boson quanta, meaning that a number of them, even with the same quantum identifying properties (quantum numbers), may sit in the same state. One then says that they are *condensed* in that state. The NG quanta have zero mass, thus at their lowest kinetic energy they do not contribute to the condensed state energy. This explains why such condensed NG states are quite stable states.

Due to their zero mass, NG quanta may propagate without inertia over large domains of elementary components, which indeed accounts for the long range of the correlations. They are therefore *collective modes*, shared by the whole ordered pattern. The observation of NG collective modes is widely confirmed in experiments in condensed matter physics. They are called phonons in crystals (elastic wave quanta), magnons (spin wave quanta) in ferromagnets, etc.

The system of atoms may thus live in their symmetric, disordered energy state (called the symmetric vacuum state), as well as in the crystal ordered energy state (the ordered vacuum state). For instance, by tuning the temperature, the system may enter, driven by its own internal dynamics, a process of *phase transition*, from symmetry to order, and vice versa. The permanence time (life-time) of the system in the dynamical regime of the symmetric phase or the one of the ordered phase depends on a number of parameters specific to the system under study and on the external environment in which it is embedded. It may be very long or quite short. Ordered states may survive in a wide range of temperatures, from very high to very low temperatures; for example, diamond melts, i.e. its crystal ordering is lost, at about *3550°C* in the absence of oxygen; common kitchen salt *NaCl* melts at *804°C*; the coherence of elementary iron magnets is lost at *770°C*; for some niobium superconducting compounds the critical temperature is *–252°C*.

In conclusion, the NG condensation produces macroscopic (long-range correlated) patterns. In this sense we have therefore 'macroscopic quantum systems', namely, as a result of the boson condensation we have a *change of scale: from micro to macro* (Umezawa, 1993). *This is a quantum effect, not attainable in a classical physics approach*.

These phenomena do not occur in quantum mechanics (QM). Contrary to QM, in QFT there exist many physically non-equivalent spaces of states which may describe different phases accessible to the system (the von Neumann theorem — von Neumann, 1955; Umezawa, 1993; Blasone, Jizba and Vitiello, 2011), i.e. dynamical regimes with physically distinct properties; a crystal phase behaves in quite a different way than the gas-like phase, indeed. If one wants to describe e.g. a crystal and its possible phase transitions, one needs QFT.

B. The Dissipative Quantum Model of the Brain, its Gauge Field Structure, and Free Energy

In the Ricciardi and Umezawa (RU) model (Ricciardi and Umezawa, 1967; Stuart, Takahashi and Umezawa, 1978; 1979) and in its extension to dissipative quantum dynamics (Vitiello, 1995), neurons, glia cells, and other cellular biological entities are classical objects. The quantum entities and variables are the quantum excitations of the molecular electrical dipoles. All the biological macro-molecules in brains and in biological systems in general are endowed with electrical dipoles characterizing their physical and chemical properties. Moreover, all of it is embedded in the water matrix, without which there is no brain or biology in general. Water molecules are in weight about the 70% of the whole molecular content. In number water molecules are more than the 95% of the present molecules. One cannot even think to talk about the brain or living matter without considering the role of water molecules.

In the original RU model the main problem to be solved was to obtain a collective mode describing the transition from a multitude of elementary components to a system with global behaviour:

> 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 he 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. (Ricciardi and Umezawa, 1967)

The idea is then that external inputs reaching the brain through the perception channels may induce the breakdown of the symmetry, with consequent formation of an ordered state as the result of the NG boson condensate. Such a condensation represents in the model the printing of the memory of the triggering input. Memory recall is obtained by a similar input exciting the condensed bosons.

In 1983 Del Giudice *et al*. (1983; 1985; 1986; 1988a,b; Del Giudice and Vitiello, 2006), inspired by Fröhlich's work (Fröhlich, 1968), proposed a model for living matter based on the quantum gauge field theory paradigm, with breakdown of the rotational symmetry of the molecular electrical dipoles. In 1992 Jibu and Yasue (1992; 1995; Jibu, Pribram and Yasue, 1996) proposed that in the RU model the electrical dipole rotational symmetry was the one getting broken by the external input.

The problem with the RU model was, however, the reduced memory capacity. Any subsequent input produces a further symmetry breaking with consequent NG boson condensation and *overprinting* of the new memory on the previously recorded one, which thus gets cancelled. However, if one considers that brains are open dissipative systems, then the QFT formalism for such systems implies that the dynamics involves infinitely many unitarily inequivalent spaces of the states. One can thus record different memories in different, not interfering, spaces, which indeed solves the overprinting problem of the RU model. The richness of the QFT structure thus proves to be essential for the modelling of brain dynamics. In this respect, the dissipative quantum model of the brain is substantially different to other models based on quantum mechanics (Hameroff and Penrose, 2014), where all the spaces of the states are unitarily equivalent (and thus physically equivalent).

As said, the NG boson waves (the long-range correlation waves) consequent to the spontaneous breakdown of symmetry act so as to facilitate the interactions among neurons, glia cells, and other cellular biological entities, synapses formation, axon and dendritic interconnections resulting in the formation of neuropil and cortical/subcortical interactions, all of it allowing firing patterns in amplitude and phase modulated (AM and PM) assemblies of myriad neurons, as observed in laboratories. The dynamical scenario is such that one cannot consider solely pulses or solely wave fields in the description of the brain activity. One must consider both of them. On the other hand, 'the modeling of burst propagation and their associated waves can become increasingly complex as the number of overlapping patterns increases. In such a case, theoretical frameworks that allow keeping track of the creation and annihilation of propagation waves, inspired for example from Quantum Field Theory, may likely become very useful tools' (Leleu and Aikara, 2016). An explicit computational example is provided in Freeman *et al.* (2015), where data from neurological processes, such as impulse responses of the cortex to electric shocks (average evoked potentials), presenting Bessel-like functional distribution, have been studied. This is also consistent with the analysis (Wright, 2009) showing that 'large-scale electrocortical field [can be] treated as a linear wave medium, driven by intrinsic episodes of burst firing, as well as by extrinsic specific and non-specific inputs. The control and coordination of the global system can be then viewed as the interaction of the cortical and subcortical system, and of local bursting interacting with the background field' (Wright, 2016).

One may list specific QFT results which agree with laboratory observations. Some of these results are certainly *described* in neuroscience at a phenomenological level by specific modelling or *simulating* them by numerical analysis; however, they are not *derived* in a unified view from a basic *dynamical* model of the system, as instead it happens in the dissipative quantum model. The list of these dynamical results includes, besides the ones mentioned in the text: coexistence of physically distinct AM patterns in distinct frequency bands, the rapid onset of AM patterns into (irreversible) sequences, duration, size, and power of AM patterns are decreasing functions of their carrier wave number *k*, the insurgence of a phase singularity associated with the abrupt decrease of the order parameter and the concomitant increase of spatial variance of the phase field, etc. (Freeman and Vitiello, 2006; 2008; 2010; 2016).

The question still remains as to why one could not simply use classical field theory, but has to work instead with quantum field theory. Apart from the mentioned fact, which cannot be ignored, that the basic system components are quantum units, the problem is that, as mentioned in the text and in Appendix A, there is no classical physics approach, based on analytic, mechanical, or statistical analysis, or even numerical simulation, able to describe the change of scale from the molecular quantum microscopic dynamics to the macroscopic ordered functional activity so highly efficient and sharply tuned, with so sophisticated a level of organization. One of the most relevant features of QFT with spontaneous breakdown of symmetry is the possibility to obtain dynamically the formation of coherent states. These are characteristic of quantum dynamics, not of classical dynamics. Coherence is crucial since it accounts for the brain's functional macroscopic stability against its fluctuating microscopic activity. Indeed, quantum fluctuations ΔN become negligible in coherent states since $\Delta N/N \approx 1/|\alpha|$, with α denoting the degree of coherence. We have in fact large N in coherent states (so that $\Delta N << N$, indeed, and $N = |\alpha|^2$), which then requires the use of fields. Thus we need a quantum field with a coherent dynamics.

In conclusion, coherence in QFT allows the possibility that the state of the system as a whole may be described by *classical* fields, i.e.

independent of quantum fluctuations (typically called order parameters). This is the 'change of scale' mentioned above (Appendix A), from micro to macro: the coherent quantum dynamics *manifests* itself at the level of the cellular biochemical activity of neurons, synapses, and glia cells observed in laboratories. In other words, at the level of the *classical* behaviour of the system *as a whole*. This is the sense ('quantitatively' well defined) of Schrödinger's words on the distinction between the *two ways of producing orderliness* (Schrödinger, 1944/1967, p. 80): ordering generated by the 'statistical mechanisms' and ordering generated by 'dynamical' interactions, '…it needs no poetical imagination but only clear and sober scientific reflection to recognize that we are here obviously faced with events whose regular and lawful unfolding is guided by a *mechanism* entirely different from the *probability mechanism* of physics' (*ibid.*, p. 79). Schrödinger's statement is therefore a 'technical' remark, not an arrogant one, stressing that the attempt to explain biological functional stability in terms of the regularities of statistical origin would be the '*classical physicist's expectation* that *far from being trivial, is wrong*' (*ibid.*, p. 19). In Appendix A it was recalled that the transition from micro to macro is indeed a *quantum* dynamical result, *not attainable in a classical physics approach.* As said in the text, in the dissipative quantum model, brains are not quantum systems, they are *macroscopic quantum systems*, namely systems whose *classical* functional behaviour cannot be understood without recourse to the basic dynamics of their quantum components. Such a state of affairs is what offers to us current theoretical physics, it is not at all something 'exotic': coherent QFT is experimentally well verified in all the systems exhibiting ordered patterns, in a wide range of temperatures and boundary conditions; examples are crystals, magnets, superconductors, etc., many phenomena in elementary particle physics and cosmology; all of them are understood as classically behaving macroscopic quantum systems and phenomena. Our modelling suggests that living matter systems, including brains, are classically behaving macroscopic quantum systems, in the specific sense stated above.

Details of the QFT formalism of the dissipative model can be found in Vitiello (1995) and in subsequent papers (Freeman and Vitiello, 2006; 2008; 2010; 2015; Freeman *et al.*, 2012; Alfinito and Vitiello, 2000; Pessa and Vitiello, 2003; 2004; Capolupo, Freeman and Vitiello, 2013; Vitiello, 2015a,b). Here, in Box 1 and Box 2, a few of the characterizing features of the model's formalism are briefly summarized. Spontaneous breakdown of the rotational SU(2) dipole symmetry generates the NG modes (the dipole wave quanta (DWQ) modes). Considering then that the global phase symmetry (the U(1) gauge symmetry) survives the SU(2) breakdown (Del Giudice *et al.*, 1985; 1986), one can show that the doubled fields introduced in the doubling process actually play the role of the gauge field as in the conventional gauge theory paradigm of QFT (Celeghini *et al.*, 1992; 1993). As shown in Box 2, the connection with free energy and its minimization is built into the model and it appears to be crucial for the dynamical description of the brain's functional activity. This is described by trajectories through the brain states at time *t*; in each one of these states, in the quasi-equilibrium approximation, free energy is minimized.

Box 1

In order to balance the flow of the energy exchanged between the brain and the environment in which it is embedded, we need to double the system degrees of freedom. Let A_k and $\tilde{A}_k$ be the annihilation operators for the dipole wave quanta (DWQ) mode (the NG mode) and its doubled mode, respectively, with the subscript k denoting the momentum and other specifications of the A operators. The creation operators are denoted by $A_k^\dagger$ and $\tilde{A}_k^\dagger$. The $\tilde{A}$ system represents the sink (the bath or environment) where the energy dissipated by the A system flows.

Let $\mathcal{N}$ be the *memory record* of the input imprinted in the least energy state (the vacuum state) $|0\rangle_{\mathcal{N}}$ at $t_0 = 0$, thus representing the memory state at $t_0 = 0$. The code $\mathcal{N}$ is the set of the numbers $\mathcal{N}_{A_k}$ of modes A_k, for any k, condensate in $|0\rangle_{\mathcal{N}}$. $\mathcal{N}_{A_k}(t)$ is given, at each t, by (Vitiello, 1995):

$$\mathcal{N}_{A_k}(t) \equiv {}_{\mathcal{N}}\langle 0(t)|A_k^\dagger A_k|0(t)\rangle_{\mathcal{N}} = \sinh^2(\Gamma_k t - \theta_k)\ . \tag{1}$$

A similar expression is obtained for the modes $\tilde{A}_k$. $|0(t)\rangle_{\mathcal{N}} \equiv |0(\theta, t)\rangle$ here denotes the time-evolved of $|0\rangle_{\mathcal{N}}$. Γ is the damping constant, related to the memory life-time, and θ_k fixes the code value at $t_0 = 0$. $|0\rangle_{\mathcal{N}}$ and $|0(t)\rangle_{\mathcal{N}}$ are normalized to 1. $|0(\theta, t)\rangle$ is a generalized $SU(1,1)$ squeezed coherent state, where the A and $\tilde{A}$ modes are entangled. In the infinite volume limit it is

$${}_{\mathcal{N}}\langle 0(t)|0\rangle_{\mathcal{N}'} \underset{V\to\infty}{\longrightarrow} 0 \quad \forall\, t \neq t_0,\ \forall\, \mathcal{N}, \mathcal{N}'\ , \tag{2}$$

$${}_{\mathcal{N}}\langle 0(t)|0(t')\rangle_{\mathcal{N}'} \underset{V\to\infty}{\longrightarrow} 0,\ \forall\, t, t' \text{with} \quad t \neq t'\ ,\ \forall\, \mathcal{N}, \mathcal{N}'\ , \tag{3}$$

with $|0(t)\rangle_{\mathcal{N}'} \equiv |0(\theta', t)\rangle$. These equations hold also for $\mathcal{N} \neq \mathcal{N}'$, $t = t_0$ and $t = t'$, respectively. They show that in the infinite volume limit, the vacua with same $\mathcal{N}$ at $t \neq t'$, for any t and t', and, similarly, at equal times, but different $\mathcal{N}$s, are orthogonal (vacuum) states and their corresponding Hilbert spaces are unitarily inequivalent spaces. The number $\left(\mathcal{N}_{A_k} - \mathcal{N}_{\tilde{A}_k}\right)$ is a constant of motion for any k. The constraint $\mathcal{N}_{A_k} - \mathcal{N}_{\tilde{A}_k} = 0$, for any k, ensures then the balance of the energy flows between the system and the environment. Under such a constraint, however, the code $\mathcal{N} \equiv \{\mathcal{N}_{A_k},$ for any $k\}$ is not uniquely fixed. The energy flow balance is also ensured by $|0\rangle_{\mathcal{N}'}$ with $\mathcal{N}' \equiv \{\mathcal{N}'_{A_k}; \mathcal{N}'_{A_k} - \mathcal{N}'_{\tilde{A}_k} = 0,$ for any $k\}$, so that also $|0\rangle_{\mathcal{N}'}$ is an available memory state. It corresponds to a different code number, $\mathcal{N}'$, namely to an information different from the one of code $\mathcal{N}$.

Thus, an infinite number of memory states may exist, each one of them labeled by a different code $\mathcal{N}$. Infinitely many vacua $|0\rangle_{\mathcal{N}}$, for all $\mathcal{N}$, are indeed independently accessible in the recording process of sequential inputs. They may coexist without destructive interference due to Eqs. (2) and (3).

The collection of the full set of states (the space of the memory states) $|0\rangle_{\mathcal{N}}$, for all $\mathcal{N}$, such that the constraint $\mathcal{N}_{A_k} - \mathcal{N}_{\tilde{A}_k} = 0$, for any k, and for all $\mathcal{N}$ (i.e. $\mathcal{N} \equiv \{\mathcal{N}_{A_k}; \mathcal{N}_{A_k} - \mathcal{N}_{\tilde{A}_k} = 0,$ for any $k\}$), is satisfied, represents the "brain (ground) state".

The constraint $\mathcal{N}_{A_k} - \mathcal{N}_{\tilde{A}_k} = 0$, for all k, for all $\mathcal{N}$, expresses the so-called thermal state condition in the real time formalism of thermal field theory (thermo field dynamics (TFD)): $(A_k^\dagger A_k - \tilde{A}_k^\dagger \tilde{A}_k)|0(t)\rangle_{\mathcal{N}} = 0$, for all k (Umezawa, 1993). This confirms that the dissipative model is a thermal model, with the tilde modes representing the bath in which the system is embedded.

Box 2

The state $|0(t)\rangle_{\mathcal{N}}$ may be written as:

$$|0(t)\rangle_{\mathcal{N}} = \exp\left(-\frac{1}{2}S_A\right)|\mathcal{I}\rangle = \exp\left(-\frac{1}{2}S_{\tilde{A}}\right)|\mathcal{I}\rangle,$$

where $|\mathcal{I}\rangle \equiv \exp\left(\sum_\kappa A_\kappa^\dagger \tilde{A}_\kappa^\dagger\right)|0\rangle$ with $A_\kappa|0\rangle = 0 = \tilde{A}_\kappa|0\rangle$ and

$$S_A \equiv -\sum_\kappa \left\{A_\kappa^\dagger A_\kappa \ln \sinh^2(\Gamma_\kappa t - \theta_\kappa) - A_\kappa A_\kappa^\dagger \ln \cosh^2(\Gamma_\kappa t - \theta_\kappa)\right\}$$

denotes the entropy operator. $S_{\tilde{A}}$ is given by a similar expression with $\tilde{A}_\kappa$ and $\tilde{A}_\kappa^\dagger$ replacing A_κ and $A_\kappa^\dagger$, respectively (Vitiello, 1995). We shall simply write S for either S_A or $S_{\tilde{A}}$. We have

$$\frac{\partial}{\partial t}|0(t)\rangle_{\mathcal{N}} = -\left(\frac{1}{2}\frac{\partial S}{\partial t}\right)|0(t)\rangle_{\mathcal{N}},$$

showing that time-evolution is controlled by the entropy variations, which reflects the irreversibility of time evolution (breakdown of time-reversal symmetry, *the arrow of time*) characteristic of dissipative systems. The free energy functional is given by

$$\mathcal{F}_A \equiv {}_{\mathcal{N}}\langle 0(t)|\left(H_A - \frac{1}{\beta}S_A\right)|0(t)\rangle_{\mathcal{N}}.$$

β is the (time-dependent) inverse temperature $T(t)$: $\beta(t) = \frac{1}{k_B T(t)}$; $H_A = \sum_\kappa \hbar\Omega_\kappa A_\kappa^\dagger A_\kappa$. The stationarity condition $d\mathcal{F} = 0$ leads to the Bose distribution for A_κ at time t

$$\mathcal{N}_{A_\kappa}(\theta, t) = \sinh^2(\Gamma_\kappa t - \theta_\kappa) = \frac{1}{e^{\beta(t)E_\kappa} - 1},$$

where $E_\kappa \equiv \hbar\Omega_\kappa$. The entropy $\mathcal{S}(t) = \langle 0(t)|S|0(t)\rangle_{\mathcal{N}}$ is a decreasing function of time in the interval $(t_0 = 0, \tau)$: the memory state, although not conserved in time, is however protected from "going back" to the vacuum state (memory cancelation). Moreover, the entropy, for both A and $\tilde{A}$ system, grows monotonically with t from value 0 at $t = \tau$ to infinity at $t = \infty$. The entropy for the complete system is given by $(S_A - S_{\tilde{A}})$ and is constant in time. The change in the energy $E_A \equiv \sum_\kappa E_\kappa \mathcal{N}_{A_\kappa}$ and in the entropy is given by

$$dE_A = \sum_\kappa E_\kappa \dot{\mathcal{N}}_{A_\kappa} dt = \frac{1}{\beta} d\mathcal{S}_A,$$

i.e. $d\mathcal{F}_A = dE_A - \frac{1}{\beta}d\mathcal{S}_A = 0$ (assuming quasi-equilibrium or stationary approximation, i.e. slow changes in inverse temperature, $\frac{\partial\beta}{\partial t} = -\frac{1}{k_{\bar{A}}T^2}\frac{\partial T}{\partial t} \approx 0$). As usual heat is $dQ = \frac{1}{\beta}dS$. Thus the change in time of condensate, $\dot{\mathcal{N}}_{A_\kappa}$, turns out into heat dissipation dQ.

Time evolution of the $\mathcal{N}$-coded memory state is represented as a trajectory of initial condition $\mathcal{N} = \{\mathcal{N}_{A_\kappa}\}$ running over the space of the representations $\{|0(t)\rangle_{\mathcal{N}}\}$, each one minimizing the free energy functional (at each t in the quasi-equilibrium or stationary limit).