Artificial Intelligence Versus Natural Intelligence

Article · January 2022

DOI: 10.1007/978-3-030-85480-5

7 authors, including:

Fabio Scardigli
Politecnico di Milano and Leiden University

Ines Testoni
University of Padova

Giuseppe Vitiello
Università degli Studi di Salerno

Giacomo Mauro D'Ariano
University of Pavia

Roger Penrose · Emanuele Severino ·
Fabio Scardigli · Ines Testoni · Giuseppe Vitiello ·
Giacomo Mauro D'Ariano · Federico Faggin *Authors*
Fabio Scardigli *Editor*

Artificial Intelligence Versus Natural Intelligence

Springer

Artificial Intelligence Versus Natural Intelligence

Roger Penrose ·
Emanuele Severino ·
Fabio Scardigli ·
Ines Testoni ·
Giuseppe Vitiello ·
Giacomo Mauro D'Ariano ·
Federico Faggin
Authors

Fabio Scardigli
Editor

Artificial Intelligence Versus Natural Intelligence

Springer

Authors
Roger Penrose
Mathematical Institute
Oxford University
Oxford, UK

Fabio Scardigli
Dipartimento di Matematica
Politecnico di Milano
Milan, Italy

Giuseppe Vitiello
Dipartimento di Fisica
Università di Salerno
Fisciano, Italy

Federico Faggin
Los Altos Hills, CA, USA

Emanuele Severino
Brescia, Italy

Ines Testoni
FISPPA, Section Applied Psychology
University of Padua
Padova, Italy

Giacomo Mauro D'Ariano
Dipartimento di Fisica
Università di Pavia
Pavia, Italy

Editor
Fabio Scardigli
Dipartimento di Matematica
Politecnico di Milano
Milan, Italy

ISBN 978-3-030-85479-9 ISBN 978-3-030-85480-5 (eBook)
https://doi.org/10.1007/978-3-030-85480-5

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Contents

The Brain Is not a Stupid Star

Giuseppe Vitiello

Abstract The activity of the neocortex presents the formation of extended configurations of oscillatory motions modulated in amplitude and phase and involving myriads of neurons. As observed by Lashley, nerve impulses are transmitted from cell to cell through defined cell connections. However, all behavior seems to be determined by masses of excitations, within general fields of activity, without reference to particular nerve cells. Freeman has stressed the role played by chaos underlying the ability of the brain to respond flexibly to the outside world. These observations support the remark, attributed to Aristotle, that the brain is not a stupid star, which in its perennial

G. Vitiello (✉)
Dipartimento Di Fisica "E.R. Caianiello", Università Di Salerno, Via Giovanni Paolo II, 132, 80084 Fisciano (Salerno), Italia
e-mail: vitiello@sa.infn.it

R. Penrose et al., *Artificial Intelligence Versus Natural Intelligence*,
https://doi.org/10.1007/978-3-030-85480-5_4

trajectory passes always through the same point in a fully predictable way. On the contrary, brains appear to proceed by steps that do not necessarily belong to a strictly predictive chain of steps, but behave like a 'machine making mistakes', intrinsic erratic devices. These features of neural dynamics are discussed within the framework of the dissipative quantum model of the brain and with reference to AI systems and research programs. If it is ever possible to build a device endowed with consciousness, it must possess unpredictability of behavior, infidelity, and inalienable freedom; and must be called *Spartacus*.

1 Introduction

I have already used the title of this paper "The brain is not a stupid star" as the title of a section of my contribution to the book by Robert Kozma and Walter Freeman on cognitive phase transitions in the cerebral cortex [1]. I mentioned there that, according to Aristotle, stars have a stupid behavior since in their perennial trajectories they always pass through the same point in a fully predictable way. I do not know if such an observation was really made by Aristotle. However, the suggested idea is that the brain is not a stupid star since its behavior is not fully predictable. The point is that stupidity (non-intelligence?) is associated with fully predictable behavior within broadly unchanged boundary conditions. The brain, on the contrary, is motivated in its behavior by intentional tasks, which although partially conditioned by the environment in which it is embedded, are definitely formulated and pursued by the brain in its action–perception cycle. As stressed by Pribram [2–4], in brain activity there is always a content of 'attention' in perception and of 'intention' in action. Neuronal activity, according to Freeman, acts "as a unified whole in shaping each intentional action at each moment" [5]. In pursuing our best to-be-in-the-world, we are indeed guided by our changeable volition and intention [6, 7].

These observations might lead straight to the theme of artificial intelligence (AI), with reference to one of the possible meanings of "intelligence" and the predictability of the functioning of a device. However, let me discuss first some of the features of the brain's functional activity as described within the dissipative quantum model of brain [8, 9]. In Sect. 2 some general features in the brain studies are briefly presented. Section 3 is devoted to some notions of quantum field theory (QFT), in particular to coherence, a basic ingredient in the many-body model of the brain and the dissipative quantum model of the brain, which will be introduced in Sects. 4 and 5, respectively. In Sect. 7, I discuss some features of AI in connection with the chaotic classical trajectories in the space of memory described by the dissipative model and introduced in Sect. 6. Section 8 is devoted to concluding remarks.

2 Lashley's Dilemma

Let me start by mentioning that Karl Lashley, in commenting the experiments he conducted in the 1940s, proposed the following dilemma to neuroscience scholars [10, pp. 302–306]:

> 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.

Lashley thus arrived at the formulation of the hypothesis of mass action in brain activity. His experimental observations, fully confirmed by subsequent studies (see, for example, [11]), led Karl Pribram in the 1960s to propose the hypothesis that for the brain one could speak of coherence, a central notion in quantum optics, and use the metaphor of the hologram [2, 3]. One of the characteristic features of a hologram is that knowledge of a detail in any point of the image allows the reconstruction of the whole image. Such a possibility comes from the fact that the photons, the quanta of the electromagnetic field, which constitute the laser used to produce and read the hologram, oscillate in phase. The laser is made by *coherently* oscillating photons. The laser is what results from the harmony, if I am allowed to use this term, of the *coherence* of photons. Natural light ('non-laser' light) is instead made of photons that are not in phase, i.e., they are not coherent. Beyond the specificity of the model proposed by Pribram, the value of his intuition consists in the fact that for brain activity we can speak of coherence.

The coherence hypothesis for the brain's functional activity is actually confirmed by the observation of widespread cooperation between a huge number of neurons over vast brain areas. Analysis of the potentials measured with the electroencephalogram (EEG) and with the magnetoencephalogram (MEG) shows that the neural activity of the neocortex presents the formation of extended configurations of oscillatory motions modulated in amplitude (AM) and phase (PM) [12, 13]. These configurations extend over almost the entire cerebral hemisphere for rabbits and cats, on domains of linear dimensions up to twenty centimeters in the human brain, and have almost zero phase dispersion [14, 15]. The associated oscillation frequencies are in the 12–80 Hz range (the so-called beta and gamma waves). The patterns of neuronal oscillations dissolve in a few tens of milliseconds and others appear in different configurations, with frequencies in the 3–12 Hz range (theta and alpha waves) [12, 16–21].

A huge number of cells and other biologically active units enter into brain activity. For example, a weak olfactory stimulus activates about a thousand neurons in the olfactory bulb that produce the excitation of a million neurons and the inhibitory activity of 10 million neurons that propagates in 5–10 ms over a distance of about 10 mm, although the average axon lengths are about 1 mm and the synaptic propagation times are about 10 times longer [22]. It is evident that in the presence of such huge numbers and such complexity, the study of brain functions cannot be limited to the knowledge of the properties of the individual elementary components. This is certainly necessary, but it is by no means sufficient. Ricciardi and Umezawa write [23]:

> […] in the case of natural brains, it might be pure optimism to hope to determine the numerical values for the coupling coefficients and the thresholds of all neurons by means of anatomical or physiological methods. […] 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 a higher and higher degree of malfunctioning should be observed, unless to assume the existence of "special" neurons, characterized by an exceptionally long half life: or to postulate

> a huge redundancy in the circuitry of the brain. However, to our knowledge, there has been no evidence which shows the existence of such "special" neurons, and to invoke the redundancy is not the best way to answer the question.

Referring to biological systems in general, but his words might be applied equally well to the brain, Schrödinger observes that [24, p. 79],

> […] 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.

The discovery of the constituents of biological systems and the knowledge of their specific properties certainly constitutes a great success of molecular biology. The problem now is one of understanding how to put these elementary constituents together in such a way as to generate the complex macroscopic behavior of the system [25–30]. As observed elsewhere [31],

> In very general terms, the problem is the one of the transition from naturalism, that is, from the knowledge of the catalogs of elementary components, to understanding the dynamics that accounts for the relationships that bind these components and describes the behavior of the system as a whole. The phase of naturalism is obviously essential and requires an enormous effort of careful and patient investigation. Although it is necessary, it is not sufficient for the purposes of a full understanding of the phenomena that are the object of our study. Knowing is not yet understanding.

According to Schrödinger, in the study of living matter, the distinction has to be made between the *two ways of* *producing orderliness*: ordering generated by the "statistical mechanisms" and ordering generated by "dynamical" interactions [24, p. 80].

We might conclude that Herbert Fröhlich [25, 26], Umezawa and Ricciardi [23, 32, 33], Karl Pribram [2–4], and Walter Freeman [22, 34], have each in their own way shown how, by focusing on "masses of excitation" and "fields of activity", in Lashley's words, naturalism may become Galilean science (see [34, 35]).

The notion of coherence and the associated mathematical formalism provided by QFT have proved to be formidable tools in the study of biological systems in general [27–30] and of the brain in particular [8, 9, 18, 36]. Before beginning the discussion of brain modeling, I will therefore introduce in the next section a few general notions of QFT.

3 Coherence: From the Microscopic to the Macroscopic

The concept of coherence is central to quantum physics, where it allows us to explain the properties of many physical systems. For example, crystals, where the atoms are confined in the crystal sites with a well-defined spatial order. Or magnets, where the elementary magnets oscillate in phase and are mainly oriented in a given direction; the resulting magnetization characterizes the system of microscopic components as a whole. Without mentioning of course quantum optics and elementary particle physics.

In general, all systems that present an ordering in space or time (e.g., oscillating in phase) are regulated by microscopic dynamics characterized by coherence.

In the examples cited above, the concept of coherence is associated with the transition from the level of elementary components (microscopic level) to the level of the behavior of the system as a whole (macroscopic level). This transition from the microscopic to the macroscopic (or mesoscopic) scale is a very important and distinctive aspect of the mathematical formalism describing the phenomenon of coherence. It gives a quantitatively well-defined meaning to the notion of the emergence of a macroscopic property out of a microscopic dynamic process so that the macroscopic system possesses physical properties that are not found at the microscopic level [37, 38]. The behavior and the physical quantities that characterize the system as a whole are thus the results of the microscopic dynamics of the elementary components. Stiffness, for example, is a property of the crystal, not of its atomic or molecular components. The latter are confined to the crystal sites and cannot move freely, as an atom not belonging to a crystal would do; that is, they lose some of their degrees of freedom. However, characterization of the system at a macroscopic level (the stiffness of the crystal, its electrical conductivity, etc.) emerges dynamically from such freezing of microscopic degrees of freedom. The order, on the other hand, whether spatial or temporal, is itself a *collective* characteristic of a set of elementary components (it makes no sense to speak of order in the case of a few elementary components). It is therefore in this sense that we speak of *macroscopic quantum systems*. Crystals and magnets are examples of macroscopic quantum systems.

It should also be emphasized that, contrary to what is sometimes erroneously stated, in many systems the dynamic regime of coherence persists over a wide range of temperatures, from thousands of degrees centigrade to quite low temperatures, below zero centigrade. For example, diamond melts at the critical temperature T_C of 3545 °C, while sodium chloride crystals, the familiar kitchen salt, melt at 804 °C; in iron, the coherence between the elementary magnets which manifests itself in the magnetized state is lost at 770 °C, while in the cobalt, this occurs at 1075 °C (the critical transition temperature from the ferromagnetic to the non-magnetic phase is called the Curie temperature). In superconductors, on the other hand, the critical temperatures are very low, not higher than about −252 °C for some niobium compounds, and about −153°C for some superconductors discovered in the second half of the 1980s, such as certain copper oxides containing bismuth. The critical temperatures for the coherence phenomenon can therefore be very low or very high (compared to the ambient temperature), depending on specific conditions and dynamic properties characteristic of the system considered.

One further remark is that the coherence phenomenon preserves the macroscopic state from perturbations coming from quantum fluctuations. The latter are unavoidable at the level of the quantum dynamics of the elementary components of the system. However, in (Glauber) coherent states, we have $\langle \Delta N \rangle / \langle N \rangle = 1/|\alpha|$, where $\langle N \rangle$ denotes the number of elementary components in the coherent state, $\langle \Delta N \rangle$ the fluctuation of $\langle N \rangle$ and $|\alpha|$ is a measure of the coherence. We find that, for high $|\alpha|$, $\langle \Delta N \rangle$ is negligible compared with $\langle N \rangle$. This shows that coherence plays a crucial role in macroscopic stability against quantum fluctuations. The need to use fields, in particular quantum fields, comes from the fact that $\langle N \rangle$ is a large number for coherent states, indeed $\langle N \rangle = |\alpha|^2$, with high $|\alpha|$.

We thus see that the observed long lifetime of ordered systems, such as crystals, magnets, superconductors, etc. ("diamonds are forever" and kitchen salt "does not expire", that is, it can be kept for years, even in outdoor storage, and it is found in salt mines) is a result of the coherent dynamics of quantum fields (this is one of the major differences between QFT and quantum mechanics (QM) where the decoherence phenomenon occurs).

The degrees of freedom of the elementary components characterize the dynamics that regulate their spatial distribution and their evolution over time, and are in general closely associated with the symmetry properties of the dynamics [39]. For example, the possibility for an atom to be placed at any point in space without inducing observable variations in the system is described as space translational symmetry. Thanks to this symmetry, a set of atoms can assume different spatial configurations equivalent to each other from the point of view of observations, therefore physically equivalent, and in this respect indistinguishable from each other. In the example of the crystal, however, the atom is no longer free to be in "any" space position, but bound to sit in a specific crystal site. We then say that there is spontaneous breakdown of the symmetry (SBS). Here, spontaneous means that the state of the crystal is dynamically selected and generated among the possible accessible states.

In summary, the crystalline order results from the breaking of space translational symmetry; *order is lack of symmetry*. The different crystalline structures that are observed (cubic, rhombohedral, etc.) correspond to different ways of breaking the symmetry in the various spatial directions.

The conclusion is that, while symmetry describes the indistinguishability between states of the system linked by a symmetry transformation, order, i.e., the breaking of symmetry, allows one to distinguish between one state and another: the possibility of distinguishing, diversity, individuality of the state emerges from the establishment of order.

Much of the physics developed since the second half of the last century is based on the mechanism of symmetry breaking and the consequent formation of ordered structures, and this is linked to the notion of coherence. Quantum field theory (not QM) provides the mathematical formalism necessary for the study of spontaneously broken symmetry theories [37, 39, 40].

The Goldstone theorem in QFT states that SBS implies the existence of long-range correlations among the system elementary constituents. The quanta of these correlation waves are called Nambu–Goldstone (NG) bosons or quanta [41].

Boson particles can occupy the same physical state in any number (unlike fermion particles, where no more than one can occupy a given state, according to the Pauli exclusion principle). When many bosons sit in the same state, one says that they are *condensed* in that state. If they are massless, as NG bosons are, at their lowest (zero) momentum, they do not supply energy to that state, which can therefore be the least energy state of the system (also called the vacuum). If the condensed bosons are in phase, i.e., the long-range correlation waves of which they are the quanta are in phase, as happens in ordered states, the ground state is a coherent condensed state.

The ground state (or vacuum) of the system is then characterized by the non-zero expectation value of a quantity, characteristic of the symmetry which has been broken, called the order parameter since it is a measure of the ordering induced by the long-range correlations. In the crystal example, it is the density, in the ferromagnets the magnetization. The order parameter is a classical field of quantum origin, meaning that it is independent of quantum fluctuations. It is indeed a measure of the coherence of the system ground state generated by the Bose–Einstein *condensation* of NG bosons [37, 39–41].

The order parameter may assume different values in a given range and it depends on the temperature. Above a critical temperature T_C, it vanishes and the *phase transition* to the symmetric state is obtained with loss of the ordered structure (symmetry restoration). See above for examples of values of T_C (in diamonds, magnets, superconductors).

QFT thus allows the description of different phases in which the system may be found. These different phases present physically different types of behavior depending on the different values of the order parameter and are described by physically different spaces of states of the system, i.e., unitarily inequivalent representations of the canonical commutation relations (CCR).

In fact, infinitely many unitarily inequivalent representations of the CCR exist in QFT. They do not exist in QM due to the von Neumann theorem, which states that, for systems with a finite number of degrees of freedom, all the representations of the CCR are unitarily (and therefore physically) equivalent. Fields by definition describe systems with an infinite number of degrees of freedom, so the von Neumann theorem does not hold for them [37, 39, 40]. Systems that may have different physical phases need therefore to be described by QFT, which may account for the multiplicity of their phases and the transitions among them, not by QM.

4 The Many-Body Model of the Brain

Lashley's dilemma and the problems arising in the study of the brain, mentioned in Sect. 2, have their origin in the huge number of brain constituents at cellular and subcellular levels and in the great complexity of their organization and dynamics. The stability of the functional activity of the brain is, on the other hand, essential in any of our activities, and even for our survival in the world. How can it arise out of the myriads of brain constituents? There are of the order of 10^{11} neurons with 10^{15} synapses, each of them able to fire about 10 pulses per second, implying around 10^{16} synaptic operations per second, without mentioning glia cells and the fact that all this happens in a bath of 90% more numerous water molecules. Each of these molecules carries an oscillating electric dipole momentum subject to unavoidable quantum fluctuations.

However, the total activity of the brain requires an energy consumption per second of the order of only 25 W. This is ridiculously small compared with the power necessary for the simulation of quite elementary tasks by one of the gigantic American or European Brain Projects, which is of the order of 1.5 MW.

As already mentioned above in quoting Ricciardi and Umezawa, one should also explain how it happens that the brain's functional efficiency is not affected by the malfunctioning or even the loss of single neurons. Metabolic activity induces chemical transformations and replacements of biomolecules in intervals of time of the order of a couple of weeks. It is then hard to explain the long and medium lifetime of memories in terms of localized arrangements of biomolecules, due to their changes and renewal in such a turn-over process.

Schrödinger observed that the "enigmatic biological stability" [24, p. 47] of living matter (but, as already said, his observation may apply to the brain, too) cannot be explained in terms of "regularities only in the average" [24, p. 78] originating from the "statistical mechanisms". According to him, this would be the "classical physicist's expectation" that "far from being trivial, is wrong" [24, p. 19].

Starting from these remarks, in 1967 Ricciardi and Umezawa observed [23]:

> […] it seems that very few concrete results have been obtained, in the sense that the question of *how the brain works out the information received from the outside, and what is the logic on which the operations performed by the brain are based* is still far from receiving a satisfactory solution. […] One possibility then arises naturally: since one usually ignores the mechanism according to which the brain performs intelligent operations, […] one could try to give a more general description of the brain dynamics; […] from a phenomenological point of view it is strongly suggestive of a quantum model. In other terms, one can try to look for specific dynamical mechanisms (already known in the physics of many degrees of freedom) which can satisfy the essential requirements of the observed functioning of the brain.

In the many-body (quantum) model of the brain formulated by Ricciardi and Umezawa (RU), they assume that the external stimulus perceived by the brain is responsible for breaking the symmetry. The density of the NG correlation quanta generated by this breaking process (see Sect. 3) is assumed to be an index or distinctive code of the memory associated with the external stimulus that induced the symmetry breaking.

The same happens in the dissipative quantum model which will be discussed below. In both models the symmetry which is broken by external stimuli has been identified with the rotational (spherical) symmetry of the molecular electric dipoles [8, 27–30, 42].

It should be emphasized that, in the RU model (and in the dissipative model), neurons and other cellular units are classical systems. The quantum variables are the vibrational modes of the electric dipoles of the aqueous matrix and of the other biomolecules present. The long-range NG correlations among them promote and sustain the assembly and disassembly of oscillating domains of neuronal populations.

It is important to note that the stimulus does not affect the internal dynamics of the brain. It only induces the spontaneous breakdown of the rotational symmetry of the dipoles of water molecules. The internal dynamics then proceeds on the basis of the physical and chemical properties of the brain, independently of the stimulus. This aspect can have a clear and direct verification in the laboratory and its description constitutes a distinctive merit of the quantum model of the brain. It also accounts for the fact that an external stimulus, even dissimilar from the one originally inducing the memorization process, can stimulate the recall of the previously recorded memory [23, 43, 44]. This explains in dynamic terms the commonly experienced phenomenon of recalling a memory in perceptual conditions that are also very different from those in which it was first memorized. Here we are referring to normal or "weak" stimuli, not of a highly stressful type, such as a shock (or also an electro-shock) able to enslave the functionality of the brain. Although the stimulus can be quite weak, it does need to be "in phase" with the brain dynamics to induce SBS.

In the RU model and its subsequent developments [45, 46], the recording of a memory induced by a stimulus was canceled by that of another memory induced by a subsequent stimulus. This memory overprinting minimized the memory capacity of the model. For reasons of simplicity, the model did not consider the fact that the brain is a system in continuous, unavoidable interaction with the environment, intrinsically open to it. "Closing" the brain means damaging its functionality, as can be observed in experiments forcing a subject into isolation. The RU quantum brain model was therefore modified to include the "openness" of its dynamics. This led to the formulation of the dissipative quantum model of the brain [8, 9].

5 The Dissipative Quantum Model of the Brain

Any attempt to describe the brain cannot ignore the continuous and reciprocal energy exchange between the brain and the environment. Knowledge of the biomolecular and cellular details is fundamental but clearly insufficient for the description of brain activity. This alone cannot take into account the property of the system of being an open system.

As we have already seen, the detailed study of the elementary components is necessary, but not sufficient. It must be supplemented by knowledge of the dynamics that governs the set of elementary components. In the case of the brain, it is a dissipative form of dynamics. This leads us to the formulation of the dissipative quantum model of the brain [8, 9].

The physical need to consider the brain and, at the same time, its environment translates into the mathematical need to "double the system" [47]: we have the brain system and the environment system. The latter, which cannot be eliminated, can be schematized as the reservoir from which everything the brain absorbs comes from, and into which everything that the brain releases is poured. The overall brain–environment system is a closed one for which the energy flow at the brain–environment boundary is perfectly balanced.

From the standpoint of the balancing of flows, the environment is therefore described in the same way as the brain is described, provided that the "flow in" is changed into "flow out", and vice versa, which is obtained algebraically by changing the sign of the time variable: the environment is, therefore, a "time-reversed" copy of the brain.

Obviously, the interaction of the brain with the environment is very complex and requires the knowledge and detection of a huge number of parameters. However, if we limit ourselves to considering only the balance of the energy flows, the description of the environment as a time-reversed copy of the brain is mathematically correct and sufficient. In this description, the environment is therefore effectively a "copy", the *Double* of the brain.

The interplay between linearity and nonlinearity plays an interesting role in the dissipative model. Phase transitions between different representations (phases) occur in a nonlinear dynamical regime (criticality). SBS implies dynamical nonlinearity through which boson condensation and coherent states are formed. Linearity holds within each phase.

Such an interplay between linearity and nonlinearity is consistent with observations showing the coexistence of wave modes and pulse modes [48–50]. Pulse activity may be observed in experiments based on linear response. On the other hand, their synchronized AM patterns exhibit log–log power density versus frequency distributions, i.e., scale-free (self-similar fractal) dynamics requiring coherence consequent to nonlinear dynamics [49, 50]. Self-similar fractal properties are indeed isomorphic to coherent states [51–53], which is consistent with the underlying coherent many-body dynamics of the dissipative model [18, 54–57].

In the brain's dynamical evolution (in its "functioning"), there are variations in the flows exchanged with its environment, and therefore the state of the brain must be continuously updated, but so also must be the description of the state of the environment to balance the energy flows. In the memory states, which are two-mode coherent states, the brain modes are permanently entangled with the doubled modes (the environment modes) [43, 44, 58]. There is therefore a continuous "reciprocal updating", a process of reciprocal back-reaction, of "dialogue" between the brain and its Double, never a monologue, never resolvable. Sometimes in the conflict between the self and the Double, the dynamics of knowing, understanding, feeling, and living develop. The reciprocal influences of each on the other require a continuous updating of their relationship. Each of them is exposed to the gaze of the other [59].

It should be observed that the entanglement relation is implied by the in-phase correlation between the modes, which does not require exchange of a messenger or information and can therefore be established instantaneously without violation of the relativity postulates. Correlation is not therefore interaction, which would require the exchange of a messenger whose speed could not then be greater than the speed of light.

Returning to the dialog between the self and the Double, it is in this 'entre-deux' that the act of consciousness has its origin [8, 9]; it summarizes in itself the experience accumulated in the past, but is made up only of the present [9, 31, 59]. In this perspective, the brain appears to be "extended", in its own functionality, beyond the limits of its anatomical configuration. Consciousness expands into the environment in which the brain is immersed.

It is essential to stress that the relationship with the Double is a dynamical relationship, not one of narcissistic mirroring. In the dissipative model, there is nothing of such a mirroring. As Desideri observes [60], referring to certain discussions on mirror neurons [61, 62], mirroring is static and is not an opportunity for learning because the action observed and the action performed are structurally equivalent. What is observed in the laboratory [22, 63], and belongs to our common experience, is the property of the brain to accumulate experience and build knowledge, that is, to learn how to have "maximum grip" on the world. For this purpose, a copy, a simple mirroring is not enough; a creative operation is needed, a mimesis, in the sense of Aristotle's Poetics, which, as Desideri stresses, concerns the possible and not what simply happens. We need the amount of imaginative indeterminacy that allows learning and also a variation of the observed action model [60]. It is remarkable that the dissipative model allows such degrees of freedom and that the learning process arising from the dialogue with the Double is formally linked to minimizing the free energy of the system.

I observe that balancing the incoming and outgoing energy flows is equivalent to setting their difference to zero. This characterizes the state of equilibrium of the overall brain–environment system. However, setting the difference between two quantities to zero leaves them totally indeterminate. The balancing operation, therefore, allows an infinite series of pairs of states of the brain and the environment, respectively, for which such a difference is zero. Each of these brain states (and the corresponding environment states in each of the pairs) corresponds to a different value of the density of the condensed quanta. Each of these densities can be considered to be the index or code for a memory. It can be shown that states with different densities are orthogonal (unitarily inequivalent, see Sect. 3) to each other, therefore without mutual interference. Memories are thus protected form reciprocal "confusion". We see that the unitary inequivalence of the QFT representations thus plays a crucial role in the memory recording process. Moreover, their being infinite in number guarantees a large memory capacity. The result is that, thanks to dissipation, we may have infinitely many non-interfering memory states. Dissipation solves the memory capacity problem. The huge memory capacity is a consequence of the fact that the brain is a dissipative, open system [8].

6 Chaotic Trajectories in the Landscape of Attractors. Errare e Pensare

From what was said above, we see that the acquisition of a "new" memory corresponds to the use of one of the infinitely many unitarily inequivalent fundamental states (vacua) to which the brain–environment system has access. We can therefore describe the set of memory states (or "memory space") as the set of such coherent fundamental states, each one labeled by the code of a specific memory. These are states of minimum energy since, in them, the difference between the incoming and outgoing energy flows is zero, as mentioned above. Moreover, they are also states of minimum free energy. They are thus states towards which the system "tends" in its evolution, as towards "attractors". The set of memory states, therefore, depicts a "landscape of attractors".

It is remarkable that the strict mathematical unitary inequivalence among the representations is smoothed out in realistic situations due to defects, impurities, and surface effects. Such an "imperfection" is most welcome since it allows the evolution of memories in time and thus the possibility of "forgetting", and memories with different lifetimes, thus short-term memories and long-term memories. Moreover, it also allows transitions, or paths, trajectories through memories (through memory states), so that correlations may arise among the attractors as the brain goes from attractor to attractor; indeed along trajectories in the landscape of attractors, dwelling more or less for a long time in each of them, never, in normal (health) conditions, being trapped there. Along each trajectory, the free energy of the system is minimal. In the dissipative model, free energy and its minimization play a crucial role. This actually controls the density of the condensate labeling each memory state.

It needs to be stressed that the acquisition of a new memory involves not only the addition of a new attractor to the landscape of attractors, but the reorganization of the entire landscape, and therefore its complete updating in the light of the new acquisition.

It is in this process that the contextualization of the new acquisition and the emergence of its *meaning* consists, which never belongs to the perceptual stimulus (to the input). It belongs to the context of the redesigned landscape of attractors, always new as a whole. The meaning content of the correlations in the space of the attractors is therefore never definitive. Meanings can always be updated, better understood, or completely changed. They are always under test. Thus there emerges a dimension of novelty, surprise, even astonishment associated with suddenly seeing something unexpected [59, 64]. In this different view [65], one must seek the genesis of the imagination, and its role in determining different trajectories in the space of attractors. We are a long way from a simple mirroring. The relationship of the brain with the world is a completely dynamic one.

The process of contextualization, in which the brain calls into question its entire experiential history, constitutes one of the most salient features of the quantum dissipative model of the brain. It faithfully describes the laboratory observations in which the subject examined, animal or man, reacts to the situations in which he finds himself undergoing the process of abstraction (or exemplification necessary for the construction of the new attractor, i.e., the balancing of flows) and of generalization (or creation of categories in establishing correlations in the landscape of attractors). In this way the flow of information exchanged in the relationship with the world becomes knowledge [31, 59, 66] and memory becomes memory of meanings, not memory of information.

Each act of recognition of the attractor landscape represents an act of intuitive knowledge, the recognition of a *collective mode*, not divisible into rational steps, thinkable but "non-computational", and not translatable into the logical framework of language [59, 67]. This feature of brain activity is perhaps consistent with von Neumann's statement [68]:

> We require exquisite numerical precision over many logical steps to achieve what brains accomplish in very few short steps.

The trajectories in the landscape of attractors, from memory to memory, can be shown to be classical trajectories, although they "connect" quantum states. Moreover, they are chaotic trajectories, that is, they are not periodic (a trajectory never intersects itself) and trajectories that have different initial conditions never intersect; rather they are (exponentially) divergent. It can be shown formally that the chaoticity of the trajectories originates from the quantum nature of the memory states [38, 43, 44].

The role of chaos described by the dissipative model is confirmed by laboratory observations. Freeman has stressed that [69]:

> 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 to the outside world and to generate novel activity patterns, including those that are experienced as fresh ideas.

It is indeed interesting to note that the chaotic characteristics of the trajectories in the landscape of the attractors favours a high perceptual resolution. In fact, minimal differences in the perception (such as can occur in the recognition of images, smells, flavors, etc.) are recognized in a short time due to the divergence of the (chaotic) trajectories. Divergent trajectories are in fact easily recognizable as different. Small differences in the initial conditions would generate non-diverging trajectories in the absence of chaoticity, and the recognition of such differences would be much more difficult.

In its temporal evolution, the brain thus appears to be a system that "lives" on many microscopic configurations described by the minimum energy states corresponding to different memories, passing from configuration to configuration (from memory to memory) in its paths in the landscape of attractors (criticality of the phase transition dynamics). Even a weak external perturbation (a weak stimulus) can induce transitions through these least-energy states. In this way, occasional (random) perturbations play an important role in complex brain activity. On the other hand, one demonstrate the connection between the doubling of the degrees of freedom mentioned above and the quantum noise of the fundamental states. Nonzero double modes may indeed allow quantum effects arising from the imaginary part of the action, which would not appear at the classical level [70].

As just observed, the role of chaos and noise predicted by the dissipative model is confirmed in laboratory observations with particular reference to the resting state of the brain, whose dynamics shows fractal self-similarity [13, 19, 51, 71].

In conditions of low degree of openness of the brain toward the environment, e.g., while dreaming, or under the effects of psychoactive substances, during meditation, or in other states of reduced sensory perception, the criticality of the dynamics is enhanced [6, 7, 72]. Chaotic trajectories through the memory space then depict visual brain experiences occurring under such conditions. Indeed, these experiences are often characterized by movie-like sequences of images, with abrupt shifts from one image pattern to another. The truthfulness and realism felt in these visual experiences can be discussed in terms of the algebra of the doubling of the degrees of freedom. In the low openness states of the brain, the self almost fails to perceive the Double as distinct and their almost complete matching introduces a sort of "truth evaluation function" out of which the truthfulness and the realism of the visual experience is confirmed by the immediate and univocal feedback [6, 7].

The strong influence on trajectories due to minimal changes in their initial conditions leads us to consider the role of "doubt" [38, 59, 73] in the dissipative model. The dialogue with the Double lives on the continuous restructuring of the landscape of attractors, and this in turn can induce, in a process of self-questioning and listening [73], weak perturbations in the initial conditions of the trajectories with the consequent manifestation of their divergence. In this process, brain activity can be induced to leave other paths or to escape entrapment ("fixations") in one or another attractor. Doubts can well be understood as wandering around the landscape of attractors caused by the uncertainties linked to its constant redrawing, induced by the seduction of new perspectives opened by the unfolding of a new trajectory, questioning certainties acquired in previous perceptive experiences. It is therefore this wandering (*errare*) in search of *the possible*, not satisfied with what simply happens [60], a characteristic trait of brain activity, of thinking (of *pensare*). This is why the brain is not a stupid star. It rather behaves as an "erratic device", a "mistake-making machine" [74].

7 AI and Mistake-Making Machines. Spartacus

A machine is by definition and by construction a device that performs a succession of temporally linked operations in a strictly predictive way, like in a chain of logical steps. A machine that fails to go through such a determined chain of steps is therefore a machine that does not work properly and must be repaired or replaced. Brain activity, on the contrary, as we have seen, proceeds by steps that do not necessarily belong to a uniquely determined chain of steps.

Perhaps we might think then of the brain as a "mistake-making machine" [74]. Our great privilege of being able to make mistakes has its roots in the fact of wandering along chaotic trajectories in the attractor landscape, out of which the unpredictability of the movements of consciousness emerges, their being unfaithful to any pre-established scheme, their inalienable subjectivity, and total autonomy. As mentioned above, in the dissipative model the origin of the chaoticity of the trajectories lies in the quantum nature of the dynamics [38, 43, 44].

In AI research, the problem for the construction of an "intelligent" machine might therefore be just the problem of constructing a device able to make mistakes, an "erratic device". It is not a machine "not properly functioning" or "out of order". Its main usefulness is not in its predictable behavior, but rather in the "novelties" appearing in its behavior. The error, or mistake needs, however, to have the character of being "exceptional" with respect to the normal or "correct" behavior of the device (by definition, its stupid or boring behavior, Aristotle's stupid star). The "novel" or "intelligent" solution to a given problem proposed by the erratic device does not belong to the list of known possible solutions to possible problems, included in the device's basic instructions. Those are the predictable solutions of, e.g., the AI automatic pilot of an airplane. Such an automatic pilot must indeed be replaced by a human pilot in the case of an unforeseen emergency, requiring a solution which is "not on the list" of the automatic pilot.

In the above remarks, the reference to mistakes is not in the sense of observer-related mistakes, but to mistakes arising intrinsically in the behavior of erratic devices, not with respect to the expectations of the observer [74].

For observer-related mistakes, it is known that the problem of "right and wrong", "true and false", resides largely in the choice of the model adopted by the observer. Within the adopted model, the theory of the errors helps in the evaluation of the mistakes, also considering the possible interferences of the observer with the measurement and the phenomenon under study. The observer-related mistakes, in their departure from the observer's expectations, may have the character of "deviation" from the correct behavior. One might even define a trivial mistake-making machine, namely a machine doing other than what is expected by a single observer, and a non-trivial mistake-making machine, doing other than what is expected by any observer [74].

For the non-observer-related mistakes, the unpredictability of the mistake implies that it “cannot be expected or unexpected in any given context” [74]. Thus it is neither a negation, nor a deviation. It is “gratuitous”, not “derivable”, thus indicating a “non-computational” activity of the device.

It is interesting to note how a certain conservative attitude, confusing novelty with deviation, experiences the novelty as an attack on one's own model (status quo) and not as an addition to this, which may result in growth and strengthening of the model itself. However, the other alternative is not excluded, namely that the pure conservative, even if he does not confuse novelty with deviation, is against any possible novelty to be on the safe side and not take the risk that the novelty may invalidate the pre-existing model in whole or in part.

Summing up, we see that an intrinsic erratic device, producing non-observer-related mistakes as described, “cannot be a Turing machine, namely an algorithm generating mistakes. Indeed, it is not possible to design an algorithm doing nothing but the expected result, even if such a result is defined to be wrong with respect to certain criteria” [74].

The question then arises whether it is possible to design non-observer-related erratic devices. Remarkably, since the non-observer-related mistake is a novelty, “an emergence” in the system behavior, such a question may also be related to the one of designing “emergence”, considered as a possible error appearing in mistake-making processes [74].

The alternative to the intrinsic erratic device would just be a prosthesis useful to help us in some of our physical or behavioral deficiencies or to improve or enhance our limited abilities (an artificial arm, possibly controlled through links to our nerves, a large capacity of memories with a only very short time needed to sort one of them out, a computer, an automatic pilot, a mobile phone, referred to as smart with a subtle sense of humor, a robot, etc.), which is more or less what AI provides at present.

Perhaps the program of constructing a conscious artificial device goes through the construction of the intrinsic erratic device. If it is ever going to be possible to build a device endowed with consciousness, it must possess all the best properties that characterize the human being: the unpredictability of his behavior, his ability to learn, but also his infidelity, his inevitable involvement with the world, and his inalienable freedom. And *he/she* must be called *Spartacus* [59, 74].

8 Concluding Remarks

Summarizing, we have seen that SBS implies the dynamical generation of long-range correlation waves among the elementary components of the system and that the associated quanta, the NG boson modes, are massless. Their coherent condensation in the system's ground state is responsible for the ordering observable there.

Symmetry corresponds to an invariance of the observable properties of the system; the system states before and after the symmetry transformation are "indistinguishable". Order, which results from a breakdown of symmetry, corresponds instead to the possibility of distinguishing the state of the system before and after the symmetry transformation; "diversity" thus arises. The scenario arising through SBS in QFT is one of great richness of *forms*. The dynamical processes leading to them, which we may refer to as *morphogenetic* processes, actually describe the dynamical generation of many different observable manifestations of the same basic dynamic equations, a "proliferation of differences" in the world around us. It is the richness of diversity, *the praise of Babel*.

Dissipative systems are not closed in on themselves. They exchange energy, momenta, mass, etc., with their environment. Then in each of them, the time translational invariance is broken, implying that the origin of the time axis cannot be freely translated, whence time is no longer a dummy variable [56, 75].

Dissipative systems are aging systems. History has its origin.

The many-body model of the brain and the dissipative quantum model of the brain were born by applying the QFT formalism of SBS to answer some of the open questions in neuroscience, as described in the sections above.

The doubling of the degrees of freedom required by the mathematical formalism for dissipative systems has led to the introduction of a "mirror in time" image of the self, or Double.

In the dialogue with the Double, knowledge is built on the basis of the experience accumulated in past perceptions. A perspective, or vision of the world, arises from this. The intentionality that determines our doing finds its root in updating a never definitive balance with the world around us, generating meanings and meaningful relationships with it.

It may happen that "the perfect exchange between inside and outside" is realized, a "favorable connection" between the self and the object. According to Desideri, this is the aesthetic experience [65]. The aesthetic one is therefore not a particular experience, nor just any experience, but [65] "it presents itself as a dimension that permeates the entire field of our experience (and the perceptual texture that configures the 'landscape')".

Recognizing such an experience determines the aesthetic judgment that "always involves the first person" [65]. The result is that of "taking a new look at the world" [65], which is not alien, but rather, a competitor with the cognitive dimension [31, 76]. The divergence of the trajectory in the landscape of the attractors in fact guarantees that the aesthetic experience is always new, and subversive compared to the consolidation of already explored landscapes. The orientation it expresses "is always awaiting renewal" [65] because the balancing of flows, of which it is an expression, is a dynamical one, never definitive [31]. The emotional response to the aesthetic experience thus possesses a performative value in the intentional arc [65]. The aesthetic experience is therefore a characteristic feature of brain dynamics [77].

Chaotic classical trajectories going through memory states characterize brain dynamics, offering the brain the ability to provide unpredictable behavior and answers to perceptual experiences. This leads us to depict the brain as an intrinsically erratic device, able to proceed by steps that are not linked by a strict, univocally determined succession. As mentioned in Sect. 6 and observed by Freeman [69], chaos does indeed play a relevant role in brain activity.

These properties of the brain's functional activity seem difficult to model within the framework of an AI research program. The same motivation for the project of an intrinsically erratic AI device is difficult to justify since such a device is in some sense just the opposite of the obedient, loyal machine pursued in actual AI projects. The perfect robot is required to be faithful and unfailing in pursuing the social, industrial, or military tasks justifying the financial efforts supporting its construction. Moreover, it needs to have a relatively short lifetime so as not to saturate the market (a key requirement already applied to smartphones, automobiles, TV sets, dishwashers, etc.). Once it has been constructed (and sold), its commercial value must tend rapidly to zero (and this is indeed the case). These realistic elements of "fragility" inherent in AI devices make it difficult for them to be more than prosthetics for some of our own physical deficiencies or disabilities, as commented in Sect. 7. Unfortunately, AI projects today are still limited to the design of "stupid stars".

I would like to close with an observation on the brain–environment frontier [78]. When the environment is made up of others, the question is: where do "I" end and where do "the others" begin? The question becomes even more radical when it comes from groups of people who feel they have a "strong identity": where do "we" end and where do "they" begin?

Can we imagine the world without others? One possible answer is: "No. We are all together, we ourselves are the others". Or the opposite answer: "Not them, just us. We come first, they are different from us". But the latter is not compatible with the openness of brain dynamics. The closure it proposes is equivalent to suicide. The others are part of our Double, too, namely of ourselves. "Their elimination" would be a self-elimination. We belong to each other; all the richness of imagination and creativity of the dialogue with the Double enters in our mutual relationship. The brain has an inherent social dimension.

Finally, it is perhaps interesting here to quote a passage from "Borges and I" [79] testifying to the broad imaginative horizon of the dialogue between the self and its Double:

> The other one, the one called Borges, is the one things happen to […] It would be an exaggeration to say that

ours is a hostile relationship; I live, let myself go on living, so that Borges may contrive his literature, and this literature justifies me […] Besides, I am destined to perish, definitively, and only some instant of myself can survive him […] Spinoza knew that all things long to persist in their being; the stone eternally wants to be a stone and a tiger a tiger. I shall remain in Borges, not in myself (if it is true that I am someone) […] Years ago I tried to free myself from him and went from the mythologies of the suburbs to the games with time and infinity, but those games belong to Borges now and I shall have to imagine other things. Thus my life is a flight and I lose everything and everything belongs to oblivion, or to him.

I do not know which of us has written this page.

References

1. Vitiello, G. (2016) Filling the gap between neuronal activity and macroscopic functional brain behavior. In R. Kozma, & W. J. Freeman (Eds.), *Cognitive phase transitions in the cerebral cortex—Enhancing the neuron doctrine by modeling neural fields* (pp. 239–249). Springer Int. Pub. Switzerland.
2. Pribram, K. H. (1971). *Languages of the brain*. Prentice-Hall, Engelwood Cliffs NJ.
3. Pribram, K. H. (1991). *Brain and perception*. Lawrence Erlbaum.
4. Pribram, K. H. (2013). *The form within: My point of view*. Prospecta Press.
5. Freeman, W. J. (1997). Nonlinear neurodynamics of intentionality. *Journal Mind Behaviour, 18*, 291–304.
6. Re, T., & Vitiello, G. (2020). Nonlinear dynamics and chaotic trajectories in brain–mind visual experiences during dreams, meditation and non-ordinary brain activity states. *OBM Neurobiology, 4*(2). https://doi.org/10.21926/obm.neurobiol.2002061.

7. Re, T., & Vitiello, G. (2020) On the brain–mind visual experiences. In *Proceedings IEEE—IJCNN, Glasgow*. https://doi.org/10.1109/IJCNN48605.2020.9207327.
8. Vitiello, G. (1995). Dissipation and memory capacity in the quantum brain model. *International Journal of Modern Physics B, 9*, 973–989.
9. Vitiello, G. (2001). *My double unveiled*. John Benjamins.
10. Lashley, K. S. (1942). The problem of cerebral organization in vision. VII, Visual mechanisms*Biological Symposia* (pp. 301–322). Jaques Cattell Press.
11. Freeman, W. J. (2001). *How brains make up their minds*. Columbia University Press.
12. Freeman, W. J. (2005). Origin, structure, and role of background EEG activity. Part 3. Neural frame classification. *Clinical Neurophysiology, 116*, 1117–1129.
13. Freeman, W. J. (2006). Origin, structure, and role of background EEG activity. Part 4. Neural frame simulation. *Clinical Neurophysiology, 117*, 572–589.
14. Freeman W. J., Gaàl G., & Jornten R.: A neurobiological theory of meaning in perception. Part 3. Multiple cortical areas synchronize without loss of local autonomy. *International Journal of Bifurcation and Chaos in Applied Sciences and Engineering, 13*, 2845–2856.
15. 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 in Applied Sciences and Engineering, 13*, 2867–2887.
16. Freeman, W. J. (2004). Origin, structure, and role of background EEG activity. *Part 1. Phase Clinical Neurophysiology, 115*, 2077–2088.
17. Freeman, W. J. (2004). Origin, structure, and role of background EEG activity. *Part 2. Amplitude Clinical Neurophysiology, 115*, 2089–2107.
18. Freeman, W. J., & Vitiello, G. (2006). Nonlinear brain dynamics as macroscopic manifestation of underlying many-body dynamics. *Physics of Life Reviews, 3*, 93–117. q-bio.OT/0511037

19. Freeman, W. J., & Vitiello, G. (2008). Dissipation, spontaneous breakdown of symmetry and brain dynamics. *Journal Physics A: Mathematical Theory*, *41*, 304042. q-bio.NC/0701053.
20. Bassett, D. S., Meyer-Lindenberg, A., Achard, S., Duke, T., & Bullmore, E. (2006). Adaptive reconfiguration of fractal small-world human brain functional network. *PNAS, 103*, 19518–19523.
21. Fingelkurts, A. A., & Fingelkurts, A. A. (2004). Making complexity simpler: Multivariability and metastability in the brain. *International Journal of Neuroscience, 114*, 843–862.
22. Freeman, W. J. (1975/2004). *Mass action in the nervous system*. Academic Press, New York.
23. Ricciardi, L. M., & Umezawa, H. (2004). Brain and physics of many-body problems. *Kybernetik, 4*, 44–48 (1967). Reprint in G. G. Globus, K. H. Pribram, & G. Vitiello (Eds.) *Brain and Being* (pp. 255–266). John Benjamins, Amsterdam.
24. Schrödinger, E. (1944). *What is life? [1967 reprint]*. Cambridge: University Press.
25. Fröhlich, H. (1968). Long range coherence and energy storage in biological systems. *International Journal of Quantum Chemistry, 2*, 641–649.
26. Hyland, G. H. (2015). *Herbert Fröhlich. A physicist ahead of his time*. AG Switzerland: Springer International Publishing.
27. Del Giudice, E., Doglia, S., Milani, M., & Vitiello, G. (1983). Spontaneous symmetry breakdown and boson condensation in biology. *Physics Letters, 95A*, 508–510.
28. 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* (FS 13), 375–400 (1985)
29. Del Giudice, E. Doglia, S. Milani, M., & Vitiello, G. (1986). Electromagnetic field and spontaneous symmetry breakdown in biological matter. *Nuclear Physics, B275* (FS 17), 185–199.

30. Del Giudice, E., Preparata, G., & Vitiello, G. (1988). Water as a free electron laser. *Physical Review Letters, 61*, 1085–1088.
31. Vitiello, G. (2008). Essere nel mondo: Io e il mio Doppio. Atque 5 Nuova Serie, 155–176.
32. Umezawa, H. (1995). Development in concepts in quantum field theory in half century. *Mathamatical Japonica, 41*(1), 109–124.
33. Vitiello, G. (2011). Hiroomi Umezawa and quantum field theory. *NeuroQuantology, 9*(3), 402–412.
34. Atmanspacher, H. (2018) Walter freeman. I did it my way. *Journal Consciousness Studies, 25*(1–2), 39–44.
35. Atmanspacher, H. (2020). Quantum approaches to consciousness. *Stanford Encyclopedia of Philosophy*. http://plato.stanford.edu/entries/qtconsciousness/.
36. Vitiello, G. (1998). Structure and function. An open letter to Patricia Churchland. In S. R. Hameroff, A. W. Kaszniak, & A. C. Scott (Eds.), *Toward a science of consciousness II. The second Tucson Discussions and debates* (pp. 231—236). Cambridge: MIT Press.
37. Umezawa, H. (1993). *Advanced field theory: Micro, macro and thermal concepts*. American Institute of Physics.
38. Vitiello, G. (2004). Classical chaotic trajectories in quantum field theory. *International Journal of Modern Physics B, 18*, 785–792.
39. Itzykson, C., & Zuber, J. (1980). *Quantum field theory*. McGraw-Hill.
40. Blasone, M., Jizba, P., & Vitiello, G. (2011). *Quantum field theory and its macroscopic manifestations*. Imperial College Press.
41. Goldstone, J., Salam, A., & Weinberg, S. (1962). Broken symmetries. *Physical Review, 127*, 965–970.
42. Jibu, M., & Yasue, K. (1995). *Quantum brain dynamics and consciousness*. Amsterdam, The Netherlands: John Benjamins.
43. Pessa, E., & Vitiello, G. (2003). Quantum noise, entanglement and chaos in the quantum field theory of mind/brain states. *Mind Matter, 1*, 59–79.

44. Pessa, E., & Vitiello, G. (2004). Quantum noise induced entanglement and chaos in the dissipative quantum model of brain. *International Journal of Modern Physics B, 18*, 841–858.
45. Stuart, C. I. J., Takahashi, Y., & Umezawa, H. (1978). On the stability and non-local properties of memory. *Journal of Theoretical Biology, 71*, 605–618.
46. Stuart, C. I. J., Takahashi, Y., & Umezawa, H. (1979). Mixed system brain dynamics: Neural memory as a macroscopic ordered state. *Foundations of Physics, 9*, 301–327.
47. Celeghini, E., Rasetti, M., & Vitiello, G. (1992). Quantum dissipation. *Annalen der Physik, 215*, 156.
48. Capolupo, A., Freeman W. J., & Vitiello, G. (2013). Dissipation of dark energy by cortex in knowledge retrieval. *Physics of Life Reviews, 10*, 8594.
49. 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*, 2198–2208.
50. Capolupo A, Kozma R, Olivares del Campo A, & Vitiello G. (2017). Bessel-like functional distributions in brain average evoked potentials. *Journal of Integrative Neuroscience, 16*, S85–S98.
51. Vitiello, G. (2009). Coherent states, fractals and brain waves. *New Mathematics and Natural Computing, 5*, 245–264.
52. Vitiello, G. (2012). Fractals, coherent states and self-similarity induced noncommutative geometry. *Physics Letters A, 376*, 2527–2532.
53. Vitiello, G. (2014). On the isomorphism between dissipative systems, fractal self-similarity and electrodynamics. Toward an integrated vision of nature. *Systems, 2*, 203–216.
54. Vitiello, G. (2015) 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*, 7–12.

55. Freeman W. J., & Vitiello, G. (2010). Vortices in brain waves. *International Journal of Modern Physics A, B 24*, 326995.
56. 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*, 7–24.
57. Vitiello, G. (2018). The brain and its mindful double. *Journal Consciousness Studies, 25*, 151–176.
58. Sabbadini, S. A., & Vitiello, G. (2019). Entanglement and phase-mediated correlations in quantum field theory. Application to brain–mind states. *Applied Science, 9*, 3203. https://doi.org/10.3390/app9153203.
59. Vitiello, G. (2004). The dissipative brain. In G. G. Globus, K. H. Pribram, & G. Vitiello (Eds.), *Brain and being* (pp. 255–266). John Benjamins.
60. Desideri, F. (2008). Del comprendere. A partire da Wittgenstein. *Atque 5 Nuova Serie*, 135–154.
61. Rizzolati, G., Fogassi, V., & Gallese, V. (2001). Neurophysiological mechanisms underlying the understanding and imitation of action. *Nature Neuroscience Reviews, 2*, 661–670.
62. Rizzolati, G., & Craighero, L. (2004). The mirror-neuron system. *Annual Review of Neuroscience, 27*, 169–192.
63. Freeman, W. J. (2005). NDN, volume transmission, and self-organization in brain dynamics. *Journal Integrative Neuroscience, 4*(4), 407–421.
64. Vitiello, G. (2006). Oggetto, percezione e astrazione in fisica. In F. Desideri & G. Matteucci (Eds.), *Dall'oggetto estetico all'oggetto artistico* (pp. 11–21). University Press.
65. Desideri, F. (2007). Il nodo percettivo e la meta-funzionalità dell'estetico. In F. Desideri & G. Matteucci (Eds.), *Estetiche della percezione* (pp. 13–24). University Press.
66. Atmanspacher, H., & Scheingraber, H. (1990). Pragmatic information and dynamical instabilities in a multimode continuous-wave dye laser. *Canadian Journal of Physics, 68*, 728–737.

67. Piattelli-Palmarini, M., & Vitiello, G. (2015). Linguistics and some aspects of its underlying dynamics. *Biolinguistics, 9*, 96–115.
68. Neumann von, J. (1958). *The Computer and the brain* (p. 63). New Haven: Yale University Press.
69. Freeman, W. J. (1991). The physiology of perception. *Scientific American, 264*, 78–87.
70. Srivastava, Y. N., Vitiello, G., & Widom, A. (1995). Quantum dissipation and quantum noise. *Annals of Physics, 238*, 200–207.
71. Freeman, W. J. (2000). *Neurodynamics*. An exploration of mesoscopic brain dynamics. Springer.
72. Alfinito, E., & Vitiello, G. (2000). Formation and lifetime of memory domains in the dissipative quantum model of brain. *International Journal of Modern Physics B, 14*, 853–868.
73. Desideri, F. (1998). L'ascolto della coscienza. Una ricerca filosofica. Milano: Feltrinelli.
74. Minati, G., & Vitiello, G. (2006). Mistake making machines. In G. Minati, E. Pessa, & M. Abram (Eds.), *Systemics of emergence: Research and development* (pp. 67–78). Springer.
75. Vitiello, G. (2016). ... and Kronos ate his sons .... In I. Licata & G. 't Hooft (Ed.), *Beyond peaceful coexistence. The emergence of space, time and quantum* (pp. 465–486). London: Imperial College Press.
76. Diodato, R. (1997). Vermeer, Góngora, Spinosa. L'estetica come scienza intuitiva. Milano: Bruno Mondatori.
77. Vitiello, G. (2015). The aesthetic experience as a characteristic feature of brain dynamics. *Aisthesis, 8*(1), 71–89. https://oajournals.fupress.net/index.php/aisthesis/article/view/859/85.
78. Vitiello, G. (2008). Campo dei fiori. In P. Poinsotte & M. Hack (Eds.) Scienza e Società (pp. 79–98). Aracne, Roma.
79. Borges J. L. (1960). Borges and I. In El hacedor, Biblioteca Borges, Alianza Editorial.