Double Trouble: Memory Formation as Emergence in the Brain

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Abstract

This essay lays out arguments in favour of considering functions of the brain as emergent phenomena arising out of neuronal interactions. The brain is modeled as a non linear, dynamical, many body, open quantum system that is constantly interacting with its environment by means of external stimuli. The phenomenon of memory formation is described by means of this model by employing quantum many body theories. Finally, experimental evidence in support of employing a quantum model of the brain, and the dissipation model in particular are laid out.

1 Introduction

Though popular culture deems it an unknowable and endlessly complex machine, we know many things about the brain and its functions. The anatomy of the brain is well understood. We know that the brain is composed of individual microscopic components, like neurons and glia cells, which are organized in terms of specific regions that are associated with specific brain functions. We also understand many details of brain chemistry and how regions of the brain respond to changes in brain chemistry. What is unclear, however, is how brain functions occur through these microscopic details. For the most part, the approach to understanding brain function has been phenomenological or experimental. The classical picture of the brain is to consider it as a collection of neurons connected in highly specific and complicated pathways, and to suppose that brain functions arise out of impulses traveling along these neuronal networks, much like a circuit board in a computer. Multiple experiments have refuted this idea. There exists evidence of continued brain activity despite severed neurons, or even severed regions of the brain, disproving the notion of specific networks being important. This evidence seems to point toward the notion of emergence of brain dynamics, as opposed to computer-like architecture (Schmidtt 1966).That is, brain functions are diffuse in the mass of neurons, rather than localized or arising out of specific network configurations.

We would like to develop a clear picture of how microscopic components and interactions between them lead to macroscopic emergent brain functions - processing external stimuli, manifesting phenomena like memory, recall, intelligence and consciousness, however we choose to define these terms. In this essay, the formation of memory "states" in the brain, in response to an external stimulus, is explored, through the quantum brain model.

1.1 Long Range Order in the Brain

Anatomically, certain functions seem to be associated with specific regions in the brain. But we know that the regions that respond to any particular stimulus aren't localized. That is, several separate regions of the brain simultaneously respond to a given stimulus, demonstrating a kind of long range correlation (John 1966). This comparison is further cemented by experimental observations that there is no single special, crucial neuron in the brain. Individual neurons don't matter - it is their combined interactions that give rise to "brain dynamics".

Umezawa and Ricciardi first suggested that these interpretations of long range order and stable, diffuse dynamics mimic the effects seen in many body physics, and proposed a model describing the brain as a quantum many body system. They also described features that any theory that aimed at fully describing brain functions must satisfy. The model focuses on explaining how the brain forms memories by recording information in response to external stimuli.

This quantum brain model posits that the brain is a system that interacts with its surroundings by means of stimuli. The system is characterized by many states that it can possibly take, which must be described by dynamical variables. These dynamical variables could be thought of as vectors in some Hilbert space, and must possess some symmetries. Each state must then be identified by means of some quantum number. It must be mentioned here that these variables are not necessarily neurons. The crucial idea is that the brain could occupy a certain state, codified by the associated quantum number, as a result of excitation by external stimuli. This would translate to formation of a memory. Since we require stability as an important criterion, it is only sensible to require that the brain takes the ground state, which maintains the defining code or quantum number, in response to a stimulus.

We can readily borrow from the language of Bose-Einstein condensation and spontaneous symmetry breaking to fully detail this model. But before describing the quantum model of memory states in the brain, it is useful to consider whether this sort of long range order can be brought about by classical models of brain dynamics. It turns out that this isn't possible. Clearly, models based on classical statistical physics can neither explain the occurrence of this order nor its stability. Another interesting property was identified by Bugoliubov, who lays out the "principle of correlation weakening" for collections of classical particles. It (heuristically) describes the dying of correlations in the infinite volume limit. That is, even if a macroscopic ordered state emerges out of a classical system, it will be unstable as correlations (and Goldstone modes) vanish. Therefore, if we accept the idea of brain dynamics in terms of long range correlations, then it has to necessarily be described by a quantum model of spontaneous symmetry breaking.

The usage of this language requires the presence of boson-like "particles" in the brain, whose interactions give rise to long range correlation, which results in regulation of brain dynamics. We will find that enforcing the bosonic nature of the fundamental quanta in the system is equivalent to minimizing the free energy functional, and hence ensures stability of the information encoded in the state of the brain.

2 Where is the "Quantum" in the Quantum Brain Model?

We must first identify the fundamental quantum dynamic elements in the problem before writing down a Hamiltonian or modeling them in any way. This model is by no means the only quantum model describing the brain. There are several papers treating the brain as a spin glass model, where the neurons take on the role of quantum objects. But there is little evidence to suggest that neurons have quantum properties. There are some idealizations where neurons are considered as objects with no definite spatial boundary - they are objects with a fuzzy cloud around them. This doesn't necessarily make them "quantum".

In this model, the fundamental quantum object is, indeed, not the neuron, but the electric dipole of the water molecule. Some literature refers to them as corticons. The only symmetry demanded of them is rotational invariance. They seem to be analogous to spin quanta. So the process of spontaneous symmetry breaking will be analogous to that in the Heisenberg spin model. The Goldstone modes that emerge out of the symmetry breaking are called DWQ or Dipole Water Quanta (sometimes referred to as symmetrons). The action of the gapless Goldstone modes is described in the next section.

It may be noted that the electric dipole of the water molecule plays an important role in determining the electrical properties of cell membranes and fluctuations in the neuronal membrane polarization. It's effects are non trivial and cannot be ignored.

There are several experiments hinting at quantum effects in the brain, particularly from early experiments investigating the source of outputs from EEGs (Electro-encephalograms). Roy John's experiments showed differences between spontaneous brain activity and brain activity evoked by stimulus, not explained by the classical picture of neural pathways. Adey And Bawin's experiments showed that brain tissue responds to electromagnetic radiation, and could even induce behavioral changes in small animals, despite the radiation being several orders of magnitude lower than the usual neural signal. Similarly the John-Bartlett experiments identified 2 components to an EEG - an exogenous component reflecting the external input, and an endogenous component reflecting memory release. These experiments were suggestive in that they show that the classical model is incomplete and that neural phenomena demand non-classical explanations.

3 The Dissipation Model

The quantum brain model, as originally proposed, can be summed up in the following way. The brain is initially in some indeterminate state, because of symmetries possessed by its dynamical variables. An external stimulus causes a spontaneous breaking of symmetry causes the brain to condense to one of infinitely many ground states, identified by a code. This code is the memory that has been recorded now. The infinitely many ground states are unitarily inequivalent, and hence, to go from one brain state to another, a phase transition has to occur.

This model has the practical disadvantage of not being able to explain memory capacity. If each memory state is a ground state inequivalent with others, there needs to be many, many symmetries to explain the fact we can commit more than one thing to memory. This is a Hilbert space of huge number of dimensions. Extending this model by means of the dissipation model makes it simpler and more plausible. The only symmetry that is demanded is the rotational symmetry of the dipole wave quanta, as explained before.

A quote from Vitiello's 1995 paper on the dissipation model is a good place to begin -

"Let us start by the (trivial) observation that "only the past can be recalled". This means that *memory printing breaks the time-reversal symmetry of the brain dynamics* and is another way to express the (obvious) fact that the brain is an open, dissipative system coupled with the external world."

That is, the brain can initially be in any one of infinitely many inequivalent vacua. Once the stimulus or information is received, the dipole rotational symmetry is spontaneously broken and the information is recorded. As a consequence of this, time reversal symmetry is also broken, since the brain cannot go back to the state in which it existed before you "knew" the information. This introduction of the notion of an "arrow of time" in the dynamics begs the question of entropy in the process. This will be addressed again once the model has been laid out.

3.1 Mathematical Formulation

The dissipation model was originally part of the thermal field theory formalism and necessarily involves doubling of degrees of freedom, or correspondingly, modes present in the system. The idea is to think of dissipation as modes of the system exchanging energy with "time reversed mirror image" modes that are coupled to it. These are the "environmental" modes. In thermal field theory, this is equivalent to a system coupled to a temperature bath. These doubled modes are required in canonically quantizing damped systems.

Therefore, let a_k and $\tilde{a}_k$ be the gapless Goldstone modes of the dipole water quanta formed after symmetry breakdown, and the environment mode respectively. Here k represents some spatial degree of freedom, like momentum. These are bosonic operators and hence, we can establish canonical commutation relations -

$$[a_k, a_l^\dagger] = \delta_k l = [\tilde{a}_k, \tilde{a}_l^\dagger] \tag{1}$$

$$[a_k, \tilde{a}_l^\dagger] = 0 = [a_k, \tilde{a}_l] \tag{2}$$

For notational convenience, we switch to the operators $A_k = \frac{1}{\sqrt{2}}(a_k + \tilde{a}_k)$ and $\tilde{A}_k = \frac{1}{\sqrt{2}}(a_k - \tilde{a}_k)$. Therefore, we have

$$[A_k, A_l^\dagger] = \delta_k l = [\tilde{A}_k, \tilde{A}_l^\dagger] \tag{3}$$

$$[A_k, \tilde{A}_l^\dagger] = 0 = [A_k, \tilde{A}_l] \tag{4}$$

The $\tilde{A}$ modes are also known as mirror modes. We can now write the Hamiltonian as

$$H = H_0 + H_I \tag{5}$$

$$H_0 = \sum_k \hbar\Omega_k (A_k^\dagger A_k - \tilde{A}_k^\dagger \tilde{A}_k) \tag{6}$$

$$H_I = i \sum_k \hbar\Gamma_k (A_k^\dagger \tilde{A}_k^\dagger - A_k \tilde{A}_k) \tag{7}$$

This is a hamiltonian of an infinite collection of damped harmonic oscillators with frequency Ω_k and coupling constant Γ_k. We can also define number operators $\mathcal{N}_{A_k} = A_k^\dagger A_k$ and $\mathcal{N}_{A_k} = \tilde{A}_k^\dagger \tilde{A}_k$. The two parts of the Hamiltonian commute and hence have the same eigenstates. The memory state is a ground state of H_0, which is, at time $t = 0$, a condensate state which satisfies $\mathcal{N}_{A_k} = \mathcal{N}_{A_k}$ for all k. Clearly, this ground state is infinitely degenerate as there are infinite ways of achieving this constraint.

Consider the set $\mathcal{N} = \{\mathcal{N}_{A_k} = \mathcal{N}_{A_k} \forall k, t = 0\}$. This set of numbers describes the memory state at the initial instant of time. And hence, is the "code" that is associated with the information recorded at $t = 0$. It describes the ground state.

For finite volume, the ground state itself can be expressed as a generalized coherent state of the lie group su(1,1) (the two mode coherent Glauber state). The reason for this representation is explained further. Therefore,

$$|0\rangle_{\mathcal{N}} = \exp(-iG)\,|0\rangle_0 = \prod_k \frac{1}{\cosh\theta_k} \exp\Big(-\tanh\theta_k J_+^{(k)}\Big)\,|0\rangle_0 \tag{8}$$

Here,

$$J_+^{(k)} = A_k^\dagger \tilde{A}_k^\dagger \tag{9}$$

$$G = -i\sum_k \theta_k (A_k^\dagger \tilde{A}_k^\dagger - A_k\tilde{A}_k) \tag{10}$$

$$|0\rangle_0 = \big|\mathcal{N}_A = 0 = \mathcal{N}_{\tilde{A}}\big\rangle \tag{11}$$

Since these are bosonic modes, we expect

$$\mathcal{N}_{A_k} = \langle 0_{\mathcal{N}}|\, A_k^\dagger A_k \,|0_{\mathcal{N}}\rangle = \frac{1}{e^{\beta E_k} - 1} \tag{12}$$

On explicitly performing the average, we find the relationship between the parameter θ_k and $\mathcal{N}_{A_k}$ to be $\mathcal{N}_{A_k} = \sinh^2\theta_k$.

Before proceeding further to see where this thesis leads, it might be useful to interpret the formulation so far. For every code $\mathcal{N}$, there exists an associated ground state $|0\rangle_{\mathcal{N}}$. $|0\rangle_{\mathcal{N}}$ and $|0\rangle_{\mathcal{N}'}$ are unitarily inequivalent representations when $\mathcal{N} \neq \mathcal{N}'$. Therefore, when a stimulus is received, the brain undergoes a spontaneous symmetry breaking to attain one of infinitely many degenerate ground states, each of which is codified by $\mathcal{N}$. Thus, the space of states splits into infinitely many unitarily inequivalent representations of canonical commuting relations. This degeneracy lies at the heart of the dissipation model's explanation of memory capacity in the brain. These inequivalent states can coexist and don't interfere. So we may think of the brain as a collection of a large number of macroscopic coherent states.

We can explore this idea further. We first identify that the modes are related by the SU(1,1) group. The su(1,1) algebra associated with it is

$$J_+^k = A^\dagger \tilde{A}^\dagger \tag{13}$$

$$J_-^k = A\tilde{A} \tag{14}$$

$$J_3^k = \frac{1}{2}(A^\dagger A + \tilde{A}^\dagger \tilde{A} + 1) \tag{15}$$

$$[J_+^k, J_-^k] = -2J_3^k \tag{16}$$

$$[J_3^k, J_\pm^k] = \pm J_\pm^k \tag{17}$$

Thus, it is suitable to write the ground state in a representation of this group. Also, analogous to SU(2), the states may be identified as simultaneous eigenstates of the Casimir operator and J_3^k as $|j, m\rangle$, $m \geq |j|$. The ground state corresponds to $j = 0$, and m indicates the splitting of the state space into inequivalent representations.

It may also be noted that this group generates the "squeeze" operation (which is essentially the time evolution of the interaction Hamiltonian), and hence, the coherent states we have written correspond to two-mode squeezed coherent states. Therefore, a succinct description of model is simply that instead of having a single microscopic coherent ground state, we have a large number of squeezed coherent states which differ from each other by their squeezing parameter.

3.2 Time evolution of the memory state

We can define, again at finite volume,

$$|0(t)\rangle_{\mathcal{N}} = \exp(-itH/\hbar)\,|0\rangle_{\mathcal{N}} = \exp(-itH_I/\hbar)\,|0\rangle_{\mathcal{N}} \tag{18}$$

$$= \prod_k \frac{1}{\cosh(\Gamma_k t - \theta_k)} \exp\Big(\tanh(\Gamma_k t - \theta_k) J_+^{(k)}\Big)\,|0\rangle_0 \tag{19}$$

This is still a Glauber state, and still a ground state. Therefore, for everyt k, $\mathcal{N}_{A_k}$ and $\mathcal{N}_{\tilde{A}_k}$ can both change, but their difference is still zero.

We note that for every time t, $\langle 0(t)_{\mathcal{N}}|0(t)_{\mathcal{N}}\rangle = 1$. When we take the continuous limit $\sum_k \to \frac{V}{(2pi)^3}\int d^3k$, and then the infinite volume limit, we see that

$$\langle 0(t)_{\mathcal{N}}|0_{\mathcal{N}}\rangle \to 0, \forall t \tag{20}$$

$$\big\langle 0(t)_{\mathcal{N}}\big|0(t')_{\mathcal{N}}\big\rangle \to 0, \forall t \neq t' \tag{21}$$

That is, in the infinite volume limit, the initial code $\mathcal{N}$ evolves to other unitarily inequivalent states. This in-equivalence is necessarily a feature of dissipation, and it makes printing of distinguishable information possible.

In reality, the brain has boundaries and doesn't have infinite volume. Therefore, these effects result in a finite lifetime for the state. It can also lead to interference between states, interpreted as "association" of memories, "confusion" etc. In fact, we notice that

$$\langle 0(t)_{\mathcal{N}}|0_0\rangle = \exp\left(-\sum_k \ln\cosh(\Gamma_k t - \theta_k)\right) \tag{22}$$

which implies, that after $t = \frac{\theta_k}{\Gamma_k}$, the ground state is reduced to $|0_0\rangle$, which is the empty state. Therefore, the memory has been "forgotten". A new memory may be printed, or the old one can be "refreshed" by making external stimuli sustain the code.

Another interesting feature of this model is the observation that

$$\frac{1}{\cosh(\Gamma_k t - \theta_k)} A_k^\dagger\,|0(t)_{\mathcal{N}}\rangle = \frac{1}{\sinh(\Gamma_k t - \theta_k)} \tilde{A}_k\,|0(t)_{\mathcal{N}}\rangle \tag{23}$$

$$\frac{1}{\cosh(\Gamma_k t - \theta_k)} \tilde{A}_k^\dagger\,|0(t)_{\mathcal{N}}\rangle = \frac{1}{\sinh(\Gamma_k t - \theta_k)} A_k\,|0(t)_{\mathcal{N}}\rangle \tag{24}$$

That is, creating a A_k mode is equivalent to destroying a tilde mode and vice versa. This has led to some interpretation that the tilde modes act like holes to the A_k modes.

3.3 Entropy and the Arrow of Time

After a bit of algebra, we can show that the ground state may also be written as

$$|0(t)_{\mathcal{N}}\rangle = \exp\left(-\frac{1}{2}S_A\right)|\mathcal{I}\rangle = \exp\left(-\frac{1}{2}S_{\tilde{A}}\right)|\mathcal{I}\rangle \tag{25}$$

where

$$|\mathcal{I}\rangle = \exp\left(\sum_k A_k^\dagger \tilde{A}_k^\dagger\right)|0_0\rangle \tag{26}$$

$$S_A = -\sum_k \{A_k^\dagger A_k \ln \sinh^2(\Gamma_k t - \theta_k) - A_k A_k^\dagger \ln \cosh(\Gamma_k t - \theta_k)\} \tag{27}$$

Similarly, we can write an expression for $S_{\tilde{A}}$. For dissipative systems, this operator can be interpreted as entropy. This implies that, at finite volume,

$$\frac{\partial}{\partial t}|0(t)_\mathcal{N}\rangle = -\frac{1}{2}\frac{\partial S}{\partial t}|0(t)_\mathcal{N}\rangle \tag{28}$$

which makes $\frac{i\hbar}{2}\frac{\partial S}{\partial t}$ the generator of time translations. Therefore, the time evolution of the state is controlled by entropy variations. It ties together the ideas of breaking of time reversal symmetry and establishing an arrow of time as mentioned before.

Since stability of the memory is essential, we study the free energy functional

$$\mathcal{F}_A = \langle 0(t)_\mathcal{N}|\,(H_A - \frac{1}{\beta}S_A)\,|0(t)_\mathcal{N}\rangle \tag{29}$$

We demand stability of the ground state at every point in time. Therefore, we demand the stationarity condition

$$\frac{\partial \mathcal{F}_A}{\partial \Theta_k} = 0, \forall k \tag{30}$$

where $\Theta_k = \Gamma_k t - \theta_k$ and $E_k = \hbar\Omega_k$. Hence,

$$\beta(t)E_k = -\ln \tanh^2 \Theta_k \tag{31}$$

This can be rearranged to give the time dependent constraint for a Bose-Einstein distribution as established before -

$$\mathcal{N}_{A_k}(t) = \sinh^2(\Theta_k) = \frac{1}{e^{\beta(t)E_k} - 1} \tag{32}$$

Thus, the free energy is at a minimum at every point in time.

3.4 Meaning and Chaos

As mentioned above, the limits in 20 and 21 show the nature of the evolution of the ground state. We could also think of this as the evolution of the code $\mathcal{N}$ through the space of representations, where each point specifies a code and hence, a unique ground state. Therefore, as the ground state evolves, we have a trajectory in representation space. These trajectories are bounded, don't intersect themselves at any point of time, and don't intersect trajectories of other initial conditions. These are classical trajectories, despite arising from a quantum ground state's time evolution. This is strictly true only in the infinite volume. So, in realistic situations, different ground states might have an overlap, leading to intersection between their trajectories. Thus, it is possible to switch from one trajectory to another at these intersections. This can be thought of as "association" of memories.

In general, if two codes $\mathcal{N}$ and $\mathcal{N}'$ differ in the parametrization of their initial conditions by a small amount $\delta\theta_k = \theta_k - \theta'_k$. We can show that their distance in representation space $\Delta\mathcal{N}_{A_k}$ diverges as $e^{2\Gamma_k t}$. That is, the trajectories are chaotic in nature. (The notion of "distance" between the trajectories of two codes can be associated with how small the difference between their parameters are for each k. This doesn't really have to do with their initial conditions).

It must also be noted that the set of vacua $\{|0(t)_{\mathcal{N}}\rangle, \forall\mathcal{N}, \forall t\}$ behave like attractors, in the sense of non-linear dynamical systems, This is clearly true, since they are all ground states of the system at specific times, for specific codes. This manifold of trajectories forms the attractor landscape for the brain dynamics. It is the space of all memories and their histories. Every new memory, or equivalently, new trajectory must be situated in the attractor landscape that already exists. The attractor landscape accounts for phenomena that is commonly termed "experience" or "accumulated knowledge". It provides context and meaning to any new information that enters the memory. That is, when a new vacuum is formed, it is placed on the manifold that exists, and the entire manifold undergoes a global update so that all the conditions and constraints are satisfied. Thus, the new memory has been "contextualized" and acquires "meaning".

3.5 Memory Recall

The process of memory recall in association with the dissipation model rests on less solid ground and seems like conjecture. It is nevertheless interesting to consider. In this context, the recall process is modeled as a replication signal. That is, the Goldstone modes are excited when the stimulus received is similar to the original imprinting stimulus. Finite size effects might prevent the modes from being gapless and present a threshold energy of sorts, interpreted as "difficulty in remembering".

The signal is called "replicating" for multiple reasons. It is replicating in the sense that it "mirrors" the original signal to bring forth a memory. But this "mirroring" can also be done by the actual mirrored modes - the tilde modes. This leads the authors to speculate if the tilde modes might be responsible for unconscious brain activity, as well as self-recognition, and even the basis for consciousness. While the idea is fascinating, it does lead one to wonder whether the authors took a pun on the word "reflection" a tad too far.

4 Experimental detection

The bulk of the experimental evidence supporting the dissipation model comes from analyzing EEG signals under the influence of conditioned stimuli (CS). To understand this evidence better, a brief description of some associated terms are defined below. The data comes from a human subject with intractable epilepsy, who had to undergo invasive neurosurgery when medication failed to help. This resulted in placement of intracranial electrodes arrays in the brain. While the therapeutic outcome and history of the subject are kept anonymous, their EEG/ECoG data has been utilized. The sensory stimulus in these readings was primarily olfactory in nature.

4.1 Reading an EEG

There are two features of the EEG data that are of interest here. They are, as described by the authors - *...the textured patterns of amplitude modulation (AM) in distinct frequency bands that are correlated with categories of conditioned stimuli (CS), and the tight sequencing of AM patterns in epochs that resemble cinematographic frames.* The proposal is to identify each spatial pattern of AM as a ground state, and the nature of its occurrence as a spontaneous symmetry breaking. Figure 1 shows a sample AM pattern. Since a series of CS are represented in the data, and the ground states obtained for them are unitarily inequivalent, we should also see evidence of phase transition between pattern frames from one state to another. Simply put, a 2D array of electrodes is placed on an area of the scalp (or the cortex, as the case may be), and the readout is taken as an array. After some signal processing involving sampling at appropriate frequencies, and digitizing the signal, it undergoes a Hilbert transform, giving an analytic amplitude and analytic phase

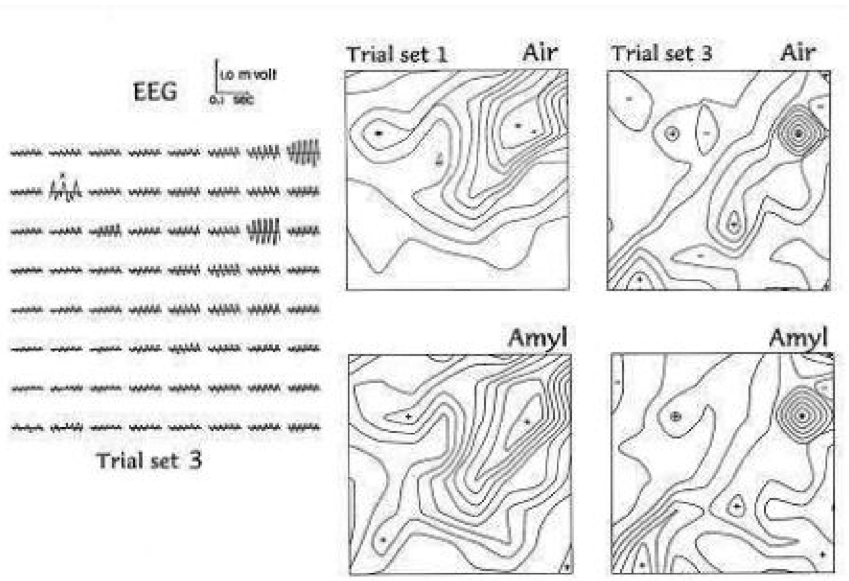

Figure 1: Left: AM waves in one frame on a carrier wave. Right: AM pattern contour plots showing invariant stimuli producing different patterns

as output for each point in time and space. The square of the analytic amplitude $A^2(t)$ is a measure of instantaneous power expended in the area. If there are n electrodes in the EEG, then these n amplitudes can be put together in the form of a vector $\mathbf{A}^2(t)$. This is the order parameter under consideration. It denotes a point in an n dimensional space, and with time, shows the formation of clusters and trajectories with time. CS that lead to clustering (defined by appropriate statistical means) are said to be of the same category. Clusters have an associated ordered AM pattern and denote an ordered wave packet. We define a normalized distance $D_e(t) = \mathbf{A}^2(t) - \mathbf{A}^2(t-1)$, which defines spatial stability of an AM pattern. We can also define $\Delta\bar{A}(t) = \bar{A}^2(t) - \bar{A}^2(t-1)$, which is the difference in the vector without normalization, and hence, simply denotes change in instantaneous power. We define the quantity $R_e(t) = \frac{\sigma_T(<\bar{A}^2(t)>_T)}{<\sigma_T(A_j^2(t))>}$. That is, the ratio of temporal standard deviation of the mean filtered EEG to the mean temporal standard deviation of the n channels. It is a measure of synchronization.

Along with measuring the analytic phase, we also measure the spatial gradient of the phase. It is convenient to do this by projecting the phase surface onto a cone. It is equivalent to a change in basis. The ratio of the spatial gradient to the temporal gradient of the phase gives the phase velocity. This phase velocity is comparable to the conduction velocity of axons, which implies that any phase delay is born out of the finite time it takes for communication through the axons. The location of the apex of the phase cone is the site at which the phase transition leading to the associated AM pattern begins. These sites are vortices that stabilize the pattern. These are explored in detail further. The sign of the phase and the phase gradient give rise to many categories of phase patterns, like expansions, contractions, rotations etc. In brief, the analytic phase gives information about the dimensions, durations and locations of the wavepackets, whereas the analytic amplitude gives information about the behavioural correlations. The phase pattern in between frames describe how the amplitude data moves, phase delays etc.

The parameters defined above indicate highly textured AM patters, that show long range correlations, within time windows smaller than the propagation delay in neurons, with sizes larger than the dimensions of neurons, all of which indicate spontaneous symmetry breaking. Also, when the system approaches a phase transition, we should see a reduction in the rate of change of the order parameter and increased oscillations in the amplitude. These can be observed from changes in $\bar{A}(t)$, $D_e(t)$ and $R_e(t)$ between frames of

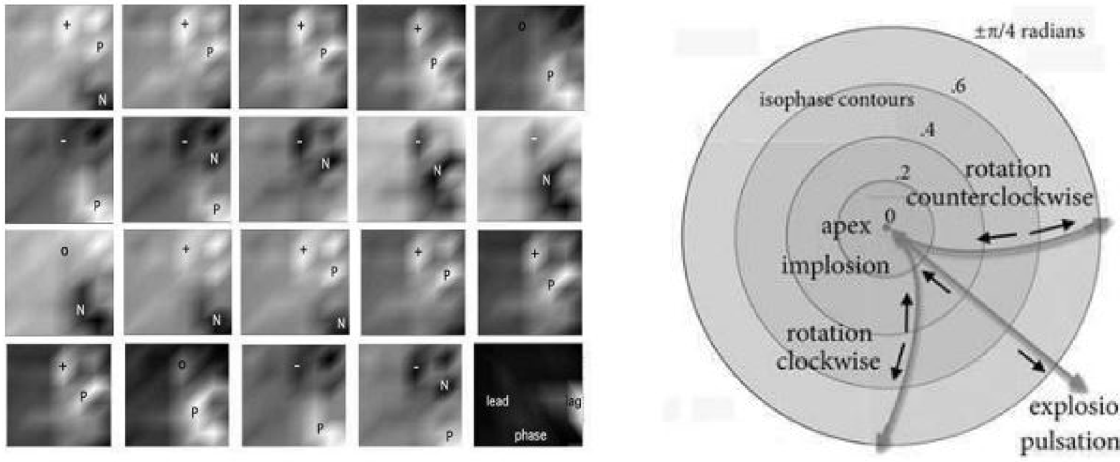

Figure 2: Left: Frames showing two overlapping AM patterns, one of which has oscillating peaks, the other is rotating with oscillating peaks. Right: The phase pattern, denoted on the phase cone, denotes the way in which the pattern behaves in time.

AM patterns. We also observe emergence of order in the phase cone, indicating phase transitions. Therefore, the brain is in a pseudo-equilibrium state of self-organized criticality. The pseudo-equilibrium denotes the fact that the order parameter is time dependent.

4.2 Conditioned Stimuli and AM patterns

As mentioned before in the attractor landscape picture, repeated trials of the same stimuli do not give rise to the same response in the brain, as the attractor landscape gets modified at every trial. This phenomenon is also experimentally observable. Successive trials of an invariant CS results in shifting of the apex of the phase cone, change in its sign etc, in a random fashion. The patterns also vary with invariant CS when the context is changed. This implies that the AM patterns are mostly functions of the many body dynamics themselves and only depend partially on the stimulus itself. Repeated trials simply result in phase transitions and time evolution of the order parameter. This agrees with our expectation out of spontaneous symmetry breaking, where the symmetry breaking field only triggers the response, and the ground state and long range order arise out of the system itself.

4.3 Phase transitions

Between AM patterns (which indicate coherence), we observe a reduction in the amplitude of the order parameter, so that the phase become indeterminate at that point of time. This is called null spike. It indicates a phase transition due to the onset of a new CS. For this reason, the null spike is associated with a vortex. This can be seen in the following way. When a spontaneous symmetry breaking occurs in the system with rotationally invariant electric dipoles, we are left with a charge density wave in the electric dipole, which can be written as

$$\sigma(x) = \sqrt{\rho(x)}e^{i\theta(x)} \tag{33}$$

This is familiar from the physics of vortices. We can associate a vector potential $a_\mu(x)$ and adopt a gauge of $\partial_\mu a^\mu = 0$. Therefore, on gauge transforming, we have

$$\theta(x) \to \theta(x) + \frac{ev^2}{Z} f(x) \tag{34}$$

$$a_\mu(x) \to a_\mu(x) - \frac{1}{e}\partial_\mu f(x) \tag{35}$$

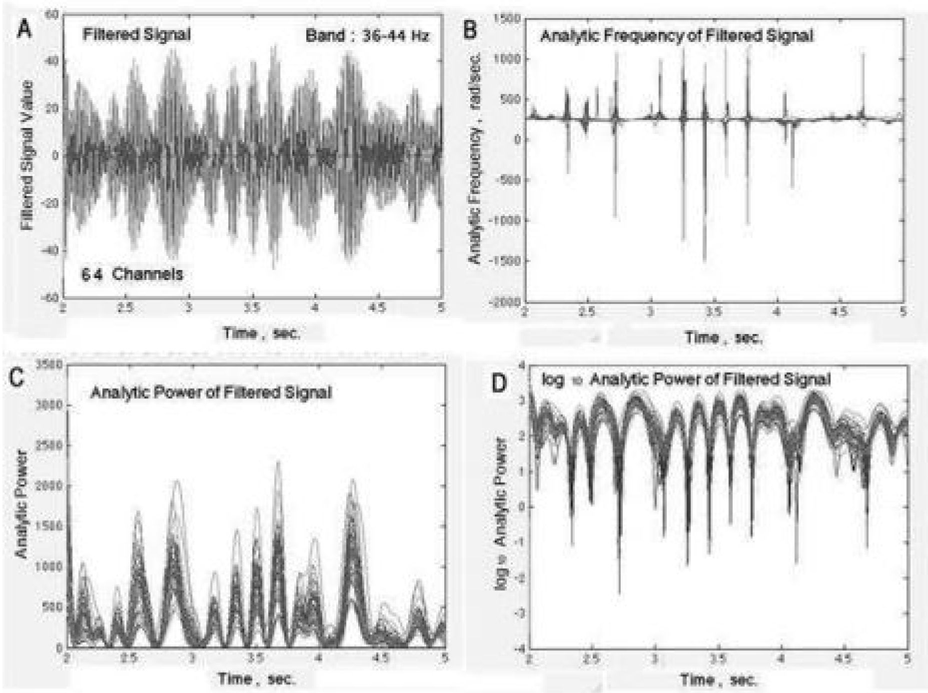

Figure 3: Null spikes seen at different stages of processing

where e is electron charge, Z is a normalization constant and v is the average charge density in the ground state. We also know that $f(x)$ has to have a singularity for non trivial solutions where there is no vector potential. This singularity corresponds to the vortex. As usual, we can impose the single valued nature of the charge density wave and see that flux is quantized as $\oint \nabla f.dl = 2\pi n$. There is a difference from the regular formalism, however, for the dissipation model. The vortex can rotate in either clockwise or anticlockwise directions. It can also grow either outward or inward. That is, there exists a "mirrored" response as well. This is inevitable, given that our model has Goldstone modes as well as their mirrored counterparts. The existence of these vortices that can be observed through the analytic phase is further evidence of the dissipation model.

5 Comments and Outlook

In 1942, Karl Lashley, one of the first people to show the non local nature of memory, wrote: *"Generalization [stimulus equivalence] is one of the primitive basic functions of organized nervous tissue. ... Here is the dilemma. Nerve impulses are transmitted from cell to cell through definite intercellular connections. Yet all behavior seems to be determined by masses of excitation. ... What sort of nervous organization might be capable of responding to a pattern of excitation without limited specialized paths of conduction? The problem is almost universal in the activities of the nervous system"*. There have been multiple efforts to explain this diffuse nature of the brain. The evidence for the occurrence of quantum phenomena in the brain is compelling and it is important to incorporate them in our models. The order and stability achieved in the brain are far beyond the explanatory powers of classical theories. At the very least, it is important to model it as a mixed system, with both classical and quantum components, as proposed by C.I.J. Stuart et al.

As for the dissipation model itself, its appearance in this context is particularly exciting, given its association with damped systems, thermal field theory, squeezed coherent states, measures of entanglement and many other rich areas. This association is primarily because of the appearance of the SU(1,1) Lie algebra, and the feature of doubling the degrees of freedom. Clearly, sharing a common algebra or similar mathematical structure doesn't really indicate similarities in physics. But there might be more to be borrowed from these areas that could be adopted in the context of the brain.

While this essay only addresses memory, there are other abstract brain functions like consciousness and intelligence that are yet to be tackled. A lot of literature in these areas veer towards philosophical discourse, since we cannot quite agree on even what we mean by these terms. Perhaps the introduction of quantum field theory to these discussions will, ironically, make them less fuzzy.

6 References

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