

A physical model of neuronal membrane excitations as a mechanism of holographic image formation in the brain

Marco Cavaglia, Jack A. Tuszynski*

DIMEAS, Politecnico di Torino, Corso Duca degli Abruzzi 24, Torino I-10129, Italy

*Correspondence: jacek.tuszynski@polito.it

DOI: <https://doi.org/10.56280/1704135468>



This article is an open access article distributed under the terms and conditions of the Creative Commons Attributions (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>)

Received: 4 July 2025

Accepted: 17 July 2025

Online Published: 21 July 2025

This paper introduces a computational model that underlies an electromagnetic theory of inter-neuronal interactions in the human brain. The hypothesis underlying this model aims to explain human perception, cognition, memory, and consciousness through an interdisciplinary approach that combines biophysics, holography, and neuroscience. The primary assumption underlying our model is that the phospholipid head groups of neuronal membranes, when exposed to the electric fields generated by propagating action potentials, may enter a metastable coherent state capable of emitting electromagnetic oscillations—a phenomenon we refer to as a lipid-centric electromagnetic wave. This is consistent with the Fröhlich theory of biological coherence. Additionally, the electromagnetic fields produced by neighboring neurons can create interference patterns that lead to the formation of holographic images. This mechanism can solve the binding problem of consciousness, where external sensory inputs are transduced into conscious perceptions.

Keywords: Membrane dipoles, electromagnetic fields, holography, action potentials, lipid-centric EM waves, biophysics

1. Introduction

Over the past century, many researchers have explored the effects of electromagnetic (EM) waves on cells and organisms leading to the development of the field called photobiomodulation (PBM). Our research presented in this paper takes a totally different approach to the examination of the interaction of EM waves and cells. Instead of investigating the effects of EM waves on biological structures, we search for mechanisms behind biological structures' use of EM waves for ultra-efficient and extremely fast storage, processing, and retrieval of data and the carrying out of functions. We investigate potential biological mechanisms that could allow for the recording of interference pattern information within biological structures, such as synapses.

Historically, information has been recorded holographically in photographic recording materials such as silver halide and photopolymer films. The recording of interference fringes themselves bears little or no resemblance to the data that are recorded within them, and yet they can reconstruct their encoded data perfectly. Holography provides the most efficient and

accurate method of storing, processing, and retrieving image data and has been demonstrated to carry out a myriad of brain functions and capabilities that no computer technology can match. We believe it is the only process that can enable the brain to accomplish what it does within such a small space, and with the expenditure of a very small amount of energy (25 J/s). Our paper aims to present a mechanistic model in which the brain can utilize holography to carry out some of its functions.

Both single neurons and their groups generate differential potentials in the extracellular medium due to the electrical currents arising from their active cellular process. The generated electric fields can be studied by extracellular electrodes (Buzsáki et al, 2012). The brain's EM waves were proposed to propagate within the cellular membrane in neuronal axons. In an ionic fluid with an electrolyte solution, a “soft material waveguide” for EM transmission can be formed (Xu et al. 2018). Since the magnetic permeability of biological tissues is similar to that of a vacuum, the magnetic field is not distorted by the scalp or skull. The source of magnetic fields is a dendritic current generated by over

50,000 pyramidal neurons that fire synchronously in parallel, while axonal and synaptic currents and magnetic fields cancel out. The amplitude of the brain's magnetic fields is smaller than 10^{-12} T (Hoseini, 2013; Singh, 2014). CSF plays a significant role in volume conductor models and current distribution, due to its relatively high electric conductivity (Latikka & Eskola, 2019; McCann et al., 2019). Living organisms tend to be favorably affected by coherent patterns of EM waves, which may induce a “biological order” (Geesink and Meijer, 2017).

In an earlier paper (Cavaglia et al., 2023), we outlined a broad structure of the holographic theory of the brain, which describes the transformation, integration, and transmission of energy between the external and internal (brain) environments. It may be applicable not only as an elucidation of normal brain function but can also provide an explanatory basis for the etiology of neurological diseases and conscious experience. It conjectures how stimuli from the physical environment are transduced by specialized cellular sensory receptors into electrical signals within neurons, and then further transformed into EM energy. These signals become integrated with other areas of the central nervous system (CNS) via specific synaptic connections and networks, which generate EM waves that can be transmitted nearly instantaneously (at the speed of light) via the cerebrospinal fluid (CSF) to distal areas within the CNS. Importantly, brain-generated EM waves can interact in neuronal membranes to form wave superposition patterns (including constructive and destructive interference) and hence generate an internal representation of external reality. The physical mechanism we propose is due to the activation of the head group dipoles in neural membranes by the action potential. We hypothesize that these EM wave interference patterns result in a structural change on neuronal membranes (i.e., synapses), similarly to holograms formed on film. The physical mechanism underlying holographic image formation is based on the Fröhlich model of biological coherence, which is briefly outlined below.

2. Revisiting the Fröhlich model of biological coherence: dipolar oscillations in neuronal membranes

Herbert Fröhlich sought evidence for frequency selection in biological systems. Starting in the late 1960s and continuing until his death in 1991. Fröhlich advocated for momentum-space correlations within substructures of a living system, such as an enzyme, a

membrane, a cell, or indeed an entire organism (Fröhlich, 1983). Interestingly, this model has never been applied to neurons, despite their perfect suitability for satisfying the prerequisites for the condensation phenomenon. They have a highly ordered geometry, large dimensions and represent excitable cells due to the presence of action potentials that supply electrical energy regularly. This dynamic order emerging in such a system would be a characteristic feature that distinguishes living systems from inanimate matter.

Fröhlich's theory of biological coherence is based on quantum interactions between dipoles of the polar head groups of cell membranes. The model requires the following pre-conditions:

- a) a continuous supply of metabolic energy (also referred to as energy pumping) above a minimum threshold level required to achieve synchronization of dynamical membrane dipole oscillations.
- b) The presence of thermal noise due to physiological temperature.
- c) Internal structural organization of the biosystem that promotes functional features.
- d) The existence of a large transmembrane potential difference.
- e) A nonlinear interaction between two or more types of degrees of freedom

The resultant coherent state is achieved due to the quantum (Bose-Einstein) condensation of dipolar vibrations. The supplied biochemical energy is channelled into a single strongly excited mode. Associated with this macroscopic quantum state is the emergence of electric polarization due to the ordering of dipoles. Fröhlich predicted the existence of coherent modes of dipolar excitation operating in the frequency range of $10^{11} - 10^{12}$ Hz, which is the microwave and terahertz range, depending on the specifics of the membrane. In this resonant frequency case, the effective interaction energy between oscillating dipoles exhibits long-range dependence on distance, r , hence, the entire biological system behaves as a giant oscillating dipole, with enormous consequences for biological function. Fröhlich argued that coherent effects involving the phospholipid head groups of biological membranes give rise to optical phonons due to the strong electric potential gradients on the order of 100 mV across the thickness of 5 nm of a membrane with a resultant electric field intensity of $1-20 \times 10^6$ V/m. These phonons were predicted to propagate at

velocities of about 10^3 m/s along the cellular membrane. Fröhlich interactions require matching frequencies of oscillation at the micrometer range, about the size of a cell. The standard electrodynamic dipole-dipole interactions are short-range molecular interactions and, therefore, of limited utility in biology, typically limited to distances on the order of several nanometers at most. However, the dynamic interactions of atomic and molecular vibrations, as described by Fröhlich, are long-range because they involve the resonance of oscillating dipoles and can extend over distances greater than the size of the cell, on the order of micrometers or more. Fröhlich compared it to the “pumping action in a laser”. The sources of energy for the induction of dipole oscillations were hypothesized to be the electric fields across cell membranes, biochemical energy sources such as ATP hydrolysis, or biophotons. Recently, three different types of Fröhlich condensation have been classified as weak, strong, and coherent (Reimers, 2009; Khrennikov, 2022). The coherent laser-like oscillation in cell membranes would require an energy input that is of the weak type, with a frequency in the THz range.

The resultant effect of biological coherence is due to the condensation of quanta of collective polar vibrations. It is a non-equilibrium property due to the interactions of the system with both the surrounding heat bath and a metabolic energy supply. This externally supplied energy is channeled into a single collective mode that becomes strongly excited. Most importantly, it relies on the nonlinearity of internal vibrational dipolar interactions. Associated with this dynamically ordered, macroscopic quantum state is the emergence of electric polarization due to the ordering of dipoles in biomolecules. Nonlinear interactions between dynamic degrees of freedom were predicted to result in the local stability of the polarized state and the long-range frequency-selective interactions between two identical systems, such as two cells or two enzymes.

In this resonant frequency case, the effective interaction energy between two oscillating dipoles exhibits long-range dependence on distance (r), dropping off as r^{-3} . Consequently, due to the resonant dipole-dipole coupling in a narrow frequency range, *the entire biological system can be seen as a giant oscillating dipole*.

The polar heads of the membrane phospholipid units refer to the phosphatidyl groups (phosphatidyl choline, phosphatidyl serine, and phosphatidyl inositol).

However, what specific molecules are theorized to oscillate is unclear, presumably these are the double-bonded phosphorous-oxygen or oxygen-carbon structures whereby the atoms of these structures coherently oscillate giving rise to optical phonons. The vibrational motions of the atoms represent the displacement of both the nuclear and electronic degrees of freedom, which alternate in a periodic fashion, moving further apart and closer together in each half-cycle. These are coherently oscillating adjacent molecules across the cell’s membrane, and possibly a similar mechanism can even involve interactions with neurons in the vicinity. The proposed role for this mechanism is to explain the possible emergence of coherence in cell biology, which would enable large-scale synchronization evident in all living systems. In our specific case, we are interested in the rapid synchronization of neuronal activities across the human brain.

The cell membrane, as described above in terms of Fröhlich long-range coherence with a given oscillation frequency, dependent on its structural integrity or rigidity, can also modulate the oscillation frequency of protein receptors embedded within the cell membrane. Importantly, cell membrane properties are affected by the state of health of the cell or even by cell death. Structural changes in neuronal membranes and the cytoskeleton in neurodegenerative diseases would have a profound impact on the generation of coherent dynamical states of membrane dipoles. Moreover, in connection with the conscious activity of neurons, anesthetic molecules are known not only to bind to cell membrane receptors but also to alter the geometrical properties of the membrane and its mechanical stiffness (Zizzi et al., 2022a, 2022b). Moreover, the receptor itself would have its characteristic frequency not initially in resonance with its ligand, for example, a hormone. The receptor’s characteristic electromagnetic oscillation frequency can, in general, be distinct from that of the cell membrane in which it is embedded. Furthermore, the state of the receptor (activated or inactive) could affect (or not) the frequency of an unattached hormone or other ligand, analogously to how a cell oscillation correlates and modulates the frequency of the embedded receptor’s oscillation. Once a receptor and ligand become bound, the receptor and attached ligand share a heavier mass and oscillate in unison, each with a shifted down (dampened) frequency. The heavier mass of the bound state of a ligand receptor can be reflected in a frequency shift downward of the oscillating atomic molecular component of the receptor and ligand now oscillating in unison. For example, a phosphorous-oxygen double

bonded structure consists of two atoms that are oscillating in unison with other like atomic molecular structures that generate an optical phonon.

It must also be said that various experiments appeared to demonstrate the sensitivity of metabolic processes to certain frequencies of EM radiation above the expected Boltzmann probability level (Prirogova et al., 2009; Adey, 1993; Cifra et al. 2015). While some of these experiments illustrate non-thermal effects in living matter that would require non-linear and non-equilibrium interactions for an explanation, no unambiguous experimental proof has been furnished to date to support Fröhlich's hypothesis regarding biological coherence.

Reimers et al. (2009) revisited the issue of the conditions for the Bose condensations of biological dipole oscillations. As mentioned above, these authors classified Fröhlich condensates into three types: weak condensates, in which profound effects on chemical kinetics are possible; strong condensates, in which an extremely large amount of energy is channeled into a single vibrational mode; and coherent condensates, in which this energy is placed in a single quantum state. Coherent condensates are shown to involve extremely large energies and cannot be produced by the Wu–Austin dynamical Hamiltonian, which provides the simplest implementation of the Fröhlich condensation model formed using mechanically supplied energy. They are most likely inaccessible in a biological environment. Hence, the Penrose–Hameroff orchestrated objective reduction (Orch OR) model (Hameroff & Penrose, 2014) and related theories of cognitive function that incorporate coherent Fröhlich condensation in the cytoskeleton as an essential element appear to be untenable. Weak condensates, however, may have profound effects on chemical and enzyme kinetics and may be generated by either biochemical energy or from the effects of radio frequency, microwave, or terahertz radiation supplied by external sources. To achieve the necessary conditions for the weak condensate, the pumping rate of energy supply must exceed the value of the so-called driving power.

The condition for weak condensation stated by Reimers et al (2009) in terms of the minimum energy pumping rate was stated as: $S = 2 \times 10^4$ kcal/mol/ps per oscillator (implying the pumping rate should be 100 kcal/mol/ps for low-frequency protein modes), which is impossibly high since it translates into an average power supply of $P = 0.7 \mu\text{W}$ per protein mode. However, the whole brain

generates $P = 25\text{W}$, consequently, with 100 billion neurons, this equals the power received by each neuron to be on average: $P = 25 \times 10^{-11} \text{ W}$ with millions of membrane dipoles per neuron. Even if one neuron represented one mode, this would represent 70 kW per brain, which is clearly unrealistically high.

However, Preto (2017) revisited the assumptions of the Bose condensation phenomenon within the Froehlich model using a semi-classical approximation. His results indicate a much less stringent requirement for this effect. The maximum rate of energy supply should be greater than $(T=100 \text{ K}) (k_B/s)$ where K is the degree Kelvin and k_B is the Boltzmann constant. Simultaneously, the rate of energy loss due to thermal interactions should be less than $20 \text{ K } k_B/s$, i.e., 5 times lower than the rate of energy supply. In this case, the condensate can form on a timescale of 10-1000 ns. Note that at the physiological temperature of 310K, this condition translates into energy supply per mode exceeding the value of:

$$(1/3) k_B T/s = 0.39 \times 10^{-23} (\text{J/K}) \times 310 \text{ K} /s = 1.2 \times 10^{-21} \text{ W}$$

Below, we show that the action potential provides such conditions for the nerve cell membrane dipoles in its phospholipid head groups.

3. Neuronal membrane dipoles, action potentials and conditions for oscillating dipole condensation

We begin by estimating the interaction energy between two neighboring dipoles μ_1 and μ_2 , in a phospholipid bilayer (Coster, 2003). The standard formula for the dipole-dipole interaction energy $V(r_{12})$ is:

$$V(r_{12}) = -\frac{\mu_1 \mu_2}{4\pi\epsilon_0 r_{12}^3} (\cos \theta_{12} - 3 \cos \theta_1 \cos \theta_2)$$

where r_{12} is the distance between the two dipoles (assumed to be $\sim 0.5 \text{ nm}$) and the angle θ_{12} between them is approximately 0. The angles θ_1 and θ_2 are approximately 90 degrees with respect to the axis along the membrane since the dipoles are aligned perpendicularly to it. The units of $V(r_{12})$ are joules. The dipole moment of each phosphate head group, μ , is estimated to be approximately between 3 and 20 debye (Yoo & Aksimentiev, 2018; Brown et al., 1961), so the dipole-dipole interaction, assuming a range of values between 5 angstroms and 1 nm for the distance, r , between the centers of these dipoles is on the order of:

$$E_{d-d} = (k/\epsilon) \mu^2 / r^3,$$

where $k=1/(4\pi\epsilon_0)=9\times 10^9$, $\epsilon=2$ (Dilker et al., 1979), so $E_{d-d}=9\times 10^{-22}$ J. Since $k_B T=4\times 10^{-21}$ J at physiological temperature, then E_{d-d} is expected to range between $0.2 k_B T$ and $71 k_B T$ depending on the specific dipole value of the head group and the packing structure of the phospholipids in the membrane. Note that these parameters may vary depending on the cell type and the ambient conditions. Note also that each group has several neighbors ($z=6$, for example, in a hexagonal lattice), so the total dipole-dipole interaction energy can exceed thermal energy by a large margin, since its effective value will then be $E_{\text{eff}}=z E_{d-d}$. Therefore, it can range between $1.2 k_B T$ and $426 k_B T$ per phospholipid group, so the total dipole-dipole interaction energy can vastly exceed thermal energy, fulfilling one of the key criteria for Fröhlich's condensate formation.

Next, we calculate the strength of the interaction energy between the action potential and the dipoles of the phospholipid head groups. Action potentials travel with speeds between 0.5 and 100 m/s (Koch, 2004) and are generated at a rate between 10 and 100 per second, so the average time between the arrival of an action potential at a given point in the neuronal membrane varies between 10 and 100 ms. The duration of each event is approximately 2 ms, during which the voltage across the membrane, ΔV , varies between -70 mV and $+40$ mV. We therefore assume the potential difference associated with each action potential event to be approximately $\Delta V=110$ mV during the pulse, which is more than 4 times as large as thermal energy $k_B T$, when “felt” by a single electric charge e since $k_B T=25$ meV.

Next, we calculate the strength of the interaction energy between the action potential and the dipoles of the phospholipid head groups. Action potentials travel with speeds between 0.5 and 100 m/s and are generated at a rate between 10 and 100 per second (Kress & Mennerick, 2009), so the average time between the arrival of an action potential at a given point in the neuronal membrane varies between 10 and 100 ms.

The duration of each event is approximately 2 ms, during which the change in voltage across the membrane, V , varies between -70 mV and $+40$ mV. We assume the potential difference to be 100 mV, which is 4 times as large as thermal energy $k_B T$, when “felt” by a single electric charge e , since $k_B T=25$ meV.

An estimate of the interaction energy between the action potential and a phospholipid dipole moment is

given by the electric field of the action potential pulse acting on the membrane dipoles, namely:

$$E_{\text{ap-d}} = -\left(\frac{dV}{dx}\right) \mu$$

where the negative gradient of the potential represents the instantaneous electric field E that causes the dipoles to reorient themselves along the field line (Starke-Peterkovic & Clarke, 2009), since dx is approximately 4 nm, the membrane thickness, we find that $E_{\text{ap-d}}=0.5 k_B T$.

We can now calculate the rate of energy pumping to the system, knowing the rate of arrival of action potentials as,

$$(5 k_B T/s) \ 1.6 k_B T/s < S = E_{\text{ap-d}}/dt < 16 k_B T/s \ (50 k_B T/s)$$

which exceeds the minimum requirement of $0.3 k_B T/s$ based on the previously expressed minimum value using a semi-classical method. In the formula above we have provided both lower and upper values on the estimated energy supply rates depending on the dipole moments of the membrane head groups and their average separation distances. The upper limits are shown in parentheses.

Next, we calculate the power delivered to the cell by the propagating action potential using the standard formula for electrical circuits:

$$P = I \Delta V,$$

where ΔV is the potential difference, and I is the ionic current. Since $\Delta V=110$ mV and I is on the order of 2 pA, we find that $P=0.2$ pW, which is a fraction of the energy supplied on average to a human cell ($100 \text{ W}/3.7\times 10^{13} \text{ cells}=3 \text{ pW}$) and even a smaller fraction for neurons, for which we estimated $P=250$ pW above. This supports the assertion that this is a reasonable amount of energy a neuron can expend on creating conditions for the sustained maintenance of Bose-Einstein condensed EM waves generated by dipole oscillations in its membrane, triggered by the arrival of action potentials at a regular rate. For a 2 ms-duration of an action potential, the amount of energy stored this way is $0.2 \text{ pW} \times 2 \text{ ms} = 0.4 \times 10^{-15} \text{ J} = 100,000 k_B T$, so a single action potential can “flip” more than $100,000$ dipoles in the phospholipid head groups and generate a coherent wave of EM oscillations. Moreover, we should stress that it is not necessarily the complete flipping of dipoles that is required, but rather dipole oscillations around their equilibrium orientations

(perpendicular to the membrane direction), which can then emit lipid-centric EM waves. We further assert that these waves generated by neighboring neurons can undergo interference phenomena, leading to the emergence of patterns like those created by holographic technology. Holographic methods proposed here have been previously described by Dolgoff (1971, 1973) to establish an EM wave interference pattern.

If we consider an $L=100\text{ }\mu\text{m}$ -long neuron, then the number of head groups, N , can be calculated approximately from the surface area of a cylinder of this length and the radius, r , of $1\text{ }\mu\text{m}$ and an approximate cross-sectional area occupied by a head group, a , to be on the order of 1 nm^2 . We then obtain $N=2\pi r \times (L/a) = 6 \times 10^8$, which is the number of phospholipid head groups in this type of axon. However, a single action potential may not need to provide energy for each dipole to be “flipped” since there are also dipole-dipole interactions already present that can contribute to the system-wide oscillations. This is then the mechanism by which a neuron generates dipolar oscillations that emit EM waves in the brain environment. We can readily calculate the power stored in such a wave using the formula:

$$\text{Intensity}=\text{Power}/\text{Area} = (1/2) \epsilon\epsilon_0 E^2$$

where E is the electric field intensity of the emitted biophotons, assuming that the propagating electric field intensity is a very small fraction (f) of the electric field across the membrane, we obtain:

$$\text{Intensity} = 0.5 f^2 \epsilon\epsilon_0 E^2.$$

The fraction f can be estimated based on the electric field, E_d , generated by a single dipole of a phospholipid head group, compared to that across the membrane, $E_m=2.5 \times 10^7\text{ V/m}$. $E_d=2k\mu/r^3$, where we used $\mu = 10$ debye and the distance $r = 1\mu\text{m} = 10^{-6}\text{ m}$, which is assumed to be the distance to the interference plane between EM fields generated by neighboring neurons. Substituting the relevant parameters, we obtain $E_d = 0.5\text{ V/m}$, and hence $f^2 = 4 \times 10^{-16}$, and we finally obtain the predicted intensity of $22 \times 10^{-13}\text{ W/m}^2$. This number appears to be realistic considering the measured values of biophotons emitted from living systems, which are reported to be in the range of 10^{-13} W/m^2 and below (Cifra et al., 2015). It is entirely plausible that only a small percentage of biophotons are released into the environment where measurements are made, with most being reabsorbed internally, as we

claim would be the case with photons used by neurons in the brain for image formation.

Although the brain produces EM fields due to neural activity, it remains unknown whether lipid-centric EM waves—if they exist—serve any functional purpose within brain dynamics. The objective is to demonstrate that a range of lipid-centric EM waves can create an interference pattern in a fluid environment representing human brain CSF physiologic conditions, and it is possible to measure their effect on neuronal membranes under *in vitro* conditions. We hypothesize that a coherent EM stimulus applied to neuronal membranes embedded in a conductive CSF medium will allow for a measurable pattern of nodes and anti-nodes interference. To determine whether we can create EM wave interference pattern under human CSF physiological conditions, and to demonstrate the biological effects of a coherent EM wave interference pattern on neuronal membrane through direct control of EM (frequency, angle, amplitude) one should try and create a basic physical model comprised of: (1) two coherent EM waves, (2) simple bath chamber containing physiologic CSF fluid environment within the cranium; (3) neuronal cell culture; and (4) EM recording sensors. EM testing parameters will be derived from data published on human physiology.

3. Lipid-centric EM wave propagation and localized emission from neurons

Neurons are cell types characterized by dynamically active states involving lipid-centric EM waves (locally propagating) that are non-radiative (even though they are extended) and preserve their shape without losing energy to the surrounding space. Such soliton-like EM models were developed by Xu et al. (2019) and Xue & Xu (2012) based on the characterization of electrolytic EM waveguide structures in the phospholipid bilayer of myelinated axons.

However, in this paper, we propose the development of a quantitative model for the generation of coherent EM waves resulting from action potentials triggering excitations of membrane dipoles in neurons. These excitations are predicted to correspond to a higher energy metastable state of the system, as predicted by Fröhlich (1983). A critical rate of action potential generation is required to maintain such a metastable, dynamically ordered state. In the case of an insufficient energy supply, as is often the case under anesthesia, for example, this state cannot be maintained (Bojak & Liley, 2005) and loss of consciousness occurs as a consequence.

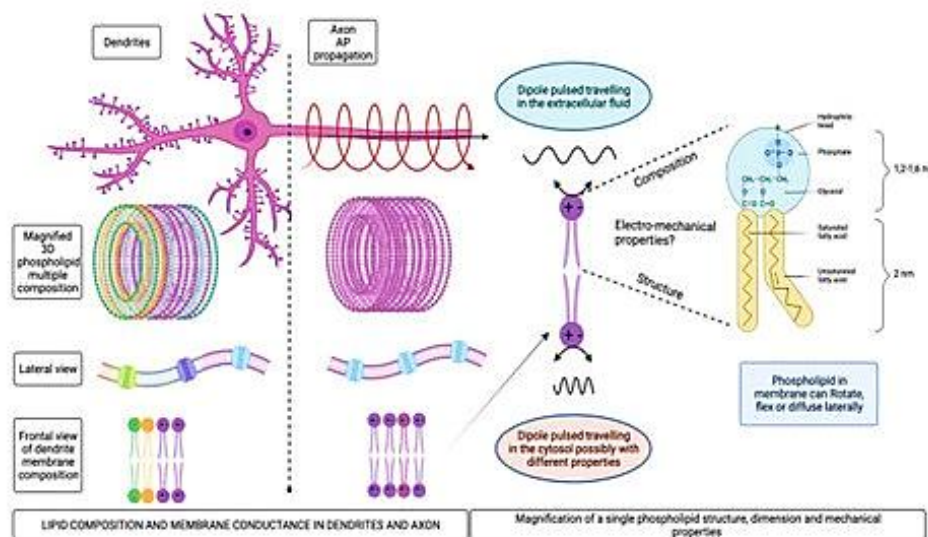
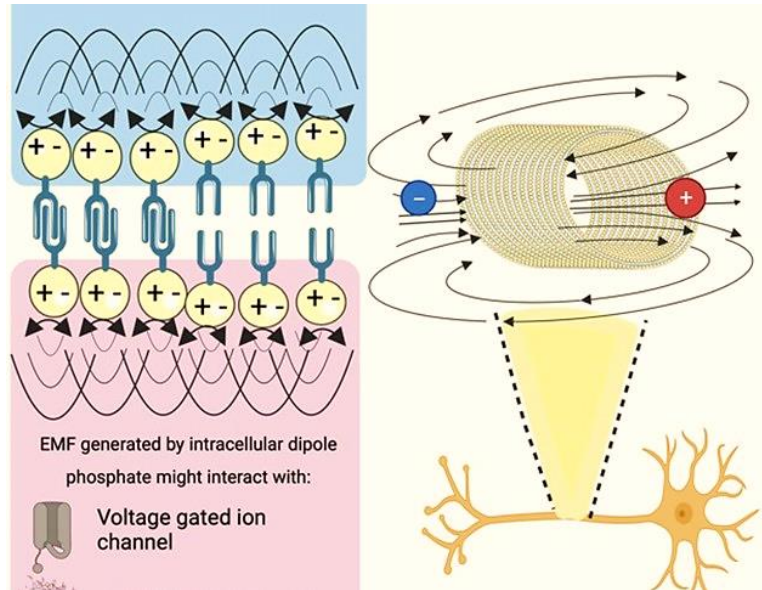


Figure 1. Schematic illustration of the mechanism of lipid-centric EM wave generation by oscillating dipoles of the phospholipid head group of the neuronal membrane, with energy supplied by action potential electric field gradients, causing long-range coherent oscillations of these dipoles (From [Cavaglia et al., 2023](#)).

Importantly, regarding the plausibility of our hypothesis, [Kumar et al. \(2016\)](#) provided conditions for neurons acting as wave guides for EM waves in the visible range. Moreover, it should be noted that spectroscopic studies ([Surovtsev et al., 2008](#)) measured the existence of two absorption peaks in phospholipid head groups in the visible and near infrared range, namely:

- (a) 1.25 μm wavelength (1.0 eV) and (b) 590 nm wavelength (2.1 eV).

- (b) The same authors also measured the acoustic wave propagation through the membrane at a speed of 2.4 km/s.

It should be noted that optimal conditions for the gain functions of an antenna of length L for EM wave of wavelength λ are $L = 1.25 \lambda$. Hence, for the operation of the neuronal segments, for example between the nodes of Ranvier, assuming the index of refraction n for the CSF ($n=1.34$) are: $L=1.25 \lambda/n$ such that $375\text{nm}<L<700 \text{ nm}$ with $400 \text{ nm}<\lambda<750 \text{ nm}$.

Importantly, the distance between nodes of Ranvier is in the 1.5 mm range while the size of each node is between 1 and 2 μm , which could fit between 2 and 10 half-wavelengths of the EM radiation in the visible range, depending on the wavelength.

The formation of holographic images is generally achieved through the constructive and destructive interference patterns of EM waves, which are designed to have specific properties and interact within a specific geometry. The information provided above should be useful in the experimental validation of the hypothesis proposed in this paper. A schematic representation of the underlying EM wave generation process is shown in **Fig. 1**.

As an important additional verification of the hypothesis, it is essential to investigate the role of anesthetic molecules. In this connection, the mechanical properties of membranes are known to change due to anesthetic binding. The membrane's bending modulus is on the order of 45 $k_B T$, but anesthetic molecules can reduce it by as much as 40% which would have a major impact on the mechanical oscillations of neuronal membranes and hence on the electro-mechanical coupling with membrane dipoles. For this reason, altering the geometrical and mechanical properties of neuronal membranes through the action of anesthetics, combined with a lower rate of action potential arrival, is expected to be sufficient to abolish the generation of sustained EM waves and eliminate their interference patterns.

4. Conclusions

In this paper, following on the hypothesis advanced in our earlier work (Cavaglia et al., 2023), we have quantitatively evaluated the conditions required for the generation of endogenous EM fields in neurons. We based our estimates on the properties of the dipoles of the phospholipid head groups in neuronal membranes and compared them to the conditions required for the formation of Bose condensates in Froehlich's biological coherence theory. The key issue addressed here was the rate of external energy supply provided in the form of electric potential gradients arriving as action potentials. Within the range of available parameter values for this system, we have concluded that it is entirely plausible for these lipid-centric EM waves to form a condensate with long-range dynamical order characteristics. Moreover, for groups of neurons in proximity, it is possible to expect that their EM waves, generated by action-potential-activated dipoles, will result in interference patterns with constructive and

destructive intensity maxima and minima, respectively. These patterns can encode information content sent to the brain via receptors and neuronal pathways. We further hypothesize that anesthesia can lead to the destruction of these patterns due to both a lower rate of energy pumping resulting from less frequent action potential activity, as well as mechanical and geometrical changes in the membranes to which anesthetic molecules bind. In this paper, we have presented the broad outlines of a quantitative model of the generation of EM waves by oscillating dipole moments in the neuronal membrane phospholipid head groups. A fully-developed mathematical model should include the cylindrical geometry of the axon as well as the interaction between dipolar degrees of freedom and the elastic deformations of the membrane. The latter aspect will likely lead to the formation of solitonic excitation waves traveling along the axon as proposed by Heimburg & Jackson (2005) and extended further by Poznanski et al. (2017). Future research should also focus on the effects on this mechanism associated with neurodegenerative pathologies, neurological disorders, exposure to psychoactive drugs, and mechanical damage caused by traumatic brain injury on the EM generated holographic images.

References

- Adey, W.R. (1993) Biological effects of electromagnetic fields. *Journal of Cellular Biochemistry* **51**, 410–416.
- Bojak, I. & Liley, D.T. (2005) Modeling the effects of anesthesia on the electroencephalogram. *Physical Review E: Statistical, Nonlinear, and Soft Matter Physics* **71**, 041902.
- Brown, T.L., Verkade, J.G. & Piper, T.S. (1961) The dipole moments of some phosphite esters and their derivatives. *The Journal of Physical Chemistry* **65**, 2051–2053.
- Butler, H.J., Ashton, L., Bird, B., Cinque, G., Curtis, K. et al., (2016) Using Raman spectroscopy to characterize biological materials. *Nature Protocols* **11**, 664–687.
- Buzsáki, G., Anastassiou, C.A. & Koch, C., (2012) The origin of extracellular fields and currents—EEG, ECoG, LFP and spikes. *Nature Reviews Neuroscience* **13**, 407–420.
- Cavaglia, M., Deriu, M.A. & Tuszyński, J.A., (2023) Toward a holographic brain paradigm: a lipid-centric model of brain functioning. *Frontiers in Neuroscience*, **17**, 1302519.
- Cifra, M., Brouder, C., Nerudová, M. & Kučera, O. (2015) Biophotons, coherence and photocount statistics: a critical review. *Journal of Luminescence* **164**, 38–51.
- Coster, H.G.L. (2003) The physics of cell membranes. *Journal of Biological Physics* **29**, 363–399.
- Dilger, J.P., McLaughlin, S.G., McIntosh, T.J. & Simon, S.A. (1979) The dielectric constant of phospholipid bilayers and the permeability of membranes to ions. *Science* **206**, 1196–1198.

- Dolgoft, G. (1971) A simplified holographic interferometric system for non-destructive testing. In *Faculty Research Award Program*, CUNY, USA.
- Dolgoft, G. (1973) Holographic brain model. In *Proceedings of the International Symposium on Holography in Biomedical Sciences*, New York, IPC Science and Technology Press, UK .
- Fröhlich, H. (1983) Coherence in biology. In *Coherent Excitations in Biological Systems*, Springer, Berlin.
- Geesink, J.H. & Meijer, D.K.F. (2017) Bio-soliton model that predicts non-thermal electromagnetic frequency bands that either stabilize or destabilize living cells. *Electromagnetic Biology and Medicine* **36**, 357–378.
- Hameroff, S.R. & Penrose, R. (2014) Consciousness in the universe: a review of the ‘Orch OR’ theory. *Physics of Life Reviews* **11**, 39–78.
- Heimburg, T., & Jackson, A. D. (2005) On soliton propagation in biomembranes and nerves. *Proceedings of the National Academy of Sciences* **102**, 9790–9795.
- Hosseini, E. (2021) Brain-to-brain communication: the possible role of brain electromagnetic fields (as a potential hypothesis). *Heliyon* **7**, 2013.
- Khrennikov, A. (2022) Order stability via Fröhlich condensation in bio, eco, and social systems: the quantum-like approach. *Biosystems* **212**, 104593.
- Koch, C. (2004) *Biophysics of Computation: Information Processing in Single Neurons*. Oxford University Press, New York.
- Kress, G.J. & Mennerick, S. (2009) Action potential initiation and propagation: upstream influences on neurotransmission. *Neuroscience* **158**, 211–222.
- Kumar, S., Boone, K., Tuszyński, J.A., Barclay, P. & Simon, C. (2016) Possible existence of optical communication channels in the brain. *Scientific Reports* **6**, 59–61.
- Latikka, J. & Eskola, H. (2019) The electrical conductivity of human cerebrospinal fluid in vivo. In *World Congress on Medical Physics and Biomedical Engineering*, June 3–8, 2018, Prague, Czech Republic, Conference Proceedings, Springer Nature Link.
- McCann, H., Pisano, G. & Beltrachini, L. (2019) Variation in reported human head tissue electrical conductivity values. *Brain Topography* **32**, 825–858.
- Pirogova, E., Vojisavljevic, V. & Cosic, I. (2009) Biological effects of electromagnetic radiation. In Carlos Alexandre Barros de Mello (ed.) *Biomedical Engineering*. IntechOpen, London, UK.
- Poznanski, R. R., Cacha, L. A., Al-Wesabi, Y. M. S., Ali, J., Bahadoran, M., Yupapin, P. P., & Yunus, J. (2017) Solitonic conduction of electrotonic signals in neuronal branchlets with polarized microstructure. *Scientific Reports* **7**, 2746.
- Preto, J. (2017) Semi-classical statistical description of Fröhlich condensation. *Journal of Biological Physics* **43**, 167–184.
- Reimers, J.R., McKemmish, L.K., McKenzie, R.H., Mark, A.E. & Hush, N.S. (2009) Weak, strong, and coherent regimes of Fröhlich condensation and their applications to terahertz medicine and quantum consciousness. *Proceedings of the National Academy of Sciences (USA)* **106**, 4219–4224.
- Singh, S.P. (2014) Magnetoencephalography: basic principles. *Annals of Indian Academy of Neurology* **17**, 20894.
- Starke-Peterkovic, T. & Clarke, R.J. (2009) Effect of headgroup on the dipole potential of phospholipid vesicles. *European Biophysics Journal* **39**, 103–110.
- Surovtsev, N.V., Salnikov, E.S., Malinovsky, V.K., Sveshnikova, L.L. & Dzuba, S.A. (2008) On the low-temperature onset of molecular flexibility in lipid bilayers seen by Raman scattering. *Journal of Physical Chemistry B* **112**, 12361–12365.
- Xu, J., Xu, Y., Sun, W., Li, M. & Xu, S. (2018) Experimental and computational studies on the basic transmission properties of electromagnetic waves in soft material waveguides. *Scientific Reports* **8**, 1–11.
- Xu, J., Xu, S., Wang, F. & Xu, S. (2019) On the delay in propagation of action potentials. *bioRxiv Preprint*.
- Xue, J. & Xu, S. (2012) Natural electromagnetic waveguide structures based on myelin sheath in the neural system. *arXiv Preprint*.
- Yoo, J. & Aksimentiev, A. (2018) New tricks for old dogs: improving the accuracy of biomolecular force fields by pair-specific corrections to non-bonded interactions. *Physical Chemistry Chemical Physics* **20**, 8432–8449.
- Zizzi, E.A., Cavaglià, M., Tuszyński, J.A. & Deriu, M.A. (2022a) Insights into the interaction dynamics between volatile anesthetics and tubulin through computational molecular modelling. *Journal of Biomolecular Structure and Dynamics* **40**, 7324–7338.
- Zizzi, E.A., Cavaglià, M., Tuszyński, J.A. & Deriu, M.A. (2022b) Alteration of lipid bilayer mechanics by volatile anesthetics: insights from μ s-long molecular dynamics simulations. *iScience* **25**, 103946.