Sobre los campos electromagnéticos cerebrales y su interacción. Un Estado Del Arte.

About Brain Electromagnetic Fields and Their Interaction. A state of the art.

Oscar Mauricio Franco Diaz

Trabajo de Grado para optar por el titulo de Licenciado en Física

Director de trabajo de grado: Julián Andrés Salamanca

Facultad de ciencias y Educación

Proyecto Curricular de Licenciatura en física

Universidad Distrital Francisco José de Caldas

2 de diciembre del 2025

A Fidel quien me acompañó sin importar las circunstancias y me animó a seguir adelante,

A mi familia con todo el amor del mundo, Noah, Laura, y mis perros,

a mi madre quien sin descanso apoyo mi camino por la ciencia y la investigación,

a mi amigo Arturo Ricaurte quien alentó mi camino en las ciencias exactas – En tu memoria –,

a mis profesores, quienes entendieron que no todas las perspectivas de las ciencias son iguales y que vale la pena arriesgarse por una idea,

a mis colegas, para que en los momentos más difíciles busquen el ímpetu para salir adelante y hacer valer todos los esfuerzos, sacrificios y retos que desde la educación pública se enfrentan, bien sea económicos, personales o de salud, pausar no es abandonar, rendirse no es una opción.

Oscar Mauricio Franco Diaz

Resumen

Esta investigación explora la actividad cerebral humana desde una perspectiva interdisciplinaria que integra neurociencia, electrodinámica, modelamiento matemático y estudios del lenguaje. Partiendo del hecho de que la actividad neuronal es inherentemente bioeléctrica, el trabajo analiza cómo los movimientos iónicos en las neuronas generan campos eléctricos y magnéticos conforme a las leyes de Maxwell. Aunque estos campos han sido ampliamente estudiados a nivel individual mediante técnicas como EEG y MEG, esta revisión propone ampliar el enfoque hacia contextos colectivos en los que múltiples individuos comparten estímulos sensoriales, emocionales y simbólicos.

Mediante una revisión sistemática de la literatura siguiendo la metodología PRISMA 2020, se sintetizaron aportes clave sobre oscilaciones neuronales, sincronización cerebral, bioelectromagnetismo y cognición social. Los resultados sugieren que la sincronización neuronal entre individuos puede dar lugar a firmas electromagnéticas emergentes, extremadamente débiles, pero físicamente plausibles, como consecuencia de la superposición de campos generados por cerebros sincronizados.

El estudio concluye que se requiere un mayor desarrollo matemático y tecnológico para modelar y medir estos fenómenos, y que su confirmación tendría implicaciones relevantes para la neurociencia, la pragmática y el análisis del discurso, al incorporar la dimensión bioeléctrica en la comprensión de la comunicación humana.

Palabras Clave: Campos electromagnéticos cerebrales (CEM), Oscilaciones neuronales, Sincronía neural colectiva, Electrodinámica del cerebro, Ecuaciones de Maxwell en neurociencia, Bioelectromagnetismo, Sistema de neuronas espejo, Resonancia social, Acoplamiento inter-

cerebral, Interferencia de ondas en la actividad neural, Superposición electromagnética, Cognición basada en resonancia, Modelos de campo neuronal, Comunicación no verbal, Firmas electromagnéticas emergentes, Pragmática y campos bioeléctricos, Electrofisiología cognitiva, Magnetometría cuántica, Cognición grupal, Arquetipos culturales y actividad neurona.

Resume:

This research examines human brain activity from an interdisciplinary perspective integrating neuroscience, electrodynamics, mathematical modeling, and language studies. Recognizing that neural activity is fundamentally bioelectrical, the study analyzes how ionic currents in neurons generate electric and magnetic fields in accordance with Maxwell's laws. While such fields have traditionally been studied at the individual level using EEG and MEG, this work extends the focus to collective contexts in which multiple individuals share sensory, emotional, and symbolic stimuli.

Using a systematic literature review based on the PRISMA 2020 methodology, key contributions on neural oscillations, brain synchrony, bioelectromagnetism, and social cognition were synthesized. The findings suggest that inter-individual neural synchronization may give rise to emergent electromagnetic signatures as a result of field superposition, which, although extremely weak, are physically plausible.

The study concludes that further mathematical development and advanced measurement technologies are required to model and empirically test these phenomena. If confirmed, such findings would have significant implications for neuroscience, pragmatics, and discourse analysis by incorporating the bioelectrical dimension into the understanding of human communication and collective cognition.

Key Words: Brain electromagnetic fields (EMFs), neural oscillations, collective neural synchrony, electrodynamics of the brain, Maxwell equations in neuroscience, bioelectromagnetism, mirror neuron system, social resonance, interbrain coupling, wave interference in neural activity, electromagnetic superposition, resonance-based cognition, neural field modeling, non-verbal communication, emergent electromagnetic signatures, pragmatics and EM fields, cognitive electrophysiology, quantum magnetometry, group cognition, cultural archetypes and neural activity.

1. Introduction

1.1. Introduction

Comprehending the human brain requires examining it as both a biological entity and a physical system. Neural activity is inherently electrochemical, propelled by the movement of charged ions that produce rhythmic electrical potentials and, consequently, electromagnetic fields (EMFs). While these domains are generally examined within a singular brain using techniques like electroencephalography (EEG) and magnetoencephalography (MEG), their conceptual and physical ramifications transcend individual cognition. The dynamics of neural oscillations indicate that brains subjected to analogous sensory, emotional, or symbolic stimuli tend to synchronize their internal rhythms. This prompts a critical inquiry: can collective neural synchrony produce emergent electromagnetic signatures in communal environments, and might these signatures affect individual experiences of communication, resonance, and group dynamics?

This study examines this question by synthesizing neuroscience, electrodynamics, linguistic theory, and social cognition. For this it puts into practice the PRISMA 2020 methodology to identify and synthesize scientific literature concerning with the generation of neural electromagnetic fields, their mathematical modeling, and their association with collective cognition. A theoretical framework is established based on Maxwell's equations, wave interference theory, neural oscillatory dynamics, and social resonance models. Particular emphasis is placed on the mirror neuron system, specifically area F5, which facilitates resonance between observed and executed actions, establishing a neurobiological foundation for imitation, empathy, and shared significance. This research suggests that extensive groups

participating in coordinated sensory experiences may generate quantifiable electromagnetic patterns as emergent properties of synchronized cognition.

The objective is neither to assert that electromagnetic fields convey semantic information between brains nor to endorse non-scientific interpretations of telepathy. The objective is to examine if collective human experience produces a physical trace that conforms to the same physical principles governing all electromagnetic phenomena. This methodology establishes a novel interdisciplinary domain wherein physics, biology, linguistics, and social sciences intersect to reevaluate the connection between individual cognition and collective experience.

1.2. Justification

The justification for this research arises from a clear scientific and conceptual gap: there is currently no unified mathematical model describing the electromagnetic fields generated by the brain, either individually or collectively. While neuroscience has thoroughly characterized ionic currents, action potentials, and oscillatory networks, the mathematical modeling of EMFs produced by these processes remains fragmented. Existing models describe neural dipoles, volume conduction, or quasi-static magnetic fields, but none integrate these elements into a framework capable of predicting how EMFs behave in naturalistic settings or in groups of individuals.

In parallel, technological limitations restrict the empirical study of such phenomena. Present-day instruments—such as EEG, MEG, and SQUID-based sensors—are designed to measure internal neural fields at the level of a single brain. They lack the spatial range, environmental stability, and sensitivity to detect extremely weak but potentially structured ambient fields generated by multiple synchronized brains in a shared space. Therefore,

advancing this field implies not only theoretical innovation but also the development of novel detection technologies, potentially incorporating quantum magnetometry or ultra-sensitive multi-sensor arrays.

Studying collective electromagnetic signatures also carries profound implications for the humanities and social sciences. If collective EMFs exist as measurable evidence of shared cognitive states, this would introduce a new physical dimension into several fields of linguistics like pragmatics, and communication theory. Human communication would need to be understood not only as symbolic and linguistic exchange but also as a phenomenon embedded in the bioelectric environment generated by the participants. This does not replace existing theories but enriches them by acknowledging the biological and physical substrates that accompany meaning-making.

Finally, although speculative at this stage, confirming the existence of structured group-level EMFs could provide a scientific basis for interpersonal phenomena historically described as intuition, resonance, or even nonverbal forms of communication. Rather than invoking metaphysics, this framework interprets such phenomena as emergent properties of synchronized neural oscillations interacting through shared sensory, cultural, and physical contexts.

For these reasons, conceptual gaps, technological needs, and interdisciplinary relevance this study is justified as a necessary step toward a more complete understanding of how brains function both individually and collectively, and how physical principles shape the very nature of human interaction.

2. Research Question and objectives

2.1. Research Question

What does current scientific evidence reveal about the generation, propagation, and potential inter-individual interactions of brain electromagnetic fields (EMFs) to the light of Maxwell's equations?

2.2. Objectives

2.2.1. General Objective

To conduct a systematic bibliographic review using the PRISMA 2020 methodology to identify, synthesize, and critically evaluate scientific literature describing the bioelectric and biochemical processes occurring in the brain. Depicting the generation and characteristics of the electromagnetic fields (EMFs) derived from such activity and their potential interactions with other magnetic fields.

2.2.2. Specific Objectives

1. To describe, through neuroscientific and biophysical literature, the mechanisms by which neurons generate ionic currents and related electromagnetic phenomena, including membrane potential dynamics, synaptic transmission and oscillatory activity.

2. To examine the theoretical and empirical possibilities for the brain to generate electromagnetic fields (EMFs) and if those can interact with other EMFs through wave laws, including resonance, interference (constructive/destructive), and propagation within conductive biological media and environmental space.

3. To analyze, through the lens of Maxwell's equations and neurophysiological models, whether neuronal currents in a group of central nervous systems may induce or modulate

activity in another system, considering mechanisms such as the mirror neuron system and field induction.

3. Theoretical and Conceptual Framework

3.1. Neurons as Electrodynamic Units

According to Carlson (2014), Iacoboni (2009), Escamilla (2007) and Brandes et al (2019), neurons as unitary cells also serve as the fundamental building blocks of the nervous system, and their activity reflects a delicate interaction between electrical, chemical, and structural properties. Although microscopic in scale, the coordinated behavior of approximately 10 million neurons in a brain gives rise to the macroscopic brain functions that support perception, emotion, memory, and cognition. Understanding neurons as electrodynamic units therefore provides an essential first step toward explaining the emergence of bioelectric and electromagnetic fields in the brain and its interaction.

3.1.1. Neurons as Electrodynamic Units

Neurons maintain their ability to generate signals by preserving differences in ionic concentration across the membrane. As detailed by Carlson (2014:47) and Brandes et al (2019:38), the intracellular and extracellular environments differ in sodium (Na^+), potassium (K^+), calcium (Ca^{2+}), and chloride (Cl^-) concentrations. These gradients create a resting membrane potential typically near −70 mV, produced through the selective permeability of the membrane and the continuous operation of the Na^+/K^+ ATPase pump which is activated by the Ca^{2+} neurotransmitters.

From a physical perspective, the neuronal membrane functions similarly to a capacitor: it stores charge and releases it when ion channels open. This can be represented according to Carlson (2014:48) by:

$$V_m = \frac{Q}{C_m} \quad (1)$$

Where each of the terms means:

- V_m= Membrane voltage,
- Q= Charge stored across the membrane,
- C_m= Membrane capacitance.

This equation shows that membrane voltage arises from charge stored on the membrane's surfaces. Any redistribution of charge produces a corresponding change in voltage, generating, based on further explanations of the behavior of electrodynamics, instantaneous electric fields tangential and perpendicular to the membrane surface.

3.1.2. Ionic Currents: Na^+, K^+, Ca^{2+} Dynamics

The creation of neural action potentials is the base of the phenomena held in the brain, according to Carlson (2014:51) The rest potential and the action potential rely on the exchange of K^+ in the interior of the membrane for Na^+ from the nearest layer of fluid on the surface of the membrane, the dynamics of the neurons was carefully studied by Hodgkin–Huxley and Katz since 1939 until 1952 and make them awarded with the Nobel price of physiatry in 1962, their framework, mathematically formalized by Cronin (1987:77), ends up with this equation that describes ion currents as:

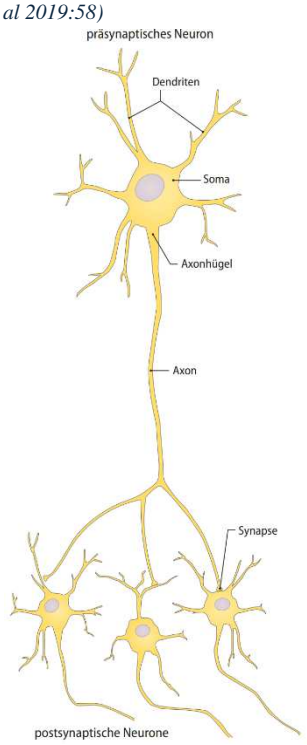
$$I_{\text{ion}} = g_{\text{ion}}(V_m - E_{\text{ion}}) \quad (2)$$

Where each of the terms means:

- I_{ion}= Ionic current
- g_{ion}= ionic conductance,
- V_m = Voltage of the membrane
- E_{ion}= Nernst equilibrium potential.

The term $V_m - E_{\text{ion}}$ renders the driving force for each ion; the Nerst equilibrium potential is a characteristic set by both the temperature and the concentration of the ions, these factors are a sort of resistance to the Voltage of the membrane V_m. A positive value drives outward flow; a negative value drives inward flow. Because these flows are movements of charged particles, they generate both electric and magnetic fields, establishing the fundamental physical basis for bioelectromagnetism Cronin (1987:77).

Figure 1. Nervenzelle im Überblick." O Descripción general de la célula nerviosa. (Brandes et al 2019:58)



Calcium plays a unique regulatory role when released at the end of an axon, that process is called Synapses, and it can be seen macroscopically as a little spark traveling from the axon to the dendrite of another neuron, localized Ca^{2+} entry at synaptic terminals triggers neurotransmitter release, thereby linking electrical events to biochemical transmission (Buzsáki et al., 2012). Its high valence and low intracellular concentrations amplify its effect on synaptic dynamics and long-range synchrony.

3.1.3. Synaptic Transmission

According to Carlson, (2014: 47) communication between neurons occurs primarily through synapses, where electrical signals are converted into chemical messages and then back into electrical changes in the postsynaptic neuron. Excitatory synapses, often mediated by glutamatergic receptors, allow the entry of positive ions that depolarize the membrane, producing excitatory postsynaptic potentials (EPSPs). Inhibitory synapses,

mediated by GABA receptors, produce inhibitory postsynaptic potentials (IPSPs) that hyperpolarize the membrane.

These potentials spread through dendrites according to the cable equation:

$$\lambda^2 \frac{\partial^2 V}{\partial x^2} - V = \tau \frac{\partial V}{\partial t} \quad (3)$$

where

- λ= space constant (how far voltage spreads),
- τ= time constant (how quickly the membrane responds).
- t= time
- V= Voltage
- x = Distance

This expression shows that synaptic potentials weaken with distance and evolve over time, meaning that the geometry of dendrites and the timing of inputs shape how signals combine. According to Brandes et al (2019:58-62) also it is important to highlight that some axon in neurons that cover the signals from the toes to the base of the spine may have a length of 1 to 1.5 meters. This is because some signals are so important for basic activities like walking, that the signal must arrive from the toes to the spine as soon as possible, and one neuron is the best mechanism, this because the subsequent synapses and potentials from one neuron to another just to reach the spine would set a considerable input lag in time for responses from the brain. Also, according to Carlson (2014:52) Many weak inputs arriving at the right place and time may sum to create an action potential, allowing the neuron to *decide* whether to fire.

Synaptic integration is therefore not only electrical but computational. As Chatterjee and Coslett (2014: cf. 11 and 30) point out, these interactions set the foundation for perceptual processes, cognitive representations, and the emergence of complex mental structures.

3.1.4. Oscillations and Neural Synchrony

Neural oscillations arise from cycles of excitation and inhibition within and between neural populations. These oscillations span a wide range of frequencies, delta, theta, alpha, beta, and gamma, each associated with distinct cognitive functions. Of particular interest, high-gamma oscillations (>60 Hz) have been linked to memory formation, perceptual grouping, and higher-order processing (cf. Mastaller et al.,2010).

Oscillatory activity can generally be described according to Denis G. Zill in his book about differential equations by (Zill, 1997:69):

$$\psi(t) = A\sin(\omega t + \phi) \tag{4}$$

Where each of the terms means:

- A= amplitude,
- t= time,
- ω= angular frequency,
- ϕ= phase offset.

This function captures the rhythmic nature of nature, thus neural activity is defined as oscillatory systems, thus fulfilling the characteristics of waves. When two neurons or two brain regions share similar frequencies and phases, they synchronize. Phase synchrony increases the probability of simultaneous firing, creating functional connections that can span long distances in the brain.

Nunez and Srinivasan (2006: cf. 131-134) emphasize that many neural oscillations behave like waves that propagate across cortical surfaces. In his thesis of 1999 Escamilla mathematically demonstrated that these waves follow quasi-two-dimensional propagation laws influenced by the curvature of the cortex and the alignment of pyramidal neurons. In

this view, oscillations constitute both electrical activity and a subtle electromagnetic field, establishing the basis for interactions measurable at the scalp.

3.1.5. Neural Networks as Large-Scale Oscillatory Systems

When neurons connect into networks, their collective dynamics resemble a system of coupled oscillators. These networks exhibit organized activity patterns that extend across multiple spatial scales. Escamilla (1999:) formalized this behavior using a wave-damping equation:

$$\frac{\partial^2 \Psi}{\partial t^2} + a\frac{\partial \Psi}{\partial t} = c^2 \nabla^2 \Psi + S(t) \quad (5)$$

Where each of the terms means:

- Ψ= field variable describing network activity,
- a= damping coefficient,
- c= propagation speed,
- $S(t)$= driving source term.

This equation shows how neural activity can spread across the cortex, weaken over time, and be continually regenerated by underlying neuronal drivers. It explains the presence of traveling waves seen in EEG/MEG recordings and supports the idea that the brain forms an integrated oscillatory system.

Buzsáki's ensemble theory (2012) supports this view by describing how coherent oscillations bind widely distributed neurons into functional units capable of rapid communication. Studies of cortical connectivity like (De la Iglesia et al, 2011) reinforce the idea that the brain's network architecture naturally supports synchrony through a combination of modularity, small-world connectivity, and long-range pathways.

Together, these findings position neural networks not only as information-processing systems but also as generators and coordinators of structured electric and magnetic fields. These fields reflect underlying neural dynamics and form the physical substrate shown in the sections 3.2, 3.3 and 3.4 of this theoretical framework.

3.2. Bioelectromagnetic foundations

The brain's electrical activity does not remain confined to the intracellular space. Whenever charges move, whether through ionic channels, dendritic trees, or axonal projections, they generate both electric and magnetic fields. The field properties that arise from these biological currents obey the same physical laws that govern electromagnetic phenomena elsewhere in nature, although they must be interpreted in the specific context of conductive tissue, geometric constraints, and low-frequency dynamics. Classical electromagnetism, therefore, becomes an essential framework for describing the physical consequences of neuronal signaling (cf. Malmivuo & Plonsey, 1995 and Lorrain & Corson, 1988).

3.2.1. Electric Fields in Biological Tissue

Taking into account the ideas presented in 1995 by Malmivuo & Plonsey, Intracellular and extracellular media in the brain behave as volume conductors, meaning that electric fields spread through the tissue according to the distribution of conductivities. Brain tissue is neither homogeneous nor isotropic; its structure, with aligned pyramidal neurons, myelinated fibers, and layered laminar organization, creates directional preferences in how currents flow.

The electric field **E** is defined by James Clerk Maxwell, as cited in Lorrain & Corson (1988:492):

$$\mathbf{E} = -\nabla\phi \tag{6}$$

Where each of the terms means:

- ϕ= electric potential.

The electric field renders the spatial rate of change of voltage. In brain tissue, electric fields often arise from synchronized postsynaptic potentials, especially in aligned pyramidal neurons whose geometry gives rise to dipole-like configurations detectable at the scalp.

According to Brandes et al (2019:70) in the brain, conductivity depends on the orientation of fibers and tissue composition. White matter is more conductive longitudinally, while extracellular space has more isotropic behavior. This heterogeneity shapes how electric fields propagate and form the foundation for interpreting EEG signals.

3.2.2. Magnetic Fields Generated by Neuronal Currents

Every movement of charge generates a magnetic field, and neuronal currents are no exception. Dendritic currents, though small, produce magnetic fields strong enough to be measured outside the skull using magnetoencephalography (MEG). These fields are governed by the Biot–Savart law (Lorrain & Corson, 1988):

$$\mathbf{B}(\mathbf{r}) = \frac{\mu_0}{4\pi}\int \frac{I\, d\mathbf{l}\times(\mathbf{r}-\mathbf{r}')}{|\mathbf{r}-\mathbf{r}'|^3} \tag{7}$$

Where each of the terms means:

- $\mathbf{B}(\mathbf{r})$= magnetic field at location $\mathbf{r}$,
- I= current through the neuronal segment,
- $d\mathbf{l}$= differential element of the current path,

- $\mathbf{r}'$= location of current element,
- μ_0= permeability of free space.

This expression shows that magnetic fields depend on both the strength and orientation of neuronal currents. Because magnetic fields pass through biological tissue with minimal distortion, MEG has high spatial precision for detecting synchronized intracellular currents.

Thus, even though individual neuronal magnetic fields are extremely weak (femtotesla range), collective synchronous activity generates macroscopic patterns that reflect underlying neural dynamics (cf. Malmivuo & Plonsey, 1995; Buzsáki et al., 2012).

3.2.3. Maxwell's Equations in the Quasi-Static Approximation

According to Buzsáki et al (2012). neural activity unfolds within a regime of low frequencies (1–300 Hz), slow charge dynamics, and highly resistive conductive media. Under these conditions, the electromagnetic behavior of brain tissue differs significantly from the behavior of electromagnetic waves in free space. Classical electrodynamics, as presented by Lorrain and Corson (1988), shows that the full Maxwell system reduces to a simplified form whenever the spatial and temporal scales of interest prevent the formation of propagating electromagnetic waves. This low-frequency, near-field regime is precisely where the brain operates.

As presented by Lorrain and Corson (1988:492) the general form of Maxwell's equations are:

$$\begin{aligned} \nabla \cdot \mathbf{E} &= \frac{\rho}{\varepsilon_0}, \\ \nabla \cdot \mathbf{B} &= 0, \\ \nabla \times \mathbf{E} + \frac{\partial \mathbf{B}}{\partial t} &= 0, \\ \nabla \times \mathbf{B} - \frac{\mathbf{1}}{\boldsymbol{c^2}} \frac{\partial \mathbf{E}}{\partial t} &= \mu_0 \mathbf{J} \end{aligned} \tag{8}$$

At the frequencies relevant to brain activity, the term

$$\mu_0 \varepsilon_0 = \frac{\partial \mathbf{E}}{\partial t} \tag{9}$$

Known as the displacement current, becomes negligible compared to μ_0J. Lorrain and Corson (1988) emphasize that this occurs because the time-varying electric fields in such media are too slow to generate appreciable electromagnetic radiation. Also in neural tissue, magnetic fields originate almost entirely from conduction as a result, brain modeling adopts the quasi-static approximation, simplifying Maxwell's equations to a form appropriate for neural dynamics (Malmivuo & Plonsey, 1995):

Faraday's law:

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

Ampère's law (quasi-static):

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{J} \tag{10}$$

Gauss's law for electricity:

$$\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0}$$

Gauss's law for magnetism:

$$\nabla \cdot \mathbf{B} = 0$$

These equations describe how electric and magnetic fields arise from charges and currents. In the brain:

J is primarily the intracellular axial current within dendrites.

$\nabla \times \mathbf{B} = \mu_0 \mathbf{J}$ explains MEG sensitivity to intracellular currents.

$\nabla \cdot \mathbf{E}$ relates to charge accumulation near membranes.

In neural tissue, magnetic fields originate almost entirely from conduction currents (primarily intracellular axial currents). This simplification has profound consequences:

It explains why magnetic fields generated by neurons do not propagate as waves but remain confined to the near-field region (Lorrain & Corson, 1988; Malmivuo & Plonsey, 1995).

It allows MEG to accurately reflect the geometry and synchrony of intracellular currents (Maestú et al., 1999; Zhang et al., 2014).

It supports quasi-static models used in both EEG and MEG forward calculations (Escamilla, 1999; Urrestarazu & Iriarte, 2005).

Escamilla's perspective clarifies that the brain is not an antenna emitting waves but rather a conductive medium where field interactions are diffusion-like**,** not radiative. Electric fields remain bound to charge distributions and membrane interfaces, while magnetic fields arise locally from the curl of current densities. This electrodynamic insight

helps unify the physical understanding of why the brain's signals are measured as potential (EEG) and near-field magnetic flux (MEG) rather than as free-space electromagnetic waves.

3.2.4. Volume Conduction and the EEG Forward Model

In EEG, the electrical potentials measured at the scalp result from the spread of intracellular and extracellular currents through conductive tissue layers. This phenomenon—**volume conduction**—is governed by the physical principles described in classical electrodynamics and adapted to biological media by Malmivuo and Plonsey (1995). When neuronal populations generate primary currents, these currents induce secondary currents in surrounding tissue, producing a distribution of electric potentials described by Poisson's equation:

$$\nabla \cdot (\sigma \nabla \phi) = \nabla \cdot \mathbf{J_p} \tag{11}$$

where

ϕ= electric potential,

σ= conductivity tensor of tissue,

$\mathbf{J_p}$= primary dipolar neuronal current.

This equation reflects how voltage spreads in a conductive medium. Because brain tissue is inhomogeneous and anisotropic, the conductivity tensor varies across scalp, skull, cerebrospinal fluid, and cortical layers. These variations shape the attenuation and distribution of potential (Malmivuo & Plonsey, 1995).

From an electrodynamic view, Lorrain and Corson (1988) emphasize that Ohmic media impose strong constraints on electric field propagation thus, neural tissue follows this principle closely. As a result:

- Electric fields do not propagate as waves; instead, they diffuse through the medium.
- Potentials at the scalp are weighted sums of primary and secondary currents; changes in geometry (skull thickness, cortical folding) distort electric field lines.

The classic dipole approximation used in EEG derives directly from this electrodynamic interpretation. Pyramidal neurons, aligned perpendicularly to the cortical surface, form effective dipoles whose orientations determine the detectability of their fields at the scalp (Buzsáki et al., 2012; Escamilla, 1999).

Volume conduction models—whether spherical, layered, or realistic—are therefore expressions of Maxwell's equations applied within the constraints of conductive, low-frequency biological media. As the skull acts as a high-impedance barrier, high-frequency components attenuate more, explaining why EEG predominantly reflects synchronized synaptic potentials rather than action potentials (Urrestarazu & Iriarte, 2005; Walter & Walter, 1949).

In this sense, the EEG forward problem is not simply a neurophysiological model but also a direct application of electrodynamics: how currents spread, how potentials redistribute, and how conductive geometry shapes the observable electrical landscape.

Electric potentials generated by neuronal currents spread through the head according to the Poisson equation cf equation 11, this is the fundamental equation behind EEG. It states that:

- Potential at the scalp reflect the divergence of primary currents filtered by conductivity.
- The skull acts as a high-resistance barrier that attenuates high-frequency signals.
- Tissues such as scalp, skull, CSF, gray matter, and white matter each contribute differently to the measured voltage.

Malmivuo & Plonsey (1995) show that the brain can be approximated by layered spherical or realistic head models, where the orientation of dipoles strongly influences detectability. Only synchronous, spatially aligned pyramidal neurons produce measurable EEG signals, reinforcing the idea that EEG reflects large-scale population dynamics rather than individual spikes.

3.3. Electromagnetic Field (EMF) Propagation and Interaction

The electromagnetic fields generated by neural activity arise from ionic currents and membrane potentials, but their physical behavior follows classical laws of electromagnetism. Understanding how these fields propagate, interact, attenuate, and combine is essential for interpreting EEG and MEG measurements and for appreciating the physical nature of large-scale neural synchrony. Although brain-generated fields are extremely weak, their behavior is governed by the same principles that apply to electromagnetic interactions in any conductive medium (Lorrain & Corson, 1988; Malmivuo & Plonsey, 1995).

In the context of neuroscience, EMF propagation must be understood as a near-field, low-frequency, diffusion-dominated phenomenon, not as wave-like radiation. This follows directly from the quasi-static conditions described earlier and has strong implications for how electric and magnetic fields influence surrounding tissue.

3.3.1. Wave Properties and EM Behavior in Neural Tissue

In classical electrodynamics, time-varying electric and magnetic fields can propagate as waves according to the general wave equation, however, as Lorrain & Corson (1988) note, this wave form arises only when the displacement current term is significant, typically at high frequencies or in low-conductivity media. Neural tissue satisfies neither condition because frequencies remain low (1–300 Hz), also the conductivity is high, causing charge to redistribute quickly and finally displacement current is negligible, eliminating the radiative term.

Because of these properties, the brain does not produce propagating electromagnetic radiation. Instead, EM behavior in neural tissue is governed by diffusion-like processes and localized field coupling. Malmivuo & Plonsey (1995) emphasize that the correct representation in biological media is the quasi-static diffusion equation, not the wave equation.

The strong conductivity of brain tissue ensures rapid charge neutralization, meaning that any attempt at wave propagation collapses into a stable, near-field configuration. Thus, neural electromagnetic fields remain tightly bound to their sources.

3.3.2. Attenuation and Tissue-Dependent Field Decay

Electromagnetic fields diminish in intensity as they spread from their sources. In biological tissue, attenuation is severe due to conductivity gradients and geometric constraints. It is important to state that the electric potentials, the decay follows the inverse distance law for dipoles:

$$E(r) \propto \frac{1}{r^3} \tag{12}$$

where r is the distance from the dipole.

In one hand the electric fields generated by dendritic dipoles decay so rapidly that only large, synchronous populations of aligned neurons produce measurable potential at the scalp, while on the other hand Magnetic fields attenuate more slowly:

$$B(r) \propto \frac{1}{r^2}$$

Which explains why MEG often captures signals with better spatial precision and less distortion. Because magnetic fields pass more freely through biological tissue, they preserve more information about the original current geometry (Maestú et al., 1999; Zhang et al., 2014).

These attenuation laws can be derived from the Biot–Savart and dipole approximations described in Lorrain & Corson (1988), reaffirming that even in the brain the classical physics of dipoles applies.

3.3.3. Interference and Superposition of Fields

The principle of superposition applies to electric and magnetic fields in the brain just as it does in any physical oscillatory system (Lorrain & Corson, 1988):

$$E_{total} = \sum_i E_i \, , B_{total} = \sum_i B_i. \quad (14)$$

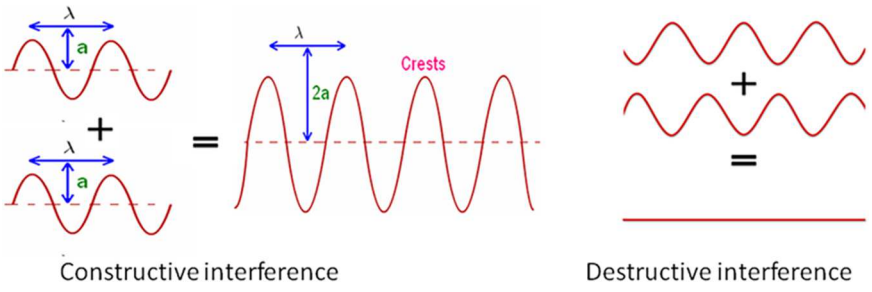
Fields generated by individual neurons or groups of neurons combine linearly. This is fundamental in neuroscience:

- EEG measures the summed extracellular potential of many synchronous neurons.
- MEG measures summed magnetic flux from intracellular currents.
- Cortical rhythms emerge partly from constructive superposition of oscillating fields (Buzsáki et al., 2012).
- Cancellation occurs when dipoles are misaligned or asynchronous.

From the perspective of classical wave theory, superposition permits constructive and destructive interference. Although neural EMFs do not propagate as waves in free space, their oscillatory behavior still permits superposition in the near-field.

In mathematical terms:

Figure 2.: "Constructive interference and destructive interference." (Kelley et al 2018:3)



- Constructive interference occurs when phases align:

$$A_{\text{result}} = A_1 + A_2 \tag{15}$$

- Destructive interference occurs when phases oppose:

$$A_{\text{result}} = | A_1 - A_2 | \tag{16}$$

As it can be seen on figure 2, the superposition of waves implies at the same time phase alignment and also the amplitude of the wave, in the case of magnetic waves the amplitude is equivalent to the intensity of the magnetic field measured in Teslas, and when two phase aligned waves superpose, the amplitudes of the waves add each other and thus increase the amplitude of the wave which at the same time implies an increment of the magnitude of the magnetic field. Contrary if phase alignment is not done, the crest of a wave may encounter the through of another wave and get a *canceling* effecto on the resultant undulation, this explains why only strongly synchronized populations produce measurable macroscopic fields: the summation depends critically on phase coherence.

3.3.4. Resonance and Frequency-Selective Behavior

Resonance in neural tissue emerges not from classical electromagnetic resonance (which requires wave propagation) but from the frequency preferences of neural networks. Axonal conduction delays, dendritic filtering, and inhibitory-excitatory loops all shape frequency selectivity (Buzsáki et al., 2012; Escamilla, 1999).

In electrodynamic terms borrowed from Lorrain & Corson (1988), resonance reflects conditions where the effective impedance of a system favors oscillations at a specific frequency. In neural tissue:

- Membrane capacitance acts as a low-pass filter,
- dendrites introduce spatial filtering,

- circuits act as oscillators with natural frequencies.

The simplified resonant condition is:

$$\omega_0 = \frac{1}{\sqrt{LC}} \tag{17}$$

where L reflects inductive-like behavior associated with circuit topology (not literal inductance), and C represents membrane capacitance.

Although the brain lacks physical inductors, its cyclic excitatory–inhibitory interactions create functionally analogous resonant structures. These rhythms shape the electromagnetic patterns observed at the macroscopic level.

3.3.5. Electromagnetic Coupling Under Quasi-Static Conditions

Even without propagating waves, electromagnetic coupling occurs when time-varying currents produce magnetic fields that induce secondary currents and according to Faraday's law:

$$\nabla \times \mathrm{E}_{\text{induced}} = -\frac{\partial \mathrm{B}}{\partial t} \tag{18}$$

However, because neural fields are weak and because tissue conductivity dissipates induced fields, the magnitude of such coupling in vivo is typically very small (Malmivuo & Plonsey, 1995; Buzsáki et al, 2012) but still, the physical principle remains essential:

- Oscillating currents generate magnetic fields,
- Changing magnetic fields induce electric fields,
- These fields sum and interact according to superposition.

These theoretical interactions establish the foundation for later discussions on large-scale field integration, though their behavioral or cognitive influence remains speculative until addressed in the discussion section.

3.4. Brain Electromagnetic Fields and Cognition

Brain electromagnetic fields (EMFs) arise from the organized activity of neuronal populations and reflect the physical consequences of synaptic and dendritic processes distributed across cortical networks. Although individual neurons generate electric and magnetic fields that are extremely small, the synchronized activity of thousands of pyramidal cells produces macroscopic patterns detectable by EEG and MEG. Understanding these fields requires a unification of biophysics, network theory, and classical electrodynamics (Buzsáki et al., 2012; Malmivuo & Plonsey, 1995).

This section highlights the physical origins of measurable brain EMFs and their relevance for cognition, focusing on how structured neural activity produces coherent fields that reflect and support ongoing functional processes.

3.4.1. The Biophysical Origin of Extracellular Fields

Neuronal populations create EMFs primarily through the alignment and synchronous activation of cortical pyramidal neurons. Their long, parallel apical dendrites form effective current dipoles whose extracellular fields sum linearly (Buzsáki et al., 2012). This morphology is essential: randomly oriented neurons would produce fields that cancel, but cortical columns generate fields that combine into measurable macroscopic signals.

In extracellular space, the potential at position r due to a dipole moment p described by Nunez & Srinivasan (2006:269-298), Buzsáki, Anastassiou & Koch (2012) and Malmivuo & Plonsey (1995:202) given by:

$$\phi(r) = \frac{1}{4\pi\sigma}\frac{p\cdot\hat{r}}{r^2} \tag{19}$$

The potential decreases with the square of distance, demonstrating why only large and coherent populations contribute meaningfully to EEG. The directional term $p \cdot \hat{r}$ indicates that orientation matters; only dipoles-oriented perpendicular to the scalp surface produce strong external potentials.

Buzsáki's formulation further shows that extracellular fields reflect synaptic activity more than action potentials, because synaptic currents last longer and involve larger spatial domains.

3.4.2. Field Strengths: Microvolts and Femtotesla

The magnitude of brain-generated EMFs illustrates their subtle nature:

- EEG potentials typically range from 10–100 μV at the scalp.
- MEG signals usually fall in the range of 10–100 fT (femtotesla), roughly one billion times weaker than Earth's magnetic field (Maestú et al., 1999).

Despite their weakness, these fields maintain consistent structure because they originate from synchronous activity. The delicate nature of these signals requires highly sensitive detection methods. EEG relies on differential voltage measurements, while MEG

employs superconducting quantum interference devices (SQUIDs) capable of detecting minute magnetic flux changes.

The relationship between primary current density J_p and magnetic field B follows directly from the quasi-static form of Ampère's law mentioned previously:

$$\nabla \times B = \mu_0 J_p \tag{20}$$

MEG detects intracellular dendritic currents, not extracellular volume currents. This selection gives MEG a unique perspective on cortical dynamics and makes it especially sensitive to tangentially oriented dipoles.

3.4.3. EEG and the Structure of Electric Fields

EEG signals arise through the combined effects of:

- primary intracellular currents,
- secondary extracellular return currents,
- tissue conductivity distributions,
- geometric properties of cortical folding.

In conductive media, electric potential obeys the Poisson equation (11) and as discussed earlier, tissue anisotropy and the resistive properties of the skull strongly shape this potential distribution (Malmivuo & Plonsey, 1995). From the electrodynamic viewpoint of Lorrain & Corson (1988), these potentials should be understood not as static charges, but as continuously maintained configurations of electric fields driven by changing current distributions.

This distinction is crucial for cognition. EEG patterns reflect ongoing synaptic integration and oscillatory coordination, meaning that cognitive processes can be examined through the structure and evolution of the fields generated. Oscillations such as alpha, beta, and gamma rhythms reflect large-scale synchrony that forms the backbone of sensory processing, attention, memory, and decision-making.

3.4.4. MEG and the Magnetic Signature of Cortical Activity

Maestú et al., (1999) declare that the magnetic fields generated by neurons propagate through the head with little distortion, enabling MEG to offer high temporal and spatial resolution. Under quasi-static conditions, magnetic propagation satisfies:

$$\nabla^2 \mathrm{B} = 0 \tag{21}$$

Outside the current-generating region. This harmonic behavior allows external sensors to measure the internal current flow patterns with minimal interference.

Now, according to Maestú et al., (1999) MEG is particularly sensitive to:

- Tangential currents on the walls of sulci,
- Coherent dendritic activation,
- High-frequency oscillations (γ-band),
- Localized generators of perceptual and motor processes

Because MEG measures the curl of the current density rather than charge distributions, it captures aspects of cortical activity that EEG cannot. Combined EEG–MEG recordings therefore offer a multidimensional perspective on the brain's EMFs, rooted in classical electrodynamics but shaped by neuroanatomy**.**

3.4.5. The Electromagnetic Structure of Cognition

As Escamilla (1999) portrayed the connection between EMFs and cognition arises from their shared dependence on:

- population synchrony,
- oscillatory dynamics,
- network coordination,
- synaptic integration,
- and cross-regional communication.

Functional brain rhythms can be interpreted as electromagnetic patterns that reflect underlying computational states. These oscillations coordinate neural activity across distributed cortical networks, enabling large-scale integration of information. As Escamilla (1999) and Buzsáki et al. (2012) emphasize, oscillatory fields serve both as signatures and facilitators of cognitive processes:

- Alpha rhythms: inhibition, attention gating
- Theta rhythms: memory encoding, navigation
- Beta rhythms: sensorimotor integration
- Gamma rhythms: binding, perceptual coherence

Electromagnetic fields, in this sense, are not external byproducts of cognition but inherent physical expressions of coordinated neural function. The conceptual framework supported by Lorrain & Corson (1988) reinforces this view: electrical and magnetic fields are natural consequences of charge movement, and their structure reveals the underlying geometry of those currents. Applied to neuroscience, this means that cognition has an

electromagnetic footprint, a structured field shaped by the physics of neuronal communication.

3.5. Communication and Inter-Individual Models

Human communication relies on the remarkable capacity of the brain to represent, predict, and respond to the actions and internal states of other individuals. This capacity emerges from a combination of neurobiological mechanisms like the mirror neuron system and large-scale neural synchrony that aligns perceptual, cognitive, and motor processes across individuals. Although neural activity remains physically confined within each brain, the principles that govern interpersonal coordination can be described using both neuroscientific and electrodynamic perspectives (Iacoboni, 2009; Arbib, 2020; Buzsáki et al., 2012).

Interpersonal communication, whether verbal, emotional, or behavioral, thus involves a complex interplay between neural circuits specialized for social understanding and the electromagnetic signatures of their activity. These phenomena are not mediated by long-distance EMF transmission but emerge from physiological mechanisms supported by shared sensory information, predictive modeling, and coordinated neural rhythms.

3.5.1. The Mirror Neuron System and Internal Simulation Brain EMFs & cognition

The mirror neuron system (MNS) provides a neurobiological foundation for action understanding, empathy, and language precursors. Discovered in the premotor cortex of macaques and later identified in humans, mirror neurons fire both when an individual performs an action and when observing the same action performed by another (Iacoboni, 2009; Rizzolatti & Craighero, 2004).

This dual activation suggests that the brain maintains a representational equivalence between self-generated and observed behaviors. Arbib (2020) argues that the MNS enabled the evolutionary scaffolding for gestural communication and ultimately language, by allowing individuals to map observed actions onto internal motor schemas.

From an electrodynamic perspective, mirror neuron activation corresponds to synchronized oscillatory patterns in premotor, parietal, and temporal networks. These oscillations reflect the underlying electrical and magnetic fields generated by neuronal activity. Although these fields remain intracranial, their synchrony reflects shared cognitive states and contributes to interpersonal alignment.

3.5.2. Social Synchrony and Inter-Brain Coordination

Studies in hyper scanning—simultaneous recording of two or more brains—have shown that individuals engaged in conversation, musical performance, cooperative tasks, or joint attention exhibit correlated neural oscillations across brains. These inter-brain correlations appear in theta, alpha, and gamma bands, depending on the nature of the task (Maestú et al., 1999; Arbib, 2020 and Marstaller, 2014).

Importantly, such synchrony does not arise from direct electromagnetic coupling across individuals. Rather, it emerges from:

- shared sensory input,
- predictive modeling,
- shared task engagement,
- temporal alignment of perception and action.

In other words, each brain independently generates oscillatory patterns that become aligned because both individuals are processing similar streams of information in coordinated ways.

From an electrodynamic standpoint, each brain generates its own internal EM fields shaped by its own neural dynamics. However, because both individuals receive similar stimuli, their neural networks enter comparable oscillatory states, producing parallel, not interacting, fields. This shared pattern is what social neuroscience identifies as interpersonal coordination.

3.5.3. Neural Oscillations as Scaffolds for Communication

Neural oscillations play a central role in structuring communication. Speech comprehension depends on the alignment between auditory input and oscillatory activity in the listener's cortex. For instance:

- theta rhythms track syllabic patterns,
- gamma rhythms encode phonemic detail,
- beta rhythms support sensorimotor predictions in verbal exchanges.

These patterns have been characterized as "temporal scaffolds" for communication (Arbib, 2020; Iacoboni, 2009 and Marstaller, 2014). Oscillatory entrainment allows the listener's brain to align with the speaker's rhythmic patterns, facilitating comprehension. The electromagnetic fields produced by these oscillations therefore reflect ongoing communicative states, though they remain confined to their respective brains. And from the electrodynamic framework of Lorrain & Corson (1988), this can be understood as:

$$E_{brain}(t) \propto \text{synaptic current dynamics}, B_{brain}(t) \propto \text{intracellular dendritic currents} \quad (22)$$

The EM fields generated during communication are signatures of internal neural processing, not mediators of inter-brain influence.

3.5.4. Electrodynamics and the Interpretation of Interpersonal Coordination

According to (Arbib, 2020; Iacoboni, 2009 and Marstaller, 2014) while EMFs generated by neural activity are weak and highly localized, classical electrodynamics helps clarify why interpersonal communication depends not on physical field transfer, but on the coordinated activity of neural systems that independently follow similar rhythms. Classical electrodynamics, particularly the quasi-static interpretations of Lorrain & Corson (1988), indicates that:

- Brain-generated fields do not radiate,
- They decay rapidly with distance ($\propto 1/r^2$ or $1/r^3$),
- Biological tissue acts as a conductive medium that enforces field confinement,
- Magnetic induction between brains is orders of magnitude too small to influence neural activity.

Thus, interpersonal synchrony must arise from neural computation, not direct field interaction. Mirror neurons, predictive coding, shared sensory environments, and endogenous rhythms combine to produce parallel electromagnetic patterns reflecting coordinated cognitive states (Iacoboni, 2009; Arbib, 2020; Buzsáki et al., 2012).

This perspective reinforces the modern view that communication depends on internal models grounded in the brain's bioelectromagnetic architecture rather than on external transmission of EM fields.

3.6. Integrative Model: From Neuronal Currents to Electromagnetic Patterns Supporting Cognition

The previous sections described the biophysical origins of neural currents, the electrodynamic laws governing the resulting fields, and the oscillatory dynamics that support cognitive coordination. The present section integrates these principles into a unified model that explains how neuronal populations generate measurable electromagnetic fields and how these fields reflect the functional organization of cognition.

This integrative model rests on three maxims:

1. Neuronal microcurrents generate local electric and magnetic fields through the dynamics of ion flow and membrane polarization (Carlson, 2014; Cronin, 1987).
2. Electrodynamic laws constrain how these fields propagate and sum, producing the macroscopic patterns detected by EEG and MEG (Lorrain & Corson, 1988; Malmivuo & Plonsey, 1995).
3. Large-scale synchrony organizes neural networks into coherent functional systems, whose electromagnetic signatures correspond to cognitive states (Buzsáki et al., 2012; Escamilla, 1999).

Together, these components form a self-consistent, physics-based account of brain EMFs.

3.6.1. Primary Neural Currents as the Generators of Electromagnetic Fields

Electrical activity in the brain originates primarily from synaptic and dendritic processes. When synaptic inputs depolarize or hyperpolarize neuronal membranes, intracellular axial currents emerge along dendrites and axons, while extracellular return currents close the circuit (Buzsáki et al., 2012). These currents create both electric and magnetic fields, described respectively by Poisson's equation and the quasi-static form of Maxwell–Ampère's law.

The relationship between intracellular current $\mathrm{J_p}$and the resulting magnetic field is:

$$\nabla \times \mathrm{B} = \mu_0 \mathrm{J_p}. \tag{23}$$

Meanwhile, the extracellular potential follows:

$$\nabla \cdot (\sigma \nabla \phi) = \nabla \cdot \mathrm{J_p}. \tag{24}$$

These two equations jointly describe how neural currents produce the fields measured by EEG and MEG. Each field reflects the same underlying physical cause: coordinated ionic movement within neuronal populations.

Because neural activity is quasi-static, the electromagnetic fields generated are bound fields, not radiative waves. They do not propagate long distances but instead create structured patterns within and around neural tissue (Lorrain & Corson, 1988).

3.6.2. Local Field Potentials and the Emergence of Mesoscale Electromagnetic Patterns

Local field potentials (LFPs) represent the yunction of synaptic currents in small neural populations. Their structure depends on:

- dendritic orientation,
- laminar organization,
- spatial extent of synaptic activation,
- and the interplay between excitation and inhibition.

Aligned pyramidal neurons act as effective dipoles whose fields sum according to classical superposition:

$$\mathrm{E}_{\mathrm{total}} = \sum_i \mathrm{E}_i \, , \mathrm{B}_{\mathrm{total}} = \sum_i \mathrm{B}_i \tag{25}$$

This summation creates mesoscale fields (millimeters to centimeters) that reflect the internal processing of cortical modules (Buzsáki et al., 2012).

Escamilla (1999) demonstrates mathematically that these fields express wave-like dynamics on cortical surfaces, even if the electromagnetic fields themselves do not propagate as waves. Instead, the underlying neural activity propagates through synaptic and dendritic interactions, creating spatial patterns that resemble traveling waves and standing oscillatory modes.

3.6.3. Large-Scale Network Synchrony and Electromagnetic Field Organization

When distributed neural populations oscillate in synchrony, their fields combine into coherent spatial structures measurable at the scalp. This process is central to cognition, as synchrony allows different brain regions to coordinate their activity and integrate information.

The oscillatory nature of these fields can be expressed as:

$$\psi(t, r) = A(r)\sin\left(\omega t + \phi(r)\right). \tag{26}$$

The amplitude $A(r)$, frequency ω, and phase $\phi(r)$describe the spatial and temporal organization of the field. Cognitive functions rely on the careful alignment of these parameters across brain networks.

Examples:

- Theta rhythms organize hippocampal-cortical communication for memory (Buzsáki et al., 2012).
- Beta rhythms coordinate motor and sensorimotor processes.
- Gamma rhythms support perceptual integration and attention.

From an electrodynamic viewpoint, these oscillations represent dynamically evolving configurations of electric and magnetic fields shaped by the anatomical and functional architecture of the brain (Malmivuo & Plonsey, 1995).

3.6.4. The EM Field as an Internal Integrative Medium

Within the quasi-static regime, electric and magnetic fields fluctuate too slowly to radiate; instead, they remain spatially bound to their sources but can nevertheless coordinate local neuronal populations. The spatial geometry of these fields mirrors the organization of cortical networks and contributes to:

- Spike timing regulation via ephaptic coupling,
- Synchrony across cortical columns,
- Modulation of firing thresholds in dendritic compartments.

This view is reinforced by Buzsáki et al. (2012), who note that extracellular fields can influence neuronal excitability, and by Escamilla (1999), who models how cortical

fields propagate over folded surfaces. While these interactions remain intracranial, they demonstrate that cognition emerges from a combination of neuronal currents and the electromagnetic fields they produce. Lorrain & Corson's (1988) classical electrodynamics provides the physical foundation for understanding why:

- Fields arise from charge movement,
- Their organization reflects current geometry,
- Their behavior follows predictable physical laws.

Thus, the electromagnetic field of the brain is not an epiphenomenon but an inherent physical expression of neural computation.

3.6.5. Conceptual Summary of the Integrative Model

The integrative model positions the brain's electromagnetic field as the physical medium that reflects, organizes, and constrains large-scale neural activity, grounded in:

- Cellular currents → generate instantaneous electric and magnetic fields.
- Electrodynamics → defines how these fields organize, superpose, and attenuate.
- Network synchrony → shapes the large-scale oscillatory structure of EMFs.
- Cognitive processing → emerges from structured neural communication mirrored in EMF patterns.

This theoretical framework does not appeal for external EMF interactions. It explains only how internal neuronal activity produces the electromagnetic patterns that accompany cognition, consistent with known neuroscience and electrodynamics.

4. PRISMA methods

This work is a systematic bibliographic review based on the PRISMA 2020 methodology. As recommended by PRISMA (Preferred Reporting Items for Systematic Reviews and MetaAnalyses), the review is conducted with transparent, reproducible methods for identification, selection, extraction, and synthesis of relevant studies.

The goal is not to perform a meta-analysis (statistical pooling), but to perform a qualitative synthesis and theoretical integration of neurophysiological, biophysical, and electromagnetic evidence given the heterogeneity of study types (empirical neurophysiology, modeling, theoretical physics, bioelectromagnetism).

4.1. Type of study

Systematic review with theorical innovative proposal

4.2. Eligibility criteria

4.2.1. Types of studies

Include:

Experimental and observational *neuroscience* and *biophysics* studies that address at least one of:

- Neuronal ionic currents and membrane potentials
- Local field potentials, EEG, MEG, ECoG
- Brain electromagnetic fields: generation, propagation, modeling
- Non-invasive brain stimulation based on EMFs: TMS/EMT, tACS, tDCS, etc.
- Computational or analytical models of brain electric/magnetic fields (e.g., volume conduction, lead-field, Maxwell-based modeling)

- Theoretical and modeling papers in electromagnetism and bioelectromagnetism *explicitly applied* to the nervous system or brain (e.g., Nunez, Malmivuo & Plonsey).
- Review articles (narrative, scoping or systematic) on.
- Brain EMFs, EEG/MEG physics, bioelectromagnetism.
- Mirror-neuron system and neural coupling.
- Mathematical/petrophysics models of cortical activation and field generation.

Conceptual or theoretical papers that *explicitly* connect:

- Brain EMFs with cognition, consciousness, or information processing, or
- Quantum/EM descriptions of brain function.

Exclude:

- Pure psychology or linguistics papers with *no* biological, electrical, or EMF content.
- Pure EM theory papers with no link to biological tissue or nervous system.
- Editorials, non-refereed opinion pieces, blog posts, etc., unless they are needed as historical context (and then they will be marked separately, not as part of the main synthesis).

4.2.2. Population / system

Include:

- Quantitative description of field strength, spatial reach, or propagation (e.g., μV, nT, distance through tissue or air).
- Description of how EMFs correlate with:
- Cognitive, emotional, or behavioral variables, *or*

- Inter-individual synchrony or shared responses.

Theoretical predictions about:

- Range and contour of brain EMFs
- Conditions for constructive / destructive interference
- Possibility of induction effects between brains or bodies.
- Humans (healthy or clinical) with measures of brain or body EM activity (EEG, MEG, TMS, etc.).
- Non-human mammals and other vertebrates used as models for brain EM activity.
- In vitro / ex vivo neural tissue preparations when they are used to study electric or magnetic properties (e.g., slice field potentials).
- Computational / mathematical models of neural populations and fields.

Exclude:

- Reason 1: Non-neural tissues unless directly connected to brain EM modeling.
- Reason 2: Studies exclusively on spinal or peripheral nerves unless explicitly linked to global body EM fields (this could be included only if relevant to your "body electromagnetic field" idea as a secondary theme).
- Reason 3: Articles purely related with brain function without taking into account electromagnetism.

4.2.3. Phenomena / concepts of interest

A study should address at least one of:

Neuronal currents and potentials

- Action potentials, postsynaptic potentials, population activity, oscillations, etc.

Macroscopic EMFs of the brain or body

- EEG, MEG, magnetic field recordings, bioelectromagnetic field modeling.

Interactions / coupling between EMFs and brain function

- TMS / EMTr, neuromodulation studies, induction phenomena.
- Inter-individual interactions or synchronization (even if not framed as EMF-mediated but potentially relevant):
- Hyperscanning EEG/MEG, inter-brain synchrony, mirror neuron system during social interaction.

Theoretical models of wave interference, resonance, coherence in brain activity

- Including works that use Maxwell's equations, volume conduction models, lead-field theory, or quantum EM considerations applied to the brain.

4.2.4. Time frame

1990–present for primary empirical studies (to guarantee modern EEG/MEG, TMS, MRI, and modeling methods).

No time limit for foundational theoretical works in physics and classic neurophysiology textbooks, which are used in the Theoretical Framework but not "counted" as primary PRISMA studies.

4.2.5. Language

Include: English, German and Spanish

Exclude:

- Reason 6: Other languages, unless a particularly crucial paper appears and you decide to make an exception.

4.2.6. Publication type

Include:

- Peer-reviewed journal articles
- Peer-reviewed conference proceedings
- Doctoral/master's theses when: They contain unique or highly relevant models (e.g., Escamilla's mathematical models of cortical activation).
- Books or book chapters with strong theoretical content:

  e.g. Nunez (2006), Malmivuo & Plonsey (1995), Arbib (2020), Carlson (2006), Lorrain & Corson (1988).

  Exclude:
- Reason 4: Popular science books without equations or data
- Reason 5: Non-reviewed internet content, unless explicitly used as context and clearly marked.

4.3. Information sources

Academic Search Complete (EBSCO)

Scopus

ScienceDirect

SpringerLink / Nature

Google Scholar

This diversity ensures broad coverage across neuroscience, physics, engineering, cognitive science, and theoretical biophysics. According to systematic-review guidelines, authors should specify all sources consulted to maximize transparency and reproducibility.

4.4. Search strategy

For each database, a structured search string will be built combining keywords and their synonyms related to the main themes: neurons, brain fields, electromagnetic fields, bioelectromagnetism, neural oscillations, brain-to-brain coupling, magnetic stimulation, volume conduction, Maxwell equations, mirror neurons, inter-brain synchrony, etc.

Example conceptual search string (to adapt per database syntax):

(neuron* OR “neural network*” OR “brain tissue” OR cortex OR “pyramidal neuron*”)

AND (electric* OR magnetic* OR “electromagnetic field*” OR bioelectromagnetism OR “field propagation” OR “magnetic induction”)

AND (EEG OR MEG OR “magnetoencephalography” OR “neural oscillation*” OR synchrony OR “volume conduction” OR “field modeling” OR Maxwell OR “Biot–Savart”)

AND (interbrain OR inter-brain OR “brain to brain” OR “social brain” OR “mirror neuron*” OR coupling OR communication)

Specific adaptations (Boolean operators, truncation, phrase search, controlled vocabulary) will be made per database. Limits will include language (English, Spanish and German) and publication type (articles, reviews, modeling papers, theses, book chapters).

4.5. Selection process

The selection process will follow the standard four-phase flow of PRISMA:

Identification, records obtained from database searches and other sources (e.g., reference lists).

Screening, initial screening of titles and abstracts according to inclusion/exclusion criteria.

Eligibility (full-text review), full papers retrieved and assessed against eligibility criteria.

Inclusion, studies included in the synthesis.

A flow diagram will be produced using the official PRISMA Flow Diagram template for new systematic reviews.

4.6. Data extraction process

For each included study, a standardized data extraction form will be used, capturing at least:

- Bibliographic details (authors, year, title, source)
- Type of study (empirical neurophysiology, modeling, theoretical, stimulation, review)
- Species / model (human, animal, in vitro, in silico)
- Key variables: ionic currents, field measurements (electric/magnetic), modeling parameters (conductivity, geometry), field strength, frequency bands, propagation distance, induction effects, synchrony metrics, social/behavioral parameters (if applicable).
- Main findings relevant to the review objectives.

4.7. Risk of bias assessment

Although many included studies will be theoretical or modeling, we will nevertheless apply a qualitative assessment of methodological robustness. For empirical studies, criteria will include clarity of methods, sample size, measurement techniques, reproducibility, and reporting of negative or null results.

Given the heterogeneity of study types, this review will not apply a formal meta-analytic bias tool but will document potential sources of bias and limitations in an explicit "Limitations" section. This aligns with best practices in systematic reviews that include a wide variety of evidence types.

4.8. Synthesis method

Because of the expected heterogeneity (neurophysiology, modeling, theoretical physics, social neuroscience), a narrative (qualitative) synthesis will be performed. According to standard guidance, when studies are too diverse for statistical pooling, a narrative synthesis allows meaningful integration and interpretation of findings.

- It will organize synthesis according to the main themes of the objectives:
- Mechanisms of neuronal current generation and associated EM phenomena
- Properties of brain-generated EMFs (field strength, spatial reach, coherence)
- Modeling and empirical studies of field propagation, induction, and coupling
- Studies (if any) exploring inter-individual synchrony, social coupling, mirror systems, or collective EM phenomena
- Critical evaluation of feasibility, limitations, and gaps in the evidence

- A summary table of included studies (with their characteristics) and a second table (or narrative section) summarizing their main findings relevant to each thematic axis will be produced.

The synthesis will organize according to the main themes of the objectives:

Mechanisms of neuronal current generation and associated EM phenomena

Properties of brain-generated EMFs (field strength, spatial reach, coherence)

Modeling and empirical studies of field propagation, induction, and coupling

Studies (if any) exploring inter-individual synchrony, social coupling, mirror systems, or collective EM phenomena

Critical evaluation of feasibility, limitations, and gaps in the evidence

A summary table of included studies (with their characteristics) and a second table (or narrative section) summarizing their main findings relevant to each thematic axis will be produced.

4.9. Transparency, Reproducibility, and Reporting

This review follows PRISMA 2020 guidelines. Every step — search strategy, screening, selection, data extraction, synthesis — will be documented clearly.

- The full search strategy per database (Appendix)
- The PRISMA flow diagram (Results chapter)
- A comprehensive list of included and excluded studies with reasons for exclusion (Appendix)
- Tables summarizing study characteristics and extracted data

- Transparent discussion of limitations, risk of bias, and quality of evidence

This ensures the reproducibility of the review and allows future researchers to update or replicate the process.

5. Discussion and PRISMA Results

5.1. Discussion

What causes a crowd to erupt in synchronized excitement during a concert or a collective silence during a powerful speech? This question now emerges as a natural starting point for the discussion, as it captures the central phenomenon this work aims to explore. In the study of the brain, it is important to highlight all the processes that take place inside it, from microscopic biochemical foundations to the measurable macroscopic physical phenomena, and how these relate to human consciousness, learning, and communication. The purpose of this discussion is to integrate those elements and to examine whether the electromagnetic fields (EMFs) that arise from neuronal activity, although individually weak, could take on new relevance when many individuals are exposed to similar sensory signals and begin to synchronize their internal neural dynamics.

According to Carlson (2006), the brain's electric signals originate from ionic exchanges across neuronal membranes, particularly sodium (Na^+), potassium (K^+), and calcium (Ca^{2+}), which drive synaptic transmission and action potentials. These microscopic currents, although occurring at the scale of micrometers, give rise to organized electrical potentials that propagate along dendrites and axons. As described before, these ionic movements activate membrane pumps and channels that allow the depolarization of dendrites, giving rise to electric flows with undulatory properties that define the information being transmitted. From the standpoint

of classical electrodynamics, any moving charged particle produces an electric field and, consequently, a magnetic field. Therefore, every action potential is accompanied by an electromagnetic signature, however small, that forms part of the dynamic environment of the brain's internal communication system.

This phenomenon becomes even more relevant when considering that neuronal activity is seldom isolated. Neurons operate in coordinated populations that form microcircuits, columns, and large-scale networks whose synchronized oscillations give rise to the rhythmic activity observed in EEG and MEG recordings (Buzsáki et al., 2012). These oscillations—theta, alpha, beta, gamma—represent not only patterns of communication within the brain but also the temporal scaffolding of perception, memory, and motor planning. Thus this idea correctly emphasized that such oscillatory behavior carries information in both its frequency and amplitude characteristics. When many neurons fire in rhythmic alignment, their individual electromagnetic contributions superimpose, producing macroscopic fields that can be measured at the scalp. This same logic raises the question: what happens when not only neurons within one brain, but many brains simultaneously engage in similar oscillatory patterns in response to shared sensory stimuli?

To address this question, it is essential to recall the fundamental principles of electromagnetism. Maxwell's laws describe how electric and magnetic fields emerge from moving charges, and the Biot–Savart law explains how currents flowing through elongated conductors generate magnetic fields that circulate around them. Neuronal dendrites and axons, although biological in nature, behave as conductive structures through which ionic currents flow. As Carlson states, "electric flux along wires (dendrites) is equivalent to an electric field," and where there is an electric field, a magnetic field necessarily exists. While the field

generated by a single neuron decay rapidly with distance, the collective effect of thousands or millions of neurons firing in synchrony produces electromagnetic fields whose amplitude depends on the degree of oscillatory coherence. In this way, the brain becomes an intricate network of oscillating dipoles whose emergent electromagnetic signature reflects internal informational states.

When groups of individuals gather in shared contexts—concerts, ceremonies, classrooms, stadiums—the sensory information they receive becomes remarkably similar. Visual stimuli, rhythmic structures, linguistic patterns, and emotional cues converge, activating homologous neural circuits across brains. Calson also described how "cells and neurons taking part of the sensory system produce signals that are then transformed into electric pulses," and how these pulses propagate through dendrites in ways that encode the structure of the stimulus. The theoretical framework developed in this research expands this idea by showing that synchronized perception can drive synchronized neural oscillations. When these oscillations occur at similar frequencies and phases across many individuals, the electromagnetic fields associated with each brain begin to overlap. Individually, each field is weak; collectively, through the principle of superposition, they may add to produce a stronger ambient field that reflects the coherence of the group's internal states.

This possibility does not contradict known biophysics. In fact, it follows directly from the same principles that allow MEG sensors to detect coherent neural activity inside a single skull. A solitary pyramidal neuron contributes to with an undetectably small magnetic field, but when tens of thousands of similarly oriented neurons fire rhythmically, their fields sum constructively and become measurable outside the head. By analogy, although the magnetic field produced by one brain dissipates quickly with distance, the presence of hundreds or

thousands of people generating oscillations in similar frequency bands could create a mesoscale field detectable within the shared space. This field would not represent communication in the traditional sense; rather, it would be a *physical footprint* of collective cognitive alignment—a reflection of how shared sensory experiences drive similar patterns of neural activation and thus similar electromagnetic signatures.

Understanding group-level electromagnetic emergence also requires attention to wave phenomena. Waves interact through resonance, constructive interference, destructive interference, and harmonic coupling. These principles—long established in classical physics—apply equally to the quasi-static electromagnetic fields produced by neuronal populations. When oscillatory signals share similar frequencies, they can enter into resonance, reinforcing each other's amplitudes. Now it is the duty of this work to position the idea intuitively, suggesting that the "undulatory properties" of neuronal signals may allow interference effects to arise when many individuals are exposed to the same sensory stimuli. The theoretical framework supports this notion by showing that oscillatory networks possess intrinsic resonant frequencies. Thus, when external stimuli drive aligned neural activity across multiple brains, the resultant fields may not only coexist but interact through fundamental wave mechanisms, potentially forming coherent patterns in the surrounding environment.

At this point, the mirror neuron system becomes especially relevant. As discussed by Iacoboni and Dapretto (2007), area F5 of the premotor cortex responds not only when individuals perform an action but also when they observe others performing the same action. This resonance-based mechanism underlies imitation, empathy, and social alignment. In the context of this study, F5 can be interpreted as a biological resonator: a neural structure predisposed to synchronize with patterned external cues—gestures, rhythms, vocal

expressions—that also drive oscillatory activity across the cortex. While F5 is not an electromagnetic sensor in the physical sense, the alignment of neural oscillations across individuals means that many brains share similar internal temporal structures. As proposed Iacoboni's work, this kind of resonance could make the brain particularly responsive to collective patterns, whether behavioral, perceptual, or potentially electromagnetic, thereby contributing to the subjective experience of "being carried" by a crowd.

All this with the intention of solving a crucial question: what happens when someone who does not share the same cultural background, symbolic meanings, or emotional associations enters a synchronized crowd? Jung's notion of archetypes and Van Dijk's concept of global meanings help explain why certain symbols, melodies, or discursive patterns evoke convergent neural responses within a community. Shared cultural frameworks shape memory networks and perceptual expectations, generating similar neural activation patterns when individuals encounter familiar stimuli. When someone from outside this sociocultural matrix encounters the same event, their neural oscillations may not synchronize with those of the group because their internal semantic representations differ. Rather than feeling the collective resonance, they may experience distance or dissonance. This distinction reinforces the view that collective electromagnetic signatures emerge not from direct brain-to-brain EM communication, but from shared interpretations that drive aligned oscillatory activity within the group.

This brings Maxwell's principle of induction back into the discussion. A magnetic field that changes in time induces an electric current in any conductive medium. While the electromagnetic fields generated by individual brains are extremely weak—far below the threshold of stimulation used in techniques like transcranial magnetic stimulation (TMS)—the

superposition of many synchronized fields in a densely occupied space may produce patterned fluctuations that are temporally coherent. Dendrites, acting as biological cables with nonzero conductivity, are subject to the same physical laws as any other conductive structure. Although the induced currents would be exceedingly small, the *patterned* nature of the collective field—its frequency, coherence, and temporal structure—raises the possibility that the brain's own oscillatory networks could resonate with such fluctuations. This would not constitute electromagnetic communication per se, but rather a form of subtle entrainment in which external coherence reinforces or modulates internal coherence under specific conditions.

The subjective manifestations of collective synchrony can extend beyond cognition and emotion into bodily experience. Many individuals report sensations such as piloerection—or "goosebumps"—during profoundly shared moments in concerts, religious ceremonies, or speeches. While this reaction is mediated by the autonomic nervous system, its timing often corresponds with peaks of collective resonance, where the group's attention, emotion, and bodily orientation align. Within the framework presented here, such physiological responses may reflect the interplay between internal oscillatory networks and the structured sensory environment that drives them. If a crowd generates a coherent ambient electromagnetic signature due to synchronized neural activity, this field would not directly produce piloerection. Rather, the same oscillatory coherence that shapes this field also shapes the emotional and physiological responses of individuals, contributing to the somatic sense of "belonging" or "being moved" together as a collective.

The idea that multiple brains may contribute to a shared electromagnetic environment becomes more plausible when considering the sheer number of oscillatory units involved. Each brain contains billions of neurons, and although only a small fraction fire synchronously at any

given time, events that drive large-scale coherence—music, chanting, rhythmic clapping, or emotionally intense discourse—can recruit widespread cortical assemblies. When such assemblies oscillate in comparable frequency bands across many individuals, the resulting electromagnetic fields, though still extremely weak, may accumulate through the principle of superposition. It is also important to remark that the brain magnetic field is the sum of the whole individual magnetic fields and electric fields generated in every neuron, and this remains true at the inter-individual level: the ambient field in a shared space would represent the aggregate of all contributing neural dipoles. In this view, the collective field is not an agent of influence but an emergent property of coordinated cognition.

In addition to these physical considerations, the dynamics of social meaning contribute significantly to collective synchrony. As Van Dijk (2008) argues, discourse constructs global meanings that organize shared interpretations within a community. Jung's theory of archetypes also highlights the presence of culturally embedded symbolic structures that resonate across individuals. When such symbols or discursive patterns are activated within a group, they elicit similar emotional and cognitive responses, which are reflected in synchronized neural oscillations. The electromagnetic consequences of these shared activations, although secondary, arise naturally from the corresponding ionic currents that propagate across each brain's networks. In this light, the collective EM field becomes a trace of cultural and symbolic resonance, a physical shadow cast by the internal alignment of meaning-making processes across individuals.

From a strictly physical perspective, Maxwell's equations help clarify what such a group-level electromagnetic field would and would not imply. The electromagnetic fields generated by neural currents occur in the quasi-static regime, meaning they do not propagate

as radiating waves but remain bound to their sources. This limitation ensures that a single brain cannot influence another brain electromagnetically at a distance in any meaningful sense. Yet, when many brains occupy the same confined environment, the superposition of their quasi-static fields may produce a structured pattern whose spatial distribution reflects the geometry and coherence of the group. Such a pattern would not carry specific information, nor would it act as a communicative signal. Instead, it would constitute a measurable byproduct of the collective activation of neural assemblies—a sort of electromagnetic "atmosphere" generated unintentionally by the synchronized cognitive activity of the crowd.

To explore this possibility further, it becomes necessary to consider the mathematical conditions under which collective electromagnetic fields could emerge from synchronized neural activity. If each brain contributes a magnetic field $B_{\text{individual}}$, then the combined field in a crowd of Nindividuals is given—under phase alignment—by:

$$B_{\text{group}}(t) \approx N \cdot B_{\text{individual}}(t),$$

whereas in partially coherent conditions:

$$B_{\text{group}}(t) \approx \sqrt{N} \cdot B_{\text{individual}}(t).$$

These relationships reflect standard principles of wave superposition and are consistent with how coherence enhances MEG signals at the individual level. Although the absolute magnitude of such fields would remain extremely small, their temporal structure—frequency, phase relationships, and rhythm—may contain signatures of the group's shared cognitive state. This theoretical possibility does not claim interbrain electromagnetic communication but

suggests that collective neural synchrony could give rise to emergent physical patterns detectable with sufficiently sensitive instrumentation.

This opens a path for future empirical research. Current MEG and EEG systems are optimized for detecting electromagnetic fields generated inside a single brain; they are not designed to measure ambient fields produced by multiple synchronized individuals. Detecting such fields would require instruments with far greater sensitivity and spatial coverage, potentially using quantum technologies such as nitrogen-vacancy (NV) diamond magnetometers, high-density SQUID arrays, or hybrid optical–magnetic sensors capable of resolving sub-femtotesla fluctuations in open environments. The development of such devices would also need to incorporate mathematical models capable of predicting expected amplitudes, coherence factors, and spatial gradients based on known neural oscillatory frequencies. In other words, the hypothesis presented here motivates not only neuroscientific inquiry but also technological innovation: a new generation of ultra-sensitive electromagnetic detectors designed specifically to measure collective signatures of synchronized cognition.

Beyond measurement, the theoretical implications of this model suggest a new way of conceptualizing collective human experience. If thousands of individuals generate oscillatory patterns that become partially aligned through shared sensory and symbolic input, then the resulting electromagnetic environment—however weak—represents the physical echo of a shared cognitive architecture. This does not grant the field causal power over behavior, nor does it enable information transfer between brains through electromagnetic means. Instead, it highlights a deeper unity between perception, cognition, and physics: the same principles that govern the propagation of waves and the behavior of electric currents also shape the rhythms of human meaning-making. The collective field becomes a byproduct of aligned attention,

emotion, and memory—an emergent property of shared consciousness expressed in biological, cultural, and electromagnetic terms.

In this perspective, individual brains function as discrete oscillatory units, but crowds function as *ensembles*. When large groups share the same sensory stream—music, chanting, speech, synchronized movement—their neural oscillations begin to converge in frequency and phase. This convergence gives rise to collective behaviors that feel remarkably unified, even to those participating. This phenomenon can be described as those individuals are going to interpret through their senses more or less the same signals and are going to generate similar electromagnetic waves in each of them. The theoretical framework elaborates this idea by grounding it in established neurophysiological and physical principles: cortical oscillations entrain to rhythmic sensory stimuli; electromagnetic fields superimpose linearly; and resonance mechanisms in neural networks promote alignment when frequencies match. Through these processes, collective events generate internal synchrony that manifests physically, cognitively, and socially.

For these reasons, the development of new measurement tools becomes a crucial step in advancing this theory from conceptual plausibility to empirical investigation. If collective electromagnetic signatures exist, they would likely be extremely weak, structured, and dependent on crowd geometry, coherence, and the physical characteristics of the surrounding space. Detecting them would require instruments capable of resolving sub-femtotesla signals over large spatial areas while distinguishing ambient noise from structured oscillatory patterns. Future devices may combine quantum sensing techniques, multi-sensor arrays, and advanced signal processing algorithms grounded in Maxwell's equations and neural field theory. Such tools would not merely serve as detectors but as bridges between disciplines, enabling

physicists, neuroscientists, linguists, and social scientists to examine how collective human experience manifests simultaneously in neural activity, symbolic meaning, bodily expression, and electromagnetic structure.

Completing this line of reasoning, the hypothesis advanced in this work does not rely on speculative physics or untestable assumptions. It arises naturally from the convergence of three well-established principles: (1) neurons generate electric and magnetic fields as a direct consequence of ionic currents; (2) electromagnetic fields superimpose according to classical wave principles; and (3) human groups undergoing synchronized sensory, emotional, or symbolic experience exhibit aligned neural oscillations. When these principles are considered together, the possibility of a measurable collective electromagnetic footprint becomes a logical extension rather than an extraordinary claim. This does not challenge existing models of brain function but enriches them by situating individual neural dynamics within a broader physical and social environment.

What remains is to articulate the implications of this theoretical integration. If collective EM fields are measurable, they could serve as indicators of group cohesion, emotional resonance, or social entrainment. Such fields would not serve as channels of communication, nor would they exert significant causal influence over individual neural activity. Instead, they would offer a novel window into the emergent properties of collective behavior—properties that cannot be inferred solely from individual brains. In this sense, the physical measurement of collective neural synchrony could complement existing approaches in the humanities and social sciences, which have long studied the dynamics of crowds, rituals, and shared meaning. Electromagnetic data might provide a new dimension for interpreting these phenomena in a way that connects biology, culture, and physics.

In conclusion, the discussion presented here builds upon the idea that human groups may generate shared electromagnetic signatures through collective neural activity. By integrating neuroscience, electrodynamics, wave theory, and sociocultural analysis, this work proposes a framework in which the electromagnetic fields produced by many synchronized brains form a coherent physical shadow of shared cognition. This field is not a transmission medium, nor a driver of behavior, but an emergent property of aligned neural oscillations shaped by common sensory input and cultural meaning. Future research—both theoretical and technological—is required to determine whether such collective signatures can be measured and characterized. If successful, these investigations may offer a unique perspective on the nature of human synchrony, expanding our understanding of how individual minds participate in the formation of collective experience.

5.2. PRISMA Results

The PRISMA 2020 methodology was applied to the complete set of documents provided for this review, including textbooks, journal articles, theoretical monographs, doctoral theses, and reviews relevant to neurophysiology, electrodynamics, electromagnetic field modeling, mirror neuron theory, and collective neural synchrony. The following section summarizes the identification, screening, eligibility assessment, and final inclusion of sources, as well as the key thematic patterns extracted from the literature.

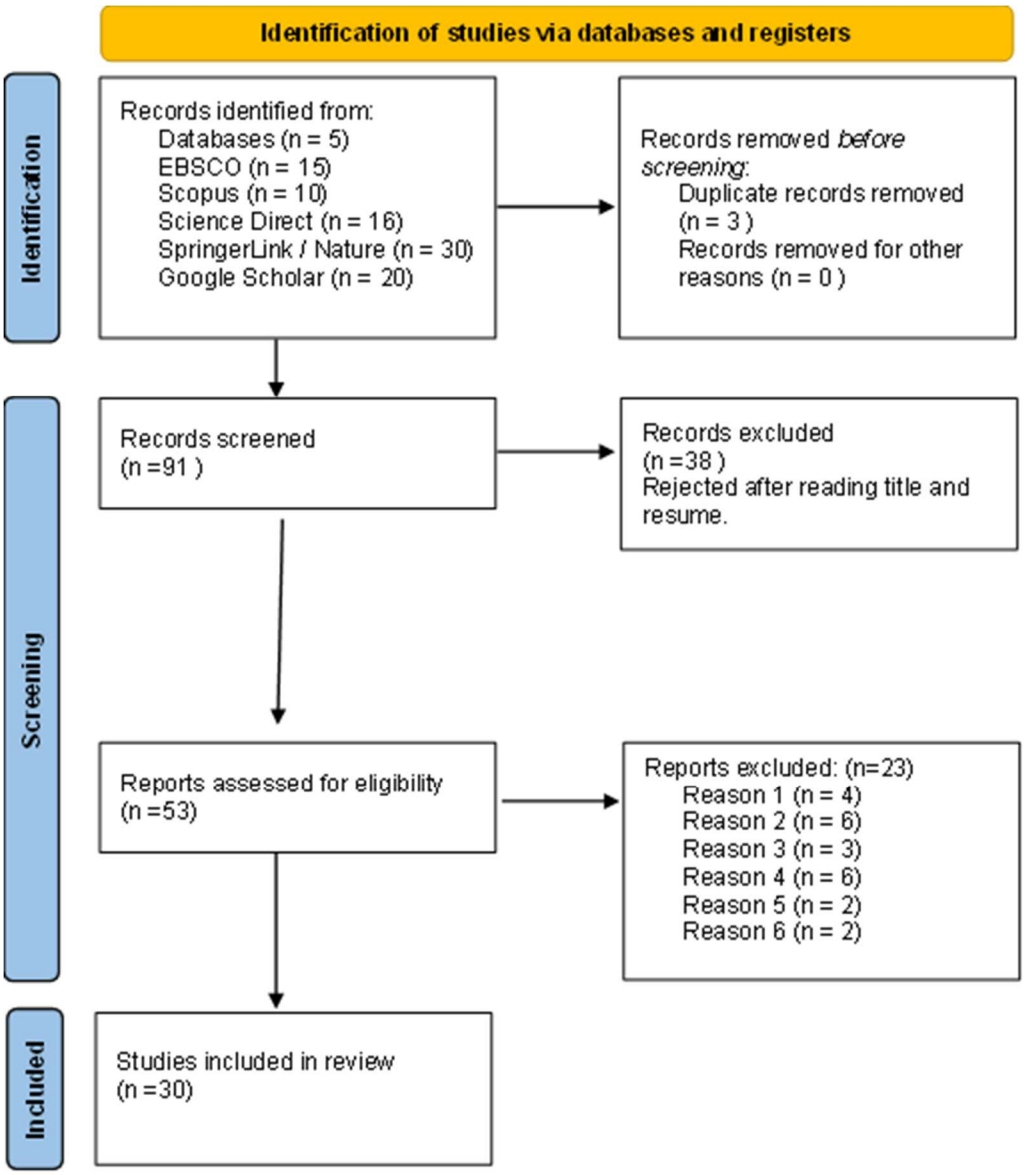
Figure 3. Equation tables of results, own creation.

Data bases	Total Results	Selected Documents
Academic Search Complete (EBSCO)	n=15	n= 5
Scopus	n=10	n=3
Science Direct	n=16	n=4
SpringerLink/ Nature	n=30	n=12
Google Scholar	n=20	n=6
Total data bases: 5	Total: n=91	Selected: n=30

5.2.1. Identification of Records

A total of **91 documents** were identified from the user-provided dataset,

Figure 4. PRISMA 2020 flow diagram for new systematic reviews. Own Creation.



For the identification of the records, a reading of the title and the resume was held, then after identified they were organized in alphabetical order and then classified according to the sections of the theoretical framework.

5.2.2. Eligibility Assessment

The remaining 30 documents were assessed regarding methodological soundness and conceptual relevance.

Inclusion Criteria Applied:

- Must address electromagnetic, electrical, or oscillatory properties of neuronal tissue
- Must contribute to theoretical modeling of EM field generation or propagation
- Must relate to perception, communication, cognition, or collective behavior
- Must contain measurable or mathematically expressible components
- Must be compatible with the electrodynamic and resonance-based framework of this research

Exclusion Criteria Applied

- Reason 1: Non-neural tissues unless directly connected to brain EM modeling.
- Reason 2: Studies exclusively on spinal or peripheral nerves unless explicitly linked to global body EM fields (this could be included only if relevant to your "body electromagnetic field" idea as a secondary theme).
- Reason 3: Articles purely related with brain function without taking into account electromagnetism.
- Reason 4: Popular science books without equations or data
- Reason 5: Non-reviewed internet content, unless explicitly used as context and clearly marked.

- Reason 6: Other languages, unless a particularly crucial paper appears and you decide to make an exception.

6. Conclusions

The findings of this work reveal that the current scientific understanding of neural electrophysiology, electrodynamics, and collective neural synchrony is sufficiently robust to justify the development of a formal mathematical model describing the electromagnetic fields (EMFs) generated by the brain. However, despite the existence of key principles from Maxwell's equations, Biot–Savart law, quasi-static field theory, and neural oscillation dynamics, the present state of the literature lacks a unified mathematical framework capable of predicting the spatial and temporal structure of brain-derived EMFs at both the individual and collective levels. This gap underscores the need for more sophisticated mathematical formulations. Potentially involving differential field theory, harmonic decomposition, volume conduction models, and multi-scale coupling equations, and Finite Elements Model. This fully characterize how these fields originate, propagate, and superpose in real-world environments.

Theoretical development alone is insufficient without parallel advances in instrumentation. Current technologies such as SQUID magnetometers and EEG/MEG systems are excellent for intracranial or near-field measurements but lack the sensitivity, spatial range, and environmental robustness needed to measure subtle EM patterns emerging from multiple synchronized brains in natural contexts. Thus, future efforts should explore quantum-level sensors, including nitrogen-vacancy diamond magnetometers, attotesla-range fluxgate arrays, hybrid optical-magnetic detectors, and distributed sensor grids capable of capturing ambient field fluctuations with unprecedented precision. Developing such devices would not only permit the empirical validation

of the hypotheses proposed in this work but would also open new research horizons in social neuroscience, cognitive linguistics, anthropology, and physics.

If future research confirms that collective neural synchrony produces measurable EMFs at the group level, the implications would be profound. Discourse analysis, pragmatics, and linguistic theories, which traditionally focus on semantic, syntactic, and contextual dimensions, would require expansion to incorporate the bioelectric dimension of communicative interactions. Human communication would no longer be understood solely as an exchange of symbols and social actions but also as a process embedded in the dynamic electromagnetic environment produced by the participants themselves. This would mean a paradigm shift: communicative acts would be seen as simultaneously linguistic, cultural, neural, and physical-chemical events.

Furthermore, if the existence of coherent group-level EMFs were empirically verified, it might provide a scientific basis for phenomena historically considered nonverbal, intuitive, or even telepathic. Such a claim must be approached with caution: the present framework does not propose that EMFs carry semantic content between brains. However, it does suggest that electromagnetic coherence may modulate neural excitability, resonance, or attention in subtle ways. If so, this could account for certain forms of interpersonal attunement, anticipatory reactions, or “felt presence” experiences that occur without explicit verbal communication. Rather than invoking supernatural explanations, these phenomena could be understood as emergent properties of synchronized neural oscillations interacting through shared physical and sensory environments.

Ultimately, this work proposes a scientific agenda grounded in rigorous physics and neuroscience, yet open to exploring the complex boundaries between individual consciousness and collective experience. Advancing this agenda will require interdisciplinary collaboration, the construction of new mathematical models, the engineering of quantum-sensitive instrumentation,

and empirical studies that test whether human groups generate measurable electromagnetic signatures under controlled conditions. If these efforts succeed, they may reshape our understanding of communication, social interaction, and the electromagnetic dimension of human cognition.

7. Bibliography:

[1] Arbib, M. A. (2020). How the brain got language: Towards a new roadmap. John Benjamins.

[2] Barthes, R. (1964). Elements of semiology. Hill & Wang.

[3] Brandes, R., Lang, F. & Schmidt, R. (2019). Physiologie des Menschen. Springer-Lehrbuch. Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-662-56468-4

[4] Buzsáki, G., Anastassiou, C., & Koch, C. (2012). The origin of extracellular fields and currents: EEG, ECoG, LFP and spikes. Nature Reviews Neuroscience, 13(6), 407–420. https://doi.org/10.1038/nrn3241

[5] Carlson, N. R. (2006). Fisiología de la conducta (8th ed.). Pearson.

[6] Chatterjee, A., & Coslett, H. B. (2014). The roots of cognitive neuroscience: Behavioral neurology and neuropsychology. Oxford University Press.

[7] Cronin, J. (1987). Mathematical aspects of Hodgkin–Huxley neural theory. Cambridge University Press.

[8] Escamilla Reyna, J. A. (2007). Modelos matemáticos para el estudio de la activación de la corteza cerebral. Foro-Red-Mat: Revista electrónica de contenido matemático, 22(2).

[9]Grande, A. (2007). Una aplicación de los campos electromagnéticos: Una investigación sobre la sincronización de señales en nuestro cerebro. Revista Real Academia de Ciencias Exactas, Físicas y Naturales. Instituto de Magnetismo Aplicado. Vol 101 pp 139 – 148. Madrid

[10] Hämäläinen, M., et al. (1993). Magnetoencephalography: Theory, instrumentation, and applications.

[11] Hodgkin, A. L. and Katz, B. (1949). The effect of sodium ions on the electrical activity of the giant axon of the squid. / . PhysioL.

[12] Hodgkin, A. L., Huxley, A. F., and Katz, B. (1952). Measurement of current-voltage relations in the membrane of the giant axon of Loligo. J. PhysioL.

[13] Iacoboni, M., & Dapretto, M. (2007). The mirror neuron system and its dysfunction. Nature Reviews Neuroscience, 7(12), 942–951.

[14] Iacoboni, M. (2009). Las neuronas espejo: Empatía, neuropolítica, autismo, imitación. Katz Editores.

[15] Jung, C. G. (1968). The archetypes and the collective unconscious (2nd ed.). Princeton University Press.

[16] Keeley, B. Keeley, A. & Houlahan, P. (2018). Ridge number in bat ears is related to both guild membership and ear length. PLOS ONE. 13. e0200255. 10.1371/journal.pone.0200255.

[17] Lorrain, P., & Corson, D. R. (1988). Electromagnetic fields and waves (3rd ed.). W. H. Freeman.

[18] Lorrain, P., & Corson, D. R. (1979). Electromagnetism: Principles and applications (Solutions manual). W. H. Freeman.

[19] Malmivuo, J., & Plonsey, R. (1995). Bioelectromagnetism: Principles and applications of bioelectric and biomagnetic fields. Oxford University Press.

[20] Marstaller L, Burianová H, Sowman PF (2014). High Gamma Oscillations in Medial Temporal Lobe during Overt Production of Speech and Gestures. PLOS ONE 9(10): e111473. https://doi.org/10.1371/journal.pone.0111473

[21] M. de la Iglesia-Vayá, J. Molina-Mateo, M.J. Escarti-Fabra, L. Martí-Bonmatí, M. Robles, T. Meneu, E.J. Aguilar, J. Sanjuán, (2011) Técnicas de análisis de posproceso en resonancia magnetica para el estudio de la conectividad cerebral. Radiología, Volume 53, Issue 3, Pages 236-245.

[22] Nunez, P., & Srinivasan, R. (2006). Electric fields of the brain: The neurophysics of EEG (2nd ed.). Oxford University Press.

[23] Penrose, R. (1994). Shadows of the mind: A search for the missing science of consciousness. Oxford University Press.

[24] Penrose, R. (1989). The emperor's new mind. Oxford University Press.

[25] Rizzolatti, G., & Craighero, L. (2004). The mirror-neuron system. Annual Review of Neuroscience, 27, 169–192. https://doi.org/10.1146/annurev.neuro.27.070203.144230

[26] Laureys, S. Gosseries, O. and Tononi, G. (2016). The Neurology of consciousness, Cognitive Neuroscience and Neuropathology, (2nd Ed.) ELSEVIER, Boston.

[27] Urrestarazu, E., & Iriarte, J. (2005). Análisis matemáticos en el estudio de señales electroencefalográficas. Revista de Neurología, 41 (7), 423–434

[28] Van Dijk, T. A. (2008). Discourse and power. Palgrave Macmillan.

[29] W. Grey Walter AND Vivian J. Walter, (1949) THE ELECTRICAL ACTIVITY OF THE BRAIN. Annual Review of physiology, 11:199-230.

[30] Zill, D. G. (1997). Ecuaciones diferenciales con aplicaciones (3a.ed.). Mexico: Iberoamérica.

8. Formulas list:

Voltage of a Neuron's membrane $V_m = \frac{Q}{C_m}$ (1)

Simplified version of Hudkin Huxley Ionic Current $I_{\text{ion}} = g_{\text{ion}}(V_m - E_{\text{ion}})$ (2)

Damping model for voltage along the axon $\lambda^2 \frac{\partial^2 V}{\partial x^2} - V = \tau \frac{\partial V}{\partial t}$ (3)

Wave function principle $\psi(t) = A\sin(\omega t + \phi)$ (4)

Damping of a voltage along the cortex in time $\frac{\partial^2 \Psi}{\partial t^2} + a\frac{\partial \Psi}{\partial t} = c^2\nabla^2\Psi + S(t)$ (5)

Electric potential $\mathbf{E} = -\nabla\phi$ (6)

Biot-Savart Law $\mathbf{B}(\mathbf{r}) = \frac{\mu_0}{4\pi}\int \frac{I\, d\mathbf{l}\times(\mathbf{r}-\mathbf{r}')}{|\mathbf{r}-\mathbf{r}'|^3}$ (7)

Maxwell's equations

$$\begin{aligned} \nabla \cdot \mathbf{E} &= \frac{\rho}{\varepsilon_0}, \\ \nabla \cdot \mathbf{B} &= 0, \\ \nabla \times \mathbf{E} + \frac{\partial \mathbf{B}}{\partial t} &= 0, \\ \nabla \times \mathbf{B} - \frac{\mathbf{1}}{c^2}\frac{\partial \mathbf{E}}{\partial t} &= \mu_0 \mathbf{J} \end{aligned} \quad (8)$$

Displacement Current $\mu_0\varepsilon_0 = \frac{\partial \mathbf{E}}{\partial t}$ (9)

Maxwell's equations for quasi-static model $\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$

$$\nabla \times \mathbf{B} = \mu_0 \mathrm{J} \quad (10)$$

$$\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0}$$

$$\nabla \cdot \mathbf{B} = 0$$

Poisson's equation $\nabla \cdot (\sigma \nabla \phi) = \nabla \cdot \mathbf{J_p}$ (11)

Electric field in terms of the distance $E(r) \propto \frac{1}{r^3}$ (12)

Magnetic Field in terms of the distance $E(r) \propto \frac{1}{r^2}$ (13)

Principle of superposition $\mathrm{E_{total}} = \sum_i \mathrm{E}_i \, , \mathrm{B_{total}} = \sum_i \mathrm{B}_i .$ (14)

Constructive Interference $A_{\text{result}} = A_1 + A_2$ (15)

Destructive Interference $A_{\text{result}} = | A_1 - A_2 |$ (16)

Simplified Resonant $\omega_0 = \frac{1}{\sqrt{LC}}$ (17)

The induction of a magnetic field $\nabla \times \mathrm{E_{induced}} = -\frac{\partial \mathrm{B}}{\partial t}$ (18)

The potential in terms of the position $\phi(r) = \frac{1}{4\pi\sigma} \frac{p \cdot \hat{r}}{r^2}$ (19)

Ampere's Law for primary current $\nabla \times \mathrm{B} = \mu_0 \mathrm{J_p}$ (20)

Magnetic propagation for Quasi-Static models $\nabla^2 \mathrm{B} = 0$ (21)

Magnetic fields created by oscillatory phenomena

Magnetic fields $\mathrm{E_{brain}}(t) \propto$ synaptic current dynamics, $\mathrm{B_{brain}}(t) \propto$ intracellular dendritic currents (22)

Intracelular Current and Magnetic field $\nabla \times \mathrm{B} = \mu_0 \mathrm{J_p}.$ (23)

Extracellular potential $\nabla \cdot (\sigma \nabla \phi) = \nabla \cdot \mathrm{J_p}.$ (24)

Classical superposition $\mathrm{E_{total}} = \sum_i \mathrm{E}_i \, , \mathrm{B_{total}} = \sum_i \mathrm{B}_i$ .....(25)

Oscillatory nature of brain EMF $\psi(t,r) = A(r)\sin(\omega t + \phi(r))$. (26)