Electromagnetic Field Models of Consciousness

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This brief literature review examines research linking brain electromagnetic fields and consciousness. We first outline the electromagnetic basis of brain function and established scientific results demonstrating their relationship to consciousness. We then discuss theories by McFadden, Pockett, Hunt and Schooler, and Strupp, which posit brain electromagnetic fields as the causal mechanism, not merely a byproduct, of consciousness. Finally, we assess supporting evidence, critiques, and open challenges in this field, consistent with ongoing debates in neuroscience.

I. INTRODUCTION

While there are various definitions of consciousness, this paper takes the stance that consciousness is the form of complex awareness most notably present in humans. Other life forms are capable of general environmental awareness and perhaps some are even capable of some level of consciousness but, strictly for simplicity, this paper defines consciousness as high-level information processing resulting in intentional motor actions as consistently demonstrated in human behavior.

Several problems persist in consciousness research that electromagnetic (EM) field theories strive to resolve: the *binding problem* questions how the brain integrates information distributed in spatially separated neurons into a unified experience; and the *Hard Problem* of consciousness asks how physical processes of the brain can produce the experience of consciousness (a mind/body problem).

Discussion begins with the EM basis of brain function and then explores several EM field theories of consciousness. The relationship between EM fields and cognition is established through analysis of the biophysical basis of neuronal EM activity, correlations between the flow of charged ions across neuron membranes and macroscopic EM fields, and processes for external detection and stimulation of intracranial EM fields. The next section addresses EM field models and mechanisms by which these fields may generate consciousness. Finally, attention is given to evidence, critiques, and current and proposed experiments intended to test and refine these theories.

II. EM BASIS OF BRAIN FUNCTION

The movement of ions in neurons produces electric and magnetic fields in the surrounding tissue. This section begins by examining the biophysics of these fields at the cellular level, then explores how they scale to produce the signals measurable by electroencephalography (EEG) and magnetoencephalography (MEG), and finally considers how external electric and magnetic stimulation methods can influence change neural activity.

A. Biophysical Basis of Neuronal EM Activity

Neurons maintain an electrical potential across their membranes (typically around −70 mV) due to selective permeability of different ions and uneven distribution of them. This resting potential provides the baseline for the action potential, or “spike,” which is a rapid fluctuation in membrane voltage. When depolarization of the membrane reaches a specific threshold, voltage-gated sodium channels open, and the membrane potential rises before falling again as potassium ions flow out. This change in voltage then travels down the axon and affects neighboring neurons.[1][2][3]

Hodgkin and Huxley explained this excitability by modeling the membrane as an electrical circuit containing a capacitor in parallel with ionic pathways for sodium, potassium, and a leak current (see Figure 1).[4] Each ionic path has a voltage-dependent conductance and an associated equilibrium potential that provides the driving force for that ion's movement.[2][4]

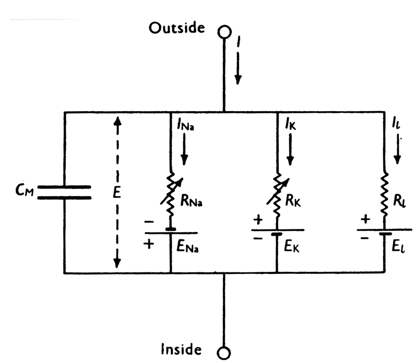

FIG. 1. Hodgkin and Huxley's electrical circuit model; reprinted from Ref. [4].

This model showed how an action potential arises from sodium entering the cell, followed by potassium leaving it which returns the membrane voltage to its resting level.[1][2][3][4] The ionic currents generated during an action potential are the main current sources in the surrounding conductive tissue. At low frequencies characteristic of neural activity, the resulting extracellular electric field can be described using the standard volume-conduction equation:

$$\nabla \cdot (\sigma \nabla \phi) = \nabla \cdot J_p,$$

where σ is the conductivity of the tissue, ϕ is the extracellular potential, and J_p is the primary transmembrane current density.[3][5]

B. From Neuronal Currents to EM Fields

Modeling of extracellular space has not stopped with treating it as an isotropic volume conductor. Building on the volume conductor model in the frequency range relevant for neural activity, Gold et al. assigned a purely ohmic conductivity ρ to the extracellular space.[6] Using this assumption, they used the Laplace equation for this medium to derive the point source solution,

$$\Phi = \frac{\rho I}{4\pi r},$$

where I is a point source of current and r is the distance from the source to the measurement. Because real neurons are elongated, they introduced the line source approximation. They used a detailed neuron model with Hodgkin–Huxley–type ion channels to compute the sodium and potassium currents flowing across the membrane during an action potential. Their simulation reproduced the waveform and amplitude of the extracellular signal, confirming that these voltages are direct physical consequences of sodium and potassium currents.[6]

C. Macroscopic EM Signals: EEG and MEG

To relate currents produced by single neurons to signals recorded outside head, it is important to define how groups of neurons collectively generate electric and magnetic fields that are measurable outside of the head. EEG records the brain's electrical fields whereas MEG records the brain's magnetic fields. These fields are mostly produced by pyramidal neurons (a type of multipolar neuron) of the cortex with dendrites roughly parallel to each other (neurons are arranged to form a palisade).[7]

When these neurons activate at the same time, the longitudinal components of these currents constructively interfere while their transverse components cancel. As a result, there is a laminar (sheet) current along the axon which creates an open electrical field that can be detected at a distance. At the same time, magnetic field lines are formed around the neuronal main axis.[8][9] These fields are the building blocks of EEG and MEG. In general, EEG shows the extracellular currents, while MEG is more sensitive to the primary intracellular currents.[7]

Because EEG measures signals at the scalp, trying to find their sources within the brain is an ill-posed problem: different combinations of sources could result in the same potential distribution on the skin. A common strategy is to make assumptions about the sources such as treating the source as an equivalent current dipole, with one pole being where current flows into the tissue (a sink) and the other where it flows out (a source). This simplification allows researchers to estimate the activity in brain.[7]

D. External EM Stimulation

So far, we considered how neural activity generates electric and magnetic fields measurable outside the head. Conversely, external electric or magnetic stimulation, including transcranial magnetic stimulation (TMS) and transcranial direct current stimulation (tDCS), can also *modulate* brain activity.

The non-invasive stimulation of the tDCS method applies a constant, low direct current (typically below 2 mA) through electrodes on the scalp.[10] This produces an electric field in the cortex that slightly shifts the resting membrane potential, making neurons slightly more or less likely to fire.[11] Because tDCS does not force neurons to fire, the direction and strength of its effects depend strongly on the baseline state of the targeted region. Cathodal stimulation hyperpolarizes neurons and reduces excitability, while anodal stimulation depolarizes neurons and increases excitability.[12] Also non-invasive, the TMS method uses brief magnetic pulses (often up to 2 Tesla and lasting around 100 microseconds) generated by a coil on the scalp to induce electric currents in the cortex based on Faraday's law of induction.[13] Unlike tDCS, the induced currents from TMS are strong enough to make neurons fire directly. The immediate effect depends on the target region of stimulation. For example, stimulation of the motor cortex produces a motor evoked potential (MEP), while stimulation of visual areas can generate phosphenes—perceived flashes of light.[14] Repetitive TMS (rTMS) uses trains of pulses over a few minutes instead of a single pulse, which can change the excitability of the targeted cortical region in a way that lasts longer than the stimulation period.[13][14]

III. EM FIELD THEORIES OF CONSCIOUSNESS

Building on research exploring how neural currents create measurable EM fields and how external fields can alter brain function, the following section discusses models explaining how these fields may *generate* conscious experience. Among these, the most developed models are the Conscious Electromagnetic Information (CEMI) model proposed by Johnjoe McFadden, Susan Pockett's EM field theory of consciousness, Hunt and Schooler's General Resonance Theory (GRT), and Strupp's EM Ion Field Theory of Consciousness (EIFT).

A. Conscious Electromagnetic Information Theory

Building on existing evidence that synchronous neuron firing correlates with consciousness, McFadden proposes that perturbations in the brain's EM field constitute the physical substrate of conscious experience.[15] In his CEMI theory, it is not simply neuronal firing that creates conscious awareness, but a feedback loop of the *synchrony* of their firing creating EM field fluctuations across the brain. These fluctuations induce local changes in membrane potentials and ion channel activity, enhancing the neuronal synchrony. This coupling between the EM field and neuronal activity is explained by the superposition principle: synchronized neural firing generates constructive interference in the field (and thus coherence supporting conscious awareness), whereas random firing generates destructive modulations yielding no net field. Evidence suggests that the evolution of capacity for higher levels of neuronal synchrony correspond with higher levels of awareness across species, such as the capacity for purposeful physical actions in humans. Although, too widespread synchrony—beyond that which supports consciousness—is considered to be pathological (e.g., in the case of seizures). In optimal function, the field coupling allows for the integration of information distributed in spatially separated neuronal processes and thus the generation of a unified conscious experience.

B. Pockett's EM Field Theory of Consciousness

In contrast, Pockett's theory posits that consciousness arises from the complex spatiotemporal patterns of the EM field rather than from neuronal behavior.[16] The property of consciousness arises only in specific *configurations* of the field. Like light and matter, consciousness is distributed through space and time non-uniformly, so specific configurations are considered to possess consciousness with any given localized region varying in the degree of conscious awareness. Pockett argues that because conscious experience is the sum of all current field configurations, the unity of experience is inherent in the theory thus eliminating the binding problem.

Pockett's models differs from McFadden's primarily in identifying of the key aspect of consciousness. McFadden focuses on the informational aspect of the EM field and its ability to "download" information to motor neurons, whereas Pockett identifies consciousness exclusively with the changing geometry of the EM field configurations.[15]

C. General Resonance Theory

Hunt and Schooler also focus on synchrony, using the term *resonance* and arguing that all matter resonates and proximal resonating matter tends to do so at the same frequency in General Resonance Theory (GRT).[17] Taking a panpsychic stance, in which all matter inherently possesses some level of "consciousness"—at rudimentary levels, termed awareness in this paper—they propose that it is the mechanisms of resonance that allow for rich manifestations of consciousness to occur. They further describe a hierarchy of consciousness in which shared resonance among micro-conscious entities (e.g., atomic particles and, at a higher level, cells) allows the formation of resonant macro-conscious entities (e.g., brains) and how this shared resonance results in a phase transition in the speed and bandwidth of information processing and exchange as the system transitions from electrochemical information exchange to faster, EM field exchange.

Hunt and Schooler refer to the binding problem as the "combination problem" or, as in their paper title, "the easy part of the Hard Problem," arguing like McFadden that consciousness arises from coherence.[17] In GRT however, consciousness occurs once a resonance coupling constant is reached. GRT also advances a more general, panpsychic perspective, with a focus on oscillatory hierarchy, in which consciousness arises from rudimentarily conscious matter via greater resonant connections.

D. EM Ion Field Theory of Consciousness

Building on these and other models for explaining consciousness with EM theory, Strupp suggests that the EM field activity in the brain does not serve the integrating role that allows for consciousness, but instead that *basic EM interactions* integrate disparate neuronal processes and thus resolve the binding problem.[18] This EM Ion Field Theory of Consciousness (EIFT) focuses on the Coulomb force, its electrostatic and magnetic influence on ions (detectable by EEG and MEG), and the inductive force. The charge parity of the Coulomb force contributes the differentiation necessary for information processing (positives and negatives), and the changing magnetic flux creates changes in membrane potentials and ion gradients, enabling long-distance effects. In this context, pyramidal cells function as dipoles with fluctuating, local epineural field potentials, and these serve as both transmitters and receivers (like antennas).

Like McFadden's and Pockett's theories but in contrast with GRT, EIFT posits the EM field of the brain as a field of consciousness.[18] EIFT takes a "reductive-physicalisitic" stance, claiming that physical theories alone can justify conscious experience and that consciousness does not lead to any non-physical properties. Thus, EIFT purports that just as the objective world is shaped by the EM properties, so too is the subjective world.

IV. SUPPORTING EVIDENCE AND CRITIQUES OF EM FIELD THEORIES

While research on EM field theories of consciousnesses is still in its experimental infancy, there have been critiques to both the theoretical and experimental work completed thus far.

For example, McFadden notes that EEG signals correlate to specific activity in the brain, but there are an infinite number of electrical sources that can induce the same EEG signal. Moreover, neural firing patterns originating from different parts of the brain or even from similar parts of the brain but for different reasons can lead to the same or similar patterns that could wrongly be construed as specific brain functions.[19]

EEG readings are a good indicator of brain function pertaining to neural firings, but do not conclusively indicate a state of consciousness.[19] For example, EM waves associated with certain conscious attributes cannot be isolated from preconscious processing.[16] An individual's actions can be monitored via EEG waves as seen in Table I, which can be considered as the "end result" of thought processing, but currently, the thought process that leads to that end result, in terms of EM waves, cannot be demonstrated. Pockett does note that EEG can be associated with "wakefullness" in patients, but it must be noted that this is separate from specific processing and actions of the individual. Because of this, only limited studies have shown that there is a link between EEG data and the subject's intent to perform an action.[19]

Constructive and destructive interference between coexisting EM fields due to multiple neural firings could misconstrue EEG readings. External EMF sources have been experimentally proven to alter neural firings in brain matter.[19] This was experimentally shown in thinly sliced slabs of brain tissue, but the effects on an "insulated," functioning human brain is limited.

The link between EM waves and processing is also not quite known as well. For example, EM waves could be coupled with something else that accompanies consciousness such as voluntary and involuntary attentiveness, or they could solely be the byproduct of preconscious neural processing. Experimentally though, studies trying to correlate EM waves to conscious experience such as motor reactions have not ruled out the subject's readiness factor.[16] For example, if researchers were to analyze EM wave activity in the brain with an individual's response to certain actions (such as the individual raising their left hand if they see a green light and their right hand if they see a yellow light), it is unclear how studies would explain the differences in mental pre-processing of the difference between the two colors. Studies have been limited to only demonstrating the wave activity correlated with the individual raising their hand.

Roy additionally noted that there are many causes of neural firings such as background noise in the brain and spontaneous firing. There is no way to separate meaningful firings that constitute information storage from insignificant firings. Separately, it is unknown how different parts of the brain receive separate neural firings and combine them into one information packet.[20]

Finally, McFadden conceited that in order for complex and distinct neural processes to reach consciousness, there needs to be some type of calculation that determines the processes' importance to register it as a cohesive thought. As of yet, no such neural computation is known, and the idea that certain neural firing patterns are specifically maintained for consciousness is still unknown.[19]

V. CURRENT AND FUTURE RESEARCH

Research on the brain's EM field behavior is ongoing including analysis of how communication pathways from the cerebral cortex to the thalamus—generated by pyramid neural firings—may cause depression in animals and studies on the effects of delayed electrical pulses between different types of nuclei.[20] Future research may investigate the disturbance of the electric fields between neuroanatomical regions of the brain by providing DC voltages in electrodes placed within certain regions of the brain (to warp the electric fields in areas of interest) or by providing low frequency voltages (to induce polarity between the different regions).

Additionally, proponents of EM field theories of consciousness offer potential reproducible measurements that could be used to test their theories. CEMI offers several testable predictions including: because the EM field is a wave phenomenon, information transmitted by neuron firing should scale algebraically (e.g., greater neuron involvement should correlate with a greater stimulus or response); complexity of thought should correspond with complexity in the EM field (likewise, lower complexity and outright lack of consciousness should correspond with reduced complexity); beings with more sophisticated conscious processes should have a higher level of electrical coupling between the field and neuronal activity; consciousness should demonstrate EM field dynamics (e.g., interference and Fourier analysis of information).[15] Pockett suggests a more speculative test: to replicate in detail the spatiotemporal configuration of the EM field produced in hearing a particular note and positioning a brain in the same location to assess whether the note can be "heard."[16] GRT proposes a scheme of "measurable correlates of consciousness," including "neural correlates of consciousness,' (measurable neural dynamics), "behavioral correlates of consciousness" (observable behaviors), and "creative correlates of consciousness" (spatiotemporally separate products of consciousness). However, GRT researchers lament the epistemological concern of the subjectivity of consciousness and suggest that a battery of tests would be more definitive for confirming the presence of consciousness.[17] EIFT theorists suggest further research of the effects on experience and behavior of callosotomy or methods of shielding between the hemispheres to interrupt long-distance communication and better understand the EM field of the brain.[18]

Name	Oscillation Frequency (cycles/sec)	Conscious Correlates
Fast waves (Over 8 Hz) Corresponding with Waking States		
Alpha	8 - 13 Hz	Relaxed wakefulness, eyes closed
Beta	13 - 30 Hz	Active cognition; during wakefulness, REM sleep, or occasionally slow wave sleep
Gamma	30 - 80 Hz	Scanning visual images (rare)
Slow waves (Under 8 Hz) Corresponding with Drowsiness and Sleep		
Theta	4 - 8 Hz	Drowsiness and sleep
Delta	1 - 4 Hz	Deep sleep: the deeper the sleep, the larger and slower the waves

TABLE I. Brain wave types, their frequencies, and conscious correlates; adapted from Ref. [16]

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VI. CONCLUSION

Research examining the role of EM fields in the origin of consciousness continues to be an active discipline with several cohesive theories under development. The physical processes of neuronal signaling and correlations between EM field activity and neural processes, as detected via EEG, are well established, but further research is needed to better understand the connections between patterns in neural firing and conscious decision-making.

Building on this established research, several models have been proposed to describe the relationship between the EM fields in the brain and consciousness. The Conscious Electromagnetic Information theory relates perturbations in the brain's EM field to consciousness. Pocket's theory emphasizes the changing geometry of field configurations. General Resonance Theory takes a panpsychic approach, positing a hierarchy of resonances of increasing consciousness. Strupp's EM Ion Field Theory of Consciousness argues that basic EM principles are sufficient to explain consciousness.

Future studies could investigate the communication between the cerebral cortex and thalamus, the effects of delayed electrical pulses, the disturbance of the EM fields between multiple parts of the brain, or test the various EM field models for consciousness. Continued progress in this field may clarify the nature and function of consciousness, including how EM fields influence behavior and experience and could provide insight into typical and atypical neural function, bringing the gap between material processes and the experience of consciousness.

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