Research Topics

Electromagnetic field theories of consciousness: Opportunities and obstacles

Edited by
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Electromagnetic field theories of consciousness: Opportunities and obstacles

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Editorial: Electromagnetic field theories of consciousness: opportunities and obstacles

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Editorial on the Research Topic
Electromagnetic field theories of consciousness: opportunities and obstacles

We are excited about the articles published on this Research Topic, "*Electromagnetic field theories of consciousness: opportunities and obstacles*," appearing here for the first time as a Research Topic.

While the concept of an EM field theory of mind is not new – it was first proposed over 70 years ago – it is indeed a new development to see this level of interest in this type of solution for the infamous "hard problem" of consciousness, and of course "the easy problems" of consciousness too. In fact, that's one of the key features of EM field theories of consciousness: they can address both the broader philosophical and fundamental physics questions of consciousness, and also the nuts and bolts of how the brain works from moment to moment and day to day.

Our Research Topic was, in part, a celebration of the 30th anniversary of the game-changing "neural correlates of consciousness" concept, first proposed as part of Crick and Koch's 1990 "neurobiological theory of consciousness." After now 33 years of research and theory-building, however, scholars in the science of consciousness are perhaps not much closer to a widely accepted theory of consciousness.

An electromagnetic (EM) field theory of consciousness attempts to explain the nature of consciousness and its relationship to matter in terms of fundamental EM fields and their dynamics. EM field theories view brain waves (delta, theta, etc.) and related EM fields as causally potent and functionally relevant to consciousness and the workings of the brain. EM field theories are a promising and growing subset of consciousness theories.

These theories originally emerged because they drew on considerable experimental evidence and provided potential solutions to traditional neuroscience's well-known problems. For example, how does the unity of consciousness arise from the functioning of billions of neurons and glia?

It is worth noting that most physicalist theories of consciousness boil down to a type of EM field theory of consciousness, whether or not this is acknowledged. This is the case because the atomic basis of the material comprising our brains, our bodies, and our biosphere is intrinsically electromagnetic. Other fundamental forces – gravity and the strong and weak nuclear forces – are likely not relevant to the dynamics of consciousness. In this manner, all of the physical dynamics that affect consciousness are ultimately various kinds of EM field dynamics, so even when a theory doesn't mention EM fields specifically, and if it is a physical theory of consciousness, then it will be based in some manner on EM fields.

The specific role of EM fields in the brain has been debated for many years, with some scholars maintaining the view that they are largely or entirely epiphenomenal – like the proverbial train whistle on a steam-powered locomotive – and other scholars viewing them as integral to the workings of consciousness. We are now at a point where experiments and data are being brought to bear to resolve this debate.

Our anchor article for this Research Topic was Hunt and Schooler's 2019 paper, "The easy part of the Hard Problem: A resonance theory of consciousness." The General Resonance Theory (GRT) of consciousness, described in that paper, may be viewed as a type of electromagnetic theory of consciousness and posits that electromagnetic (EM) fields may be the primary seat of consciousness. As such, the dynamics of these fields become the measurable dynamics of consciousness. This remains a hypothesis but experiments are being conducted in various labs around the world to test this exciting hypothesis. The various papers in this issue shed light on this hypothesis and related ideas surrounding EM field theories.

MacIver's paper, "*Consciousness and Inward Electromagnetic Field Interactions*," provides insights into how electromagnetic fields generated by neuronal membranes might be crucial for consciousness. The paper addresses early criticisms of EM field theories and explores the use of non-linear dynamic analyses of EEG recordings to track consciousness levels. MacIver proposes an inward view of EMF energy "clouds," suggesting that EM fields focused inward to the brain could provide stronger ephaptic connections to neural circuits and thus be causal, contrary to early critiques of EM field theories. This paper is significant for the Research Topic as it supports the idea that EM fields likely play a key role in mind-brain integration, and offers a new perspective on interpreting EEG data in the context of consciousness.

Keppler's paper, "*Building blocks for the development of a self-consistent electromagnetic field theory of consciousness*," aims to assemble the foundational elements for creating a fundamental electromagnetic field theory of consciousness. It emphasizes the quantum electrodynamics vacuum state as a vibrant energy source, termed the zero-point field (ZPF), which is central to all electromagnetic phenomena. The paper theorizes that the brain functions as a resonant oscillator, selectively coupling to specific ZPF modes to compose specific phenomenal states. This theory posits consciousness as a result of the brain's interaction with ZPF modes, highlighting the significance of neurotransmitter-ZPF interactions for future research.

Young, Robbins et al.'s paper, "*From micro to macro: the combination of consciousness*," explores the concept of consciousness extending beyond the individual to a collective level. It examines the synchronization of neuronally generated EM fields between individuals, proposing a model where individual agents may merge into a hierarchical cognitive system. The paper utilizes the axioms and conjectures of General Resonance Theory to describe this phenomenon of interpersonal resonant combination, suggesting that synchronized EM fields through behavioral interactions can optimize information flow and alter the conscious states of the agents involved. This research extends EM field approaches by proposing a physical basis for "group consciousness" and its empirical investigation.

Kitchener and Hales' paper, "*What neuroscientists think, and don't think, about consciousness*," discusses the prevailing approach of neuroscientists toward consciousness, primarily focusing on its generation and characteristics, without a consensus on its underlying mechanism. It emphasizes the integral role of neurons and electromagnetic fields in brain functioning, underscoring the complexity of electromagnetic phenomena from the atomic level upwards in the brain. This research adds to the EM field theories of consciousness by highlighting the fundamental physics of neurons and glial cells in the brain, suggesting that a deeper investigation into the electromagnetic fields at the cellular scale could offer insights into the mechanisms of consciousness.

Winters' paper, "*The temporally-integrated causality landscape: reconciling neuroscientific theories with the phenomenology of consciousness*," presents the Temporally-Integrated Causality Landscape (TICL) as a framework to understand consciousness. It compares and contrasts TICL with other neuroscientific theories like Integrated Information Theory, GRT, and Global Neuronal Workspace Theory, emphasizing the importance of electromagnetic forces in neural causality. The paper contributes to the electromagnetic field theories of consciousness by exploring the spatial-temporal dynamics of brain activity and their relation to conscious experiences, proposing a more comprehensive approach to understanding consciousness in neurological terms.

The Young, Hunt et al. paper, "*The slowest shared resonance: a review of electromagnetic field oscillations between central and peripheral nervous systems*," examines the role of EM field oscillations in both central and peripheral nervous systems. It explores the principle of the Slowest Shared Resonance (SSR) within GRT, positing that consciousness arises from the combination of micro- to macro-consciousness in coupled field systems, determined by the slowest common denominator frequency. This paper contributes to the Research Topic by suggesting a spatiotemporal hierarchy of brain-body shared resonance systems and supports the principle of SSR within EM field theories of consciousness.

Hales and Ericson's paper, "*Electromagnetism's bridge across the explanatory gap: how a neuroscience/physics collaboration delivers explanation into all theories of consciousness*," focuses on integrating neuroscience and fundamental physics to address the "explanatory gap" in consciousness research. It argues that the brain, as an electromagnetic field object, can be understood through the standard model of particle physics, suggesting that all theories of consciousness are essentially interpretations of specific EM field behaviors in brain tissue. This interdisciplinary approach aims to provide a unified explanation applicable to all theories of consciousness, exploring how subjectivity might emerge from electromagnetic fields.

Ward and Guevara's paper, "*Qualia and phenomenal consciousness arise from the information structure of an electromagnetic field in the brain*," explores the physical substrate for subjective, phenomenal consciousness (P-consciousness). It proposes that the electromagnetic (EM) field generated by the brain's electrical charges serves as this substrate. The paper posits that a part of the thalamus in mammals generates this critical EM field, which is structured by emulating information from external and internal sources, forming the basis of qualia experienced in P-consciousness. This research contributes to EM field theories by suggesting how the brain's EM fields may structure the experience of consciousness.

Bond's paper, "*The contribution of coherence field theory to a model of consciousness*," delves into the emerging paradigm in neuroscience that views resonance as central to consciousness. It discusses the role of oscillating flows within the brain's electric field in producing mind from matter and explores how vibrations in nanoscale atomic structures and photonic waves may contribute to consciousness. The paper touches on the "binding problem" in consciousness theory, questioning how trillions of atoms and billions of cells integrate to produce a unified medium of awareness. Bond also investigates how EM fields within neurons influence signal transmission, surpassing explanations based solely on ion diffusion. The paper's relevance lies in its exploration of how light interactions with biological systems and internal EM fields in the brain could contribute to consciousness, aligning with the Research Topic's focus on EM fields.

Hunt and Jones "*Fields or firings? Comparing the spike code and the electromagnetic field hypothesis*," proposes that EM fields, from the local to the global, may be the primary seat of consciousness in the brain. It contrasts this hypothesis with the conventional spike code approach that focuses on synaptic firing as the basis for consciousness. The paper posits that while neurons and synaptic transmissions are necessary for consciousness, they are not sufficient to explain its complexity. It argues that consciousness arises from the intricate interplay between neuronal activities and EM fields, suggesting that these fields, rather than being epiphenomenal, play a central role in the emergence and unification of conscious cognition. The authors highlight the importance of EM fields in various cognitive processes, including memory and perception, and call for further research in this area. They present various sources of evidence that oscillating neural EM fields may make firing in neural circuits oscillate, and these oscillating circuits may help unify and guide conscious cognition.

"*Consciousness: Meat or EMF?*" by McFadden challenges conventional theories of consciousness that rely on the brain's neuronal matter, proposing instead that the substrate of consciousness is the brain's electromagnetic field. The paper critiques existing theories, showing how EM field theories provide novel insights into consciousness and potentially offer a route toward building artificial consciousness. It distinguishes between intelligence and consciousness, arguing that EM theories account for the emergence of consciousness through natural selection and the brain's neural activity. This paper contributes significantly to the Research Topic by offering a comprehensive examination of EM theories against established criteria and by discussing the evolutionary aspects of consciousness in relation to electromagnetic fields.

"*Electromagnetic-field theories of qualia: can they improve upon standard neuroscience?*" by Jones and Hunt, explores the potential of EM field theories in explaining qualia, the subjective aspects of consciousness like colors, pains, and emotions, which have been challenging for standard neuroscience to fully account for. The authors review various EM field theories of qualia of how our various qualia arise, assessing their strengths and weaknesses, and contrasting them with traditional synaptic neuroscience approaches. They focus on three key problems: identifying neural correlates of the various qualia, integrating qualia into a unified perceptual experience, and addressing the "hard problem" of consciousness, namely the metaphysical relationship between neural events and qualia. The paper suggests that EM field theories, while still in development, could offer promising avenues for better understanding consciousness and qualia, potentially improving upon the explanations provided by standard neuroscience.

Lacalli's paper, "*Consciousness and its hard problems: separating the ontological from the evolutionary*," focuses on the role of evolution in theories of consciousness. It introduces the concept of a "consciousness machine" to explore how ontology and evolution contribute to consciousness. The paper examines whether consciousness originates from electromagnetic field effects or neural connectivity and information flow. It also discusses the evolution of consciousness and agency, suggesting that agency might be more a developmental than evolutionary process. The paper explores the emergence of consciousness and behavior links, suggesting a divide between phenomenal experience and agency in developmental and evolutionary timescales. The author concludes that understanding consciousness involves both easy problems, like the neurocircuitry innovations for consciousness, and hard problems, like the ontological basis of subjective experience.

The final paper, Gómez-Emilsson and Percy "*Don't forget the boundary problem! How EM field topology can address the overlooked cousin to the binding problem for consciousness*," explores the "boundary problem" in theories of consciousness, an issue often overshadowed by the more widely discussed binding problem. The authors propose that EM field topology could be a key to understanding how distinct boundaries of consciousness are formed. They argue that while existing theories focus on how various experiences are unified into a single first-person perspective (the binding problem), they often neglect the question of why these unified experiences have specific spatial and temporal boundaries (the boundary problem). By examining EM field theories, the paper suggests that topological segmentation within EM fields could conceptually and empirically address this boundary problem, offering a novel perspective in consciousness studies.

In closing, it is our strong hope that these papers extend discussion and research into EM field theories for many years to come — and may even lead to a more widely accepted set of solutions to the Hard Problem as well as the easy problems of consciousness.

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Building Blocks for the Development of a Self-Consistent Electromagnetic Field Theory of Consciousness

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The goal of this work is to compile the basic components for the construction of an electromagnetic field theory of consciousness that meets the standards of a fundamental theory. An essential cornerstone of the conceptual framework is the vacuum state of quantum electrodynamics which, contrary to the classical notion of the vacuum, can be viewed as a vibrant ocean of energy, termed zero-point field (ZPF). Being the fundamental substrate mediating the electromagnetic force, the ubiquitous ZPF constitutes the ultimate bedrock of all electromagnetic phenomena. In particular, resonant interaction with the ZPF is critical for understanding rapidly forming, long-range coherent activity patterns that are characteristic of brain dynamics. Assuming that the entire phenomenal color palette is rooted in the vibrational spectrum of the ZPF and that each normal mode of the ZPF is associated with an elementary shade of consciousness, it stands to reason that conscious states are caused by the coupling of the brain to a particular set of normal modes selectively filtered from the full frequency spectrum of the ZPF. From this perspective, the brain is postulated to function as a resonant oscillator that couples to a specific range of ZPF modes, using these modes as a keyboard for the composition of an enormous variety of phenomenal states. Theoretical considerations suggest that the brain-ZPF interface is controlled by altering the concentrations of neurotransmitters, placing the detailed study of the neurotransmitter-ZPF interaction at the center of future research activities.

Keywords: consciousness, electromagnetic field theory, quantum electrodynamics, zero-point field, phase transitions, coherent states, resonance, neurotransmitters

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INTRODUCTION

As is typical of the spirit of discovery, those who are involved in consciousness research are driven by the ambition to develop the most comprehensive theory possible of their central research subject. Therefore, our efforts are directed toward the goal of constructing a fundamental theory of consciousness (TOC) that we expect to reveal the nature of phenomenal qualities (qualia), incorporate qualia seamlessly into the scientific framework, explain the relationship between phenomenal states and physical states, and correctly predict the phenomenal state of any system given its physical state.

In the following, arguments will be advanced that TOC candidates must establish a link to the fundamental theories of physics, particularly to the fundamental theory of electromagnetism. Building on this groundwork, the purpose of this article is to discuss the main aspects and pitfalls that have to be considered when constructing an electromagnetic (EM, or alternatively em) field TOC, to give an idea of a promising direction of thought with regard to an EM basis of conscious states, and to briefly outline future directions of research on the way to a full-fledged TOC. The main focus here lies on addressing fundamental conceptual issues with the aim of surmounting obstacles and identifying opportunities for the advancement of the research field.

LINKING CONSCIOUSNESS TO THE FOUNDATIONS OF PHYSICS

One of the essential requirements for the development of a TOC consists in achieving a seamless integration of qualia into the edifice of science. In view of the fact that the phenomenal properties that constitute our mental inner world differ significantly from the properties we use to describe the physical world, it has long been pointed out that the prevalent variants of physicalism are fraught with explanatory gaps (Levine, 1983; Chalmers, 1995, 1996; Nagel, 2012). In the following, two of these gaps will be referred to as the cosmic latecomer problem and the demarcation problem. The *cosmic latecomer problem* arises in all approaches that consider conscious states as a product of cosmic evolution. According to such theories, consciousness awakens as soon as the structural conditions, the organizational principles, or the processes characterizing a physical system exceed a critical level of complexity, so that conscious states are assumed to emerge from or to be identical with certain activity patterns of sufficiently complex systems, as is the case for the brains of highly developed living beings (Edelman, 1989, 2003; Tononi and Edelman, 1998; Seth et al., 2006). This way of thinking, however, results in an ontological discontinuity and leaves its critics with the open questions of how, with the first-time generation of such activity patterns in a sufficiently developed brain, consciousness could appear in a previously insentient universe and what it is about these patterns that "suddenly switches consciousness on" (Velmans, 2007). Furthermore, in the absence of a properly specified basis for consciousness, the proponents of the latecomer hypothesis are confronted with the *demarcation problem*, which consists in the challenge of explaining why a certain level of organization should be associated with subjective awareness and what exactly distinguishes activity patterns that are accompanied by conscious experiences from those patterns that are devoid of any phenomenal qualities (Seager, 1999).

To get around the cosmic latecomer problem, it seems reasonable to resort to the fundamental description level of the physical world and to strive to establish a relationship between consciousness and the foundational entities and mechanisms that show up in the cosmic blueprint. This blueprint is reflected in the standard model of particle physics and cosmology (Cottingham and Greenwood, 2007; Rich, 2010), and even though there are unresolved issues and indications of physics beyond the standard model (Klapdor-Kleingrothaus et al., 2011; Nagashima, 2014; Bambi and Dolgov, 2016), the conceptual bedrock this model relies on provides a deep understanding of our universe.

Among the fundamental forces incorporated in the standard model, the EM interaction is of central importance for the development of a TOC, as it is by far the dominant force on the length scale of biological organisms. However, while the EM interaction has the status of a fundamental interaction, classical electrodynamics, being incomplete, does not have the status of a fundamental theory (Frisch, 2005). Rather, the theory that accounts for all the subtleties of the EM interaction is quantum electrodynamics (QED) which, contrary to the classical notion of the vacuum, includes a vacuum state "with a rich structure, full of energy and potentialities" (Kuhlmann et al., 2002). According to a recent school of thought, subsumed under the umbrella of stochastic electrodynamics, which strives to find a consistent description of reality and to derive the formalism of QED from this description, the vacuum state is interpreted as an omnipresent EM background field, termed *zero-point field* (ZPF), characterized by a spectrum of uncorrelated normal modes that satisfy a unique spectral energy density (Marshall, 1963, 1965; Boyer, 1975; De la Peña and Cetto, 1994, 1995, 2001, 2006; De la Peña et al., 2009, 2015). From this perspective, it is the ZPF that acts as the fundamental substrate of the EM force and, therefore, constitutes the ultimate basis of the EM interaction. The key insight, then, is that *all EM phenomena are mediated by the ubiquitous ZPF*. Thus, while the classical theory offers, for example, just a suitable calculation formula for the electric potential of a given configuration of charges, the complete theory reveals the underlying mechanisms and explains how this potential originates from the charges being embedded in the ZPF (Cohen-Tannoudji et al., 1997).

Apart from disclosing fundamental mechanisms, the relevance of QED to consciousness research rests on being pivotal to the understanding of complex dynamical systems. More precisely, a proper description of the dynamics of biological systems, particularly the dynamics of the brain that is characterized by long-range coherence and rapidly forming activity patterns resulting from *second-order phase transitions*, necessitates the theoretical foundations of QED and the presence of the ZPF (Del Giudice et al., 1985, 2005; Freeman and Vitiello, 2006). In such *macroscopic quantum phenomena*, the collective behavior of the system components is caused by their resonant coupling to a system-specific set of relevant normal modes selectively filtered from the full frequency spectrum of the ZPF (De la Peña and Cetto, 2001; De la Peña et al., 2015). In the event that the resonant system-ZPF interaction leads to the formation of a *transiently stable attractor*, a partial organization of the local field ensues in such a way that the relevant ZPF modes become highly correlated (De la Peña and Cetto, 2006; De la Peña et al., 2009), meaning that "the orchestration of an attractor requires the initially chaotic ZPF to change over to a partially ordered state" (Keppler, 2018).

The long-range order phenomena characteristic of neural activity patterns cannot be accounted for on the basis of classical physics since a viable mechanism governing the collective cooperation of system components is missing (Freeman and Vitiello, 2006). Rather, theoretical considerations on the foundations of quantum physics reveal that the emergence of coherent structures can be attributed to the unique properties of the ZPF (De la Peña and Cetto, 2001; De la Peña et al., 2009), the essential finding being that this field operates as a "formative agent behind the scenes" that has no equivalent in classical physics (Keppler, 2016).

Taken together, the above findings suggest that the ZPF could be the key entity for the development of a TOC. Before exploring this idea in detail, let us first take a brief look at classical EM approaches to consciousness.

LOOKING AT CLASSICAL ELECTROMAGNETIC FIELD THEORIES OF CONSCIOUSNESS

In order to highlight the main obstacles of classical EM field theories, the analysis will be confined to the most prominent representatives of this branch and their basic premises (Pockett, 2000, 2002, 2012; John, 2001, 2002; McFadden, 2002a,b, 2013, 2020; Fingelkurts et al., 2009, 2010, 2013). For a more extensive discussion, see Jones (2013). While all representatives share the assumption that the brain's EM field is the substrate of consciousness, the various approaches differ significantly in their conceptual underpinnings. One of the theories holds the view that "conscious experiences are identical with certain spatial EM patterns generated by neural activity" (Pockett, 2012). According to other theories, consciousness is thought of as an "emergent property of sufficiently organized energy" (John, 2002), understood as the "inner experience of information… encoded in the brain's em field" (McFadden, 2002b), or assumed to be related to the "nested hierarchy of spatiotemporal patterns of 3D electromagnetic fields produced by neuronal assemblies" (Fingelkurts et al., 2013). This means that with respect to the psychophysical nexus, i.e., regarding the relationship between phenomenal states and physical states, the theories represent markedly different positions: Pockett's approach is a variant of identity theory, John's approach a variant of emergentism, McFadden's approach is based on the double-aspect theory of information (Chalmers, 1995, 1996), whereas Fingelkurts et al. (2013) defend supervenience through isomorphism.

Ultimately, independent of the position, all these approaches consider consciousness as a cosmic latecomer and face the demarcation problem which consists in the challenge of presenting a convincing model that explains what exactly distinguishes EM field patterns which are accompanied by conscious experiences from those patterns or configurations to which phenomenal zero-states are to be assigned. In this regard, the proponents of classical EM field theories are aware of the need for a threshold criterion, emphasizing that conscious experiences are limited to "certain spatial EM patterns" (Pockett, 2012) or "sufficiently organized energy" (John, 2002), or pointing out that the "minimal characteristic of an em field to qualify as conscious must surely be that is possesses sufficient complexity" (McFadden, 2020). However, it remains largely open what counts as *sufficiently complex* to exceed the threshold of consciousness. Proposed solutions to make the criterion more tangible consist in imposing constraints on the EM field in such a way that the defining feature of conscious field configurations is hypothesized to reside in very specific spatial patterns of local field potentials (Pockett, 2012), or that the conscious component of the brain's EM field is linked to the capability of "initiating motor actions" (McFadden, 2002b) or "transferring thoughts to another conscious being" (McFadden, 2020). Yet, proposals of this kind raise the question as to why any constraint on a physical field, whether configurational, functional, or communicational, should mark the dividing line between conscious and unconscious states.

In essence, all variants of classical EM field theories of consciousness encounter an explanatory gap that can be traced back to the missing link to the fundamental theory of the EM interaction and the absence of a comprehensible mechanism which endows certain field configurations, or the brain processes that give rise to these field configurations, with phenomenal qualities. In order to find a way out of the quandary, we will now return to the conceptual basis of QED.

TOWARD A SELF-CONSISTENT ELECTROMAGNETIC FIELD THEORY OF CONSCIOUSNESS

A promising approach to the scientific understanding of conscious systems is predicated on the notion that phenomenal qualities are irreducible features of reality and that the ZPF is the substrate of consciousness (Keppler, 2012, 2013, 2016, 2018, 2020; Shani and Keppler, 2018; Keppler and Shani, 2020). In concrete terms, it is proposed that the ZPF is "an *inherently sentient medium*", i.e., "a foundational *dual-aspect* component of the cosmos, the extrinsic appearance of which is physical in nature and the intrinsic manifestation of which is phenomenological in nature" (Keppler and Shani, 2020), implying that the entire color palette of consciousness is rooted in the vibrational spectrum of the ZPF and that each normal mode is associated with an elementary shade of consciousness (see **Figure 1A**). Considering its disordered ground state, the ZPF can thus be conceived as "a *formless sea of consciousness* or unstructured ocean of awareness that carries an enormous range of potentially available phenomenal nuances" (Shani and Keppler, 2018). To sum up, the ZPF is postulated to be a psychophysical "entity that embodies the principles of physics and at the same time contains within itself the phenomenological basis of ultimate reality" (Keppler and Shani, 2020). The inner structure of the ZPF is thereby arranged in field modes which reveal themselves physically as oscillations with specific frequencies and phenomenologically as shades of awareness.

Following this line of thought, it stands to reason that conscious systems employ a universal mechanism through which they tap into the phenomenal color palette predetermined by the ZPF. Recalling the previously outlined mechanism underlying macroscopic quantum phenomena, one is led to assume that "*the formation of transiently stable coherent states is an essential prerequisite for conscious awareness*" (Keppler, 2018). According to this mechanism, it is postulated that conscious states are caused by resonant system-ZPF interaction, as a result of which the system falls into an attractor and the relevant ZPF modes involved in the interaction combine into an attractor-specific

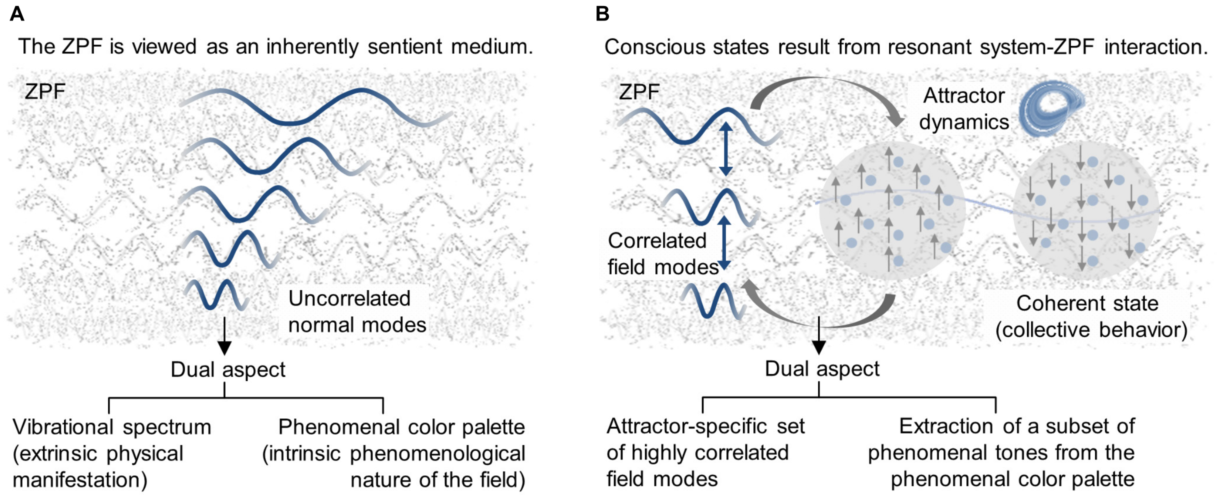

FIGURE 1 | Toward a self-consistent EM field theory of consciousness. **(A)** The zero-point field (ZPF) is assumed to be a foundational dual-aspect component of the cosmos, the extrinsic manifestation of which is physical in nature and the intrinsic manifestation of which is phenomenological in nature. **(B)** It is postulated that conscious systems employ a universal mechanism through which they tap into the phenomenal color palette predetermined by the ZPF. According to this mechanism, conscious states are caused by resonant system-ZPF interaction, as a result of which the system falls into an attractor and the relevant ZPF modes involved in the interaction combine into an attractor-specific set of highly correlated field modes.

set of highly correlated field modes (see **Figure 1B**). From this perspective, "a physical system acquires phenomenal properties by entering into a temporary liaison with the cosmic field of consciousness and extracting a subset of phenomenal tones from the spectrum of all phenomenal tones potentially present in the field" (Keppler and Shani, 2020), suggesting that "*a distinctive feature of conscious systems in comparison to non-conscious systems must be the capacity to modulate the omnipresent field of consciousness*" (ibid.). In vivid terms, then, conscious experiences are restricted to those systems that manage to play the keyboard of the ubiquitous field of consciousness.

Based on the presented approach, a clear dividing line can be drawn between conscious and non-conscious systems. Even though all types of systems are permeated by the ubiquitous ZPF and thus, from a phenomenological perspective, are surrounded by an ocean of potential, yet undifferentiated consciousness, the formation of concrete conscious states is confined to those systems that can dynamically interact with the ZPF, which requires the resonant coupling of the system to a set of ZPF modes. These dynamical properties are unique to quantum systems, whose coupling to the ZPF is reflected in long-range coherence and attractor formation. Importantly, "attractors manage the transition from potentiality to actuality," implying that "a potential conscious state is actualized once an attractor is fully unfolded" and a corresponding attractor-specific modification of the ZPF arises (Shani and Keppler, 2018). In contrast, classical systems are not dynamically coupled to the ZPF, indicating that this kind of systems cannot access the ZPF's immanent phenomenal color palette and therefore cannot engender concrete phenomenal states.

Crucially, the findings of neuroscience are fully compatible with this line of reasoning. More precisely, the body of empirical evidence indicates that a stream of consciousness is based on periodically recurring, highly synchronous neural activity (Desmedt and Tomberg, 1994; Rodriguez et al., 1999; Engel and Singer, 2001; Melloni et al., 2007; Doesburg et al., 2009; Gaillard et al., 2009; Singer, 2015). In particular, the studies of Freeman revealed that the neural correlates of conscious perception can be equated with large-scale patterns of coherent gamma-band activity that occur at theta rates and represent *attractors* in an attractor landscape (Freeman, 2004, 2005, 2007, 2009). The fact that the rapid synchronization of the large-scale patterns proceeds in the form of scale-free neuronal avalanches suggests that the attractor formations involve critical phenomena and *second-order phase transitions* (Beggs and Plenz, 2003; Kitzbichler et al., 2009; Cocchi et al., 2017), the rigorous explanation of which requires the framework of quantum field theory (Zinn-Justin, 1996; Freeman and Vitiello, 2006, 2007). These insights support the hypotheses that the orchestration of coherent neural activity patterns takes place via the ZPF and that the brain generates an individual stream of consciousness by periodically modulating the ZPF (Keppler, 2013, 2016, 2018, 2020).

In summary, the brain is postulated to function as a *resonant oscillator* that couples to a specific range of ZPF modes, using these modes as a keyboard for the composition of an enormous variety of conscious states. As far as the concept of resonance is concerned, the approach presented here shares commonalities with the theory of Hunt and Schooler (2019), according to which resonance-induced phase transitions underlie the formation of macro-conscious entities. The ZPF-based conceptual framework specifies the resonance mechanism in greater detail, sets the course for clear-cut future research projects (see the following section), and meets the key criteria to be imposed on a TOC candidate. In particular, it has explanatory power and respects the principles of parsimony and universality by spelling out how dynamical systems interacting with the ZPF gain "access to the ubiquitous substrate of consciousness" and "acquire both their physical properties and their phenomenal qualities by use of one and the same mechanism" (Keppler, 2018), the proposed modulation mechanism being "intelligible and completely transparent" (Keppler, 2020). This mechanism, which "is deeply rooted in the foundations of the universe", results in "well-defined distinctive features between conscious and non-conscious systems as well as conscious and unconscious brain processes" (Keppler and Shani, 2020), thereby remedying the demarcation problem the classical approaches struggle with. Finally, it is worth mentioning that beyond the processes behind conscious perception, the presented approach also provides satisfactory interpretations of the neural correlates of self-referential conscious processes (Keppler, 2018) and episodic memory processes (Keppler, 2020).

To conclude this section, some notes are appropriate with regard to the positioning of the ZPF-based conceptual framework in the current theory landscape and the clarification of the differences to as well as the intersections with contemporary neuroscientific theories of consciousness, the most prominent representatives of which assume conscious awareness to be associated with a global workspace that connects and coordinates widely separated brain areas (Baars, 1988, 2005; Dehaene and Naccache, 2001; Dehaene et al., 2006), with synchronously firing coalitions of neurons (Crick and Koch, 1990, 2003), with a dynamic core corresponding to a functional cluster of neurons forming transiently stable activity patterns (Tononi and Edelman, 1998; Edelman, 2003), or with recurrent processing (Lamme, 2006). Overall, the ZPF-based approach leads to a reinterpretation and reassessment of the neural correlates to the effect that they should not be held responsible for the mysterious generation of consciousness but, rather, viewed as corollaries of a deeper mechanism by which neural cell assemblies couple to an omnipresent field of consciousness. In this scenario, the recurrent formation of transiently stable activity patterns displaying gamma synchrony indicates that streams of consciousness have their origin in the periodic modification of this field. From this perspective, the ZPF, which is accountable for the coordination of brain areas and the synchronization of brain activity, may be understood as *the truly global workspace* in which conscious processes unfold. As for the comparison of the ZPF-based approach with the integrated information theory (Tononi, 2004, 2008; Oizumi et al., 2014), the reader is referred to Keppler (2016), while a detailed discussion of the positioning of the approach in the field of panpsychism can be found in Shani and Keppler (2018).

LOOKING AHEAD TO FUTURE RESEARCH AVENUES

The outlined modulation mechanism guides us to place the brain-ZPF interface at the center of future research activities. A suitable basis for the description of the phase transitions underlying the formation of coherent activity patterns can be found in the theory of *superradiant phase transitions* (Hepp and Lieb, 1973; Wang and Hioe, 1973). Such phase transitions arise when the interaction between an ensemble of molecules and the ZPF exceeds a critical coupling strength, which is precisely the case when selected ZPF modes are in resonance with the characteristic transition frequencies between molecular energy levels and the concentration (density) of molecules lies above a critical threshold (Preparata, 1995; Del Giudice et al., 2005). The wavelengths of the selected ZPF modes define the extent of the *coherence domain*, in the interior of which the molecules exhibit collective behavior, causing a decrease in the energy per molecule and energetically stabilizing the coherence domain against its environment (Preparata, 1995; Del Giudice et al., 2005). The presence of interfacial water can lead to an expansion of coherence domains and provides additional shielding from destructive thermal influences (Del Giudice et al., 2010, 2013).

Applying this theory to the brain, it is to be expected that neuromodulators control the observed phase transitions by regulating the concentrations of neurotransmitters (Chialvo, 2010), in agreement with the finding that the formation of neuronal avalanches and synchronized activity patterns depends on the density of neurotransmitters, such as the common glutamate and GABA receptor agonists, as well as neuromodulators, such as dopamine (Stewart and Plenz, 2006; Gireesh and Plenz, 2008). In conjunction with the notion that the receptor activations driving the emergence of neuronal avalanches are induced by specific vibrational modes of the participating agonists (Kubo et al., 2001, 2003), these insights point to the crucial role of neurotransmitter-ZPF interactions in the generation of conscious states (for an illustration of the mechanism, see **Figure 2**). As cortical areas differ in their receptor fingerprints (Zilles and Palomero-Gallagher, 2017), the characteristic neurotransmitter-receptor profile of an area should determine the set of selected ZPF modes and, consequently, the spectrum of accessible phenomenal tones.

The focus of future research efforts must be to understand the proposed mechanism more precisely from a theoretical point of view and to substantiate the mechanism experimentally. The corresponding research program can be divided into physical, neurochemical, neurophysiological, and phenomenological avenues of collecting evidence, taking into account the different organizational levels and dimensions of conscious processes.

At the basic physical level, corroborating empirical evidence for the proposed mechanism can be obtained by demonstrating the modulation of the ZPF during conscious states, which requires the measurement of phase correlations between ZPF modes. In recent years, the experimental basis has been developed to perform direct measurements of field correlations of the electromagnetic vacuum state (Riek et al., 2015; Benea-Chelmus et al., 2019), so that these methods may be applicable to the detailed investigation of brain-induced ZPF modulations in the foreseeable future.

The neurochemical level is primarily concerned with exploring the neurotransmitter-ZPF interface. For this purpose, following the conceptual groundwork laid by Preparata (1995), the formalism of QED needs to be applied to derive equations describing the interaction between ZPF modes and

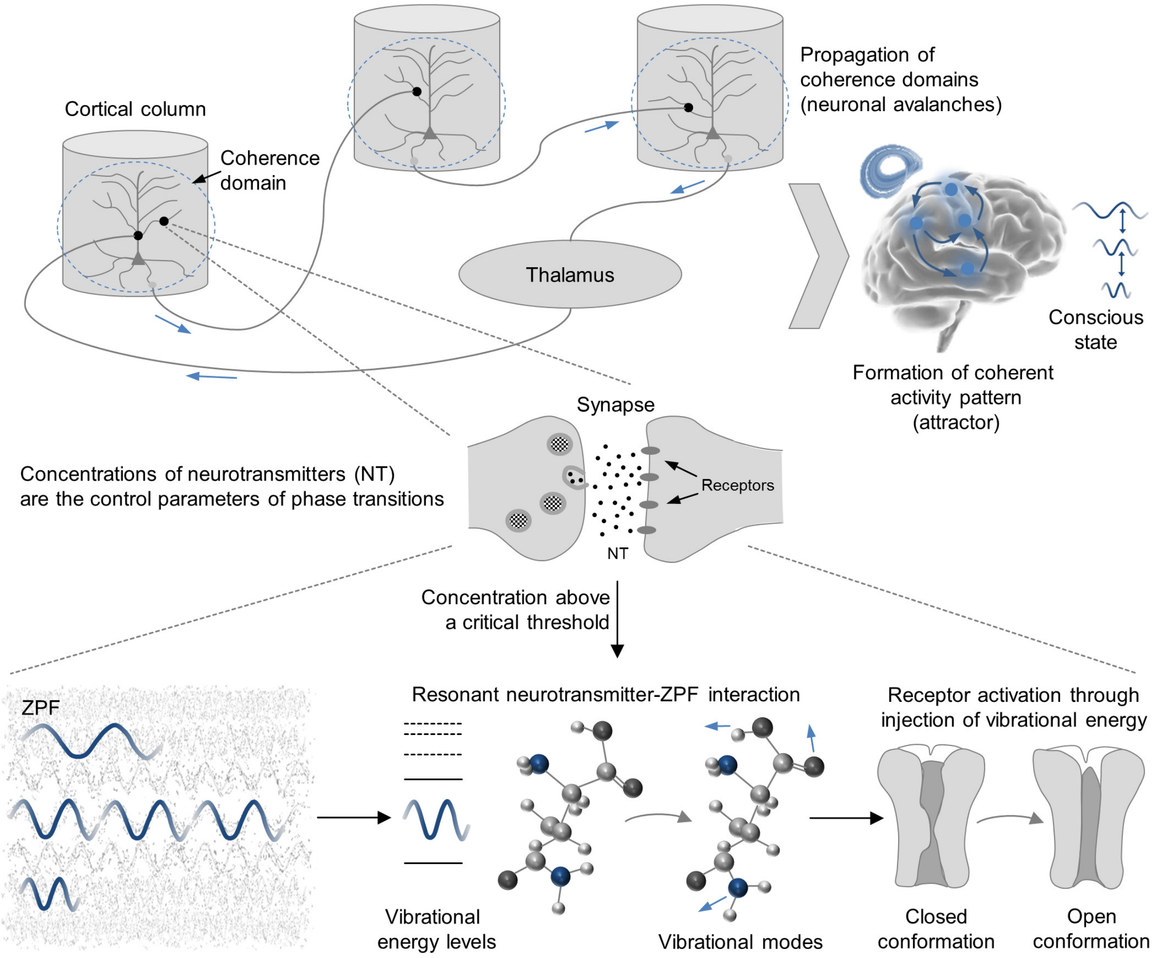

FIGURE 2 | The neurophysiological mechanisms underlying conscious processes. It is postulated that the phase transitions underlying the formation of coherent activity patterns (attractors) are triggered by modulating the concentrations of neurotransmitters. When the concentration of neurotransmitter molecules lies above a critical threshold and selected ZPF modes are in resonance with the characteristic transition frequencies between molecular energy levels, receptor activations ensue that drive the emergence of neuronal avalanches. The set of selected ZPF modes that is involved in the formation and stabilization of an attractor determines the phenomenal properties of the conscious state.

vibrational modes of the neurotransmitter molecules. Using these equations, the critical concentrations required for resonant neurotransmitter-ZPF coupling and thus for the induction of phase transitions can be calculated. Comparing the calculated critical neurotransmitter concentrations with experimentally determined concentrations will allow conclusions to be drawn about whether neurotransmitter-ZPF interactions play a crucial role in the generation of the cortical phase transitions that occur when conscious states are formed.

To get to the neurophysiological level, the theoretical apparatus may be used to perform simulations aimed at studying the macroscopic consequences of neurotransmitter-ZPF interactions and making theoretical predictions about the dynamical characteristics of the neural correlates of consciousness (NCC). Based on these predictions, advanced analysis techniques can be employed to screen the available data for signatures that, in addition to the evidence already presented in the previous section, lend further support to the notion of the ZPF being instrumental in the formation of the activity patterns constituting the NCC.

Both the level of neurotransmitters and the macroscopic system level provide the opportunity to collect supplementary empirical evidence for the existence of the brain-ZPF interaction mechanism, resulting from the prediction that the postulated "phase transitions are expected to be accompanied by collective emissions of photons" (Keppler, 2020). The experimental methods for detecting such phenomena, termed ultraweak photon emissions or biophoton emissions, are well developed (Popp et al., 1994; Cohen and Popp, 1997; Popp, 2003). At the neurotransmitter level, photon emissions should be triggered upon exceeding a critical density, and indeed studies using a biophoton imaging system revealed that above a critical threshold concentration glutamate causes a significant elevation of biophotonic activity (Tang and Dai, 2014). At the macroscopic level, characteristic photon pulses should follow the theta cycle, due to the finding that during processes of conscious perception the phase transitions that induce the formation of coherent activity patterns occur at theta rates. There is preliminary experimental evidence to support this hypothesis (Kobayashi et al., 1999), just as there are indications that biophotonic activity depends on the state of consciousness (Van Wijk and Van Wijk, 2005; Van Wijk et al., 2005). Future studies must be designed to allow comparison of measured photon signals with theoretical expectations with the goal of reconstructing the modification of the ZPF associated with a particular conscious state.

Once sufficient expertise has been accumulated in the methods outlined above for measuring or reconstructing the physical concomitants of conscious states, one can venture into the exploration of the phenomenological structure of the ZPF. This project involves guiding subjects through a variety of phenomenal states, determining the modified ZPF state associated with each phenomenal state, and systematically calibrating the determined ZPF states based on the first-person accounts (Keppler, 2016), leading to the "derivation of psychophysical mapping rules between particular qualia and particular sets of phase-locked ZPF modes" (Shani and Keppler, 2018).

In case of corroboration, the conceptual framework presented here would lead to a refinement of previously formulated ideas, according to which the activity of coherently oscillating cell assemblies is orchestrated by synaptic input to the dendrites of cortical pyramidal cells (Nunez and Srinivasan, 2006), neurotransmitters might change the resonance properties of cortical areas by altering their coupling strengths to "synaptic action fields" (ibid.), and oscillating activity in the "synaptodendritic web" is assumed to play an important role in conscious processes (Pribram and Meade, 1999).

In conclusion, the presented approach is based on the position that, in order to avoid explanatory gaps, a TOC candidate must build a bridge to the fundamental theories of physics and that particularly QED, being the fundamental theory of the electromagnetic interaction and being crucial for the understanding of complex dynamical systems, is of central importance for the development of a TOC. More specifically, the ZPF is assumed to be a foundational psychophysical component of the cosmos, implying that each normal mode of the ZPF is associated with an elementary shade of consciousness. It is argued that the brain generates conscious states by resonant coupling to ZPF modes, setting the course for a number of novel research projects on the study of consciousness.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

The author confirms being the sole contributor of this work and has approved it for publication.

REFERENCES

Baars, B. J. (1988). *A Cognitive Theory of Consciousness*. New York: Cambridge University Press.

Baars, B. J. (2005). Global workspace theory of consciousness: toward a cognitive neuroscience of human experience. *Prog. Brain Res*. 150, 45–53. doi: 10.1016/S0079-6123(05)50004-9

Bambi, C., and Dolgov, A. D. (2016). *Introduction to Particle Cosmology: The Standard Model of Cosmology and its Open Problems*. Berlin: Springer.

Beggs, J. M., and Plenz, D. (2003). Neuronal avalanches in neocortical circuits. *J. Neurosci.* 23, 11167–11177. doi: 10.1523/JNEUROSCI.23-35-11167.2003

Benea-Chelmus, I. C., Settembrini, F. F., Scalari, G., and Faist, J. (2019). Electric field correlation measurements on the electromagnetic vacuum state. *Nature* 568, 202–206. doi: 10.1038/s41586-019-1083-9

Boyer, T. H. (1975). Random electrodynamics: the theory of classical electrodynamics with classical electromagnetic zero-point radiation. *Phys. Rev. D* 11, 790–808. doi: 10.1103/PhysRevD.11.790

Chalmers, D. J. (1995). Facing up to the problem of consciousness. *J. Conscious. Stud.* 2, 200–219.

Chalmers, D. J. (1996). *The Conscious Mind: In Search of a Fundamental Theory*. Oxford: Oxford University Press.

Chialvo, D. R. (2010). Emergent complex neural dynamics. *Nat. Phys.* 6, 744–750. doi: 10.1038/nphys1803

Cocchi, L., Gollo, L. L., Zalesky, A., and Breakspear, M. (2017). Criticality in the brain: a synthesis of neurobiology, models and cognition. *Prog. Neurobiol.* 158, 132–152. doi: 10.1016/j.pneurobio.2017.07.002

Cohen, S., and Popp, F. A. (1997). Biophoton emission of the human body. *J. Photochem. Photobiol. B Biol.* 40, 187–189. doi: 10.1016/s1011-1344(97)00050-x

Cohen-Tannoudji, C., Dupont-Roc, J., and Grynberg, G. (1997). *Photons and Atoms: Introduction to Quantum Electrodynamics*. Berlin: Wiley-VCH.

Cottingham, W. N., and Greenwood, D. A. (2007). *An Introduction to the Standard Model of Particle Physics*, Second Edn. Cambridge: Cambridge University Press.

Crick, F., and Koch, C. (1990). Towards a neurobiological theory of consciousness. *Sem. Neurosci.* 2, 263–275.

Crick, F., and Koch, C. (2003). A framework for consciousness. *Nat. Neurosci.* 6, 119–126. doi: 10.1038/nn0203-119

De la Peña, L., and Cetto, A. M. (1994). Quantum phenomena and the zeropoint radiation field. *Found. Phys.* 24, 917–948. doi: 10.1007/BF02067655

De la Peña, L., and Cetto, A. M. (1995). Quantum phenomena and the zeropoint radiation field II. *Found. Phys.* 25, 573–604. doi: 10.1007/BF02059007

De la Peña, L., and Cetto, A. M. (2001). Quantum theory and linear stochastic electrodynamics. *Found. Phys.* 31, 1703–1731. doi: 10.1023/A:1012670800317

De la Peña, L., and Cetto, A. M. (2006). The foundations of linear stochastic electrodynamics. *Found. Phys.* 36, 350–368. doi: 10.1007/s10701-005-9020-1

De la Peña, L., Cetto, A. M., and Valdés-Hernández, A. (2015). *The Emerging Quantum. The Physics Behind Quantum Mechanics*. Cham: Springer International Publishing.

De la Peña, L., Valdés-Hernández, A., and Cetto, A. M. (2009). Quantum mechanics as an emergent property of ergodic systems embedded in the zero-point radiation field. *Found. Phys.* 39, 1240–1272. doi: 10.1007/s10701-009-9348-z

Dehaene, S., Changeux, J. P., Naccache, L., Sackur, J., and Sergent, C. (2006). Conscious, preconscious, and subliminal processing: a testable taxonomy. *Trends Cogn. Sci.* 10, 204–211. doi: 10.1016/j.tics.2006.03.007

Dehaene, S., and Naccache, L. (2001). Towards a cognitive neuroscience of consciousness: basic evidence and a workspace framework. *Cognition* 79, 1–37. doi: 10.1016/s0010-0277(00)00123-2

Del Giudice, E., De Ninno, A., Fleischmann, M., Mengoli, G., Milani, M., Talpo, G., et al. (2005). Coherent quantum electrodynamics in living matter. *Electromagn. Biol. Med.* 24, 199–210. doi: 10.1080/15368370500379574

Del Giudice, E., Doglia, S., Milani, M., and Vitiello, G. (1985). A quantum field theoretical approach to the collective behaviour of biological systems. *Nucl. Phys. B* 251, 375–400. doi: 10.1016/0550-3213(85)90267-6

Del Giudice, E., Spinetti, P. R., and Tedeschi, A. (2010). Water dynamics at the root of metamorphosis in living organisms. *Water* 2, 566–586. doi: 10.3390/w2030566

Del Giudice, E., Tedeschi, A., Vitiello, G., and Voeikov, V. (2013). Coherent structures in liquid water close to hydrophilic surfaces. *J. Phys. Conf. Ser.* 442:012028. doi: 10.1088/1742-6596/442/1/012028

Desmedt, J. E., and Tomberg, C. (1994). Transient phase-locking of 40 Hz electrical oscillations in prefrontal parietal cortex reflects the process of conscious somatic perception. *Neurosci. Lett.* 168, 126–129. doi: 10.1016/0304-3940(94)90432-4

Doesburg, S. M., Green, J. J., McDonald, J. J., and Ward, L. M. (2009). Rhythms of consciousness: binocular rivalry reveals large-scale oscillatory network dynamics mediating visual perception. *PLoS One* 4:e6142. doi: 10.1371/journal.pone.0006142

Edelman, G. M. (1989). *The Remembered Present: A Biological Theory of Consciousness*. New York: Basic Books.

Edelman, G. M. (2003). Naturalizing consciousness: a theoretical framework. *Proc. Natl. Acad. Sci. U. S. A.* 100, 5520–5524. doi: 10.1073/pnas.0931349100

Engel, A. K., and Singer, W. (2001). Temporal binding and the neural correlates of sensory awareness. *Trends Cogn. Sci.* 5, 16–25. doi: 10.1016/S1364-6613(00)01568-0

Fingelkurts, A. A., Fingelkurts, A. A., and Neves, C. F. H. (2009). Phenomenological architecture of a mind and operational architectonics of the brain: the unified metastable continuum. *New Math. Nat. Comput.* 5, 221–244. doi: 10.1142/S1793005709001258

Fingelkurts, A. A., Fingelkurts, A. A., and Neves, C. F. H. (2010). Natural world physical, brain operational, and mind phenomenal space–time. *Phys. Life Rev.* 7, 195–249. doi: 10.1016/j.plrev.2010.04.001

Fingelkurts, A. A., Fingelkurts, A. A., and Neves, C. F. H. (2013). Consciousness as a phenomenon in the operational architectonics of brain organization: criticality and self-organization considerations. *Chaos Solitons Fractals* 55, 13–31. doi: 10.1016/j.chaos.2013.02.007

Freeman, W. J. (2004). Origin, structure, and role of background EEG activity. Part 1. Analytic Amplitude. *Clin. Neurophysiol.* 115, 2077–2088. doi: 10.1016/j.clinph.2004.02.029

Freeman, W. J. (2005). Origin, structure, and role of background EEG activity. Part 3. Neural frame classification. *Clin. Neurophysiol.* 116, 1118–1129. doi: 10.1016/j.clinph.2004.12.023

Freeman, W. J. (2007). Indirect biological measures of consciousness from field studies of brains as dynamical systems. *Neural Netw.* 20, 1021–1031. doi: 10.1016/j.neunet.2007.09.004

Freeman, W. J. (2009). Deep analysis of perception through dynamic structures that emerge in cortical activity from self-regulated noise. *Cogn. Neurodyn.* 3, 105–116. doi: 10.1007/s11571-009-9075-3

Freeman, W. J., and Vitiello, G. (2006). Nonlinear brain dynamics as macroscopic manifestation of underlying many-body field dynamics. *Phys. Life Rev.* 3, 93–118. doi: 10.1016/j.plrev.2006.02.001

Freeman, W. J., and Vitiello, G. (2007). The dissipative quantum model of brain and laboratory observations. *Electr. J. Theor. Phys.* 4, 1–18. doi: 10.1142/9789812779953_0009

Frisch, M. (2005). *Inconsistency, Asymmetry, and Non-Locality: A Philosophical Investigation of Classical Electrodynamics*. New York: Oxford University Press.

Gaillard, R., Dehaene, S., Adam, C., Clemenceau, S., Hasboun, D., Baulac, M., et al. (2009). Converging intracranial markers of conscious access. *PLoS Biol.* 7:e1000061. doi: 10.1371/journal.pbio.1000061

Gireesh, E. D., and Plenz, D. (2008). Neuronal avalanches organize as nested theta and beta/gamma-oscillations during development of cortical layer 2/3. *Proc. Natl. Acad. Sci. U. S. A.* 105, 7576–7581. doi: 10.1073/pnas.0800537105

Hepp, K., and Lieb, E. H. (1973). On the superradiant phase transition for molecules in a quantized radiation field: the dicke maser model. *Ann. Phys.* 76, 360–404. doi: 10.1016/0003-4916(73)90039-0

Hunt, T., and Schooler, J. W. (2019). The easy part of the hard problem: a resonance theory of consciousness. *Front. Hum. Neurosci.* 13:378. doi: 10.3389/fnhum.2019.00378

John, E. R. (2001). A field theory of consciousness. *Conscious. Cogn.* 10, 184–213. doi: 10.1006/ccog.2001.0508

John, E. R. (2002). The neurophysics of consciousness. *Brain Res. Rev.* 39, 1–28. doi: 10.1016/s0165-0173(02)00142-x

Jones, M. W. (2013). Electromagnetic-field theories of mind. *J. Conscious. Stud.* 20, 124–149.

Keppler, J. (2012). A conceptual framework for consciousness based on a deep understanding of matter. *Philos. Study* 2, 689–703. doi: 10.17265/2159-5313/2012.10.001

Keppler, J. (2013). A new perspective on the functioning of the brain and the mechanisms behind conscious processes. *Front. Psychol.* 4:242. doi: 10.3389/fpsyg.2013.00242

Keppler, J. (2016). On the universal mechanism underlying conscious systems and the foundations for a theory of consciousness. *Open J. Phil.* 6, 346–367. doi: 10.4236/ojpp.2016.64034

Keppler, J. (2018). The role of the brain in conscious processes: a new way of looking at the neural correlates of consciousness. *Front. Psychol.* 9:1346. doi: 10.3389/fpsyg.2018.01346

Keppler, J. (2020). The common basis of memory and consciousness: understanding the brain as a write–read head interacting with an omnipresent background field. *Front. Psychol.* 10:2968. doi: 10.3389/fpsyg.2019.02968

Keppler, J., and Shani, I. (2020). Cosmopsychism and consciousness research: a fresh view on the causal mechanisms underlying phenomenal states. *Front. Psychol.* 11:371. doi: 10.3389/fpsyg.2020.00371

Kitzbichler, M. G., Smith, M. L., Christensen, S. R., and Bullmore, E. (2009). Broadband criticality of human brain network synchronization. *PLoS Comput. Biol.* 5:e1000314. doi: 10.1371/journal.pcbi.1000314

Klapdor-Kleingrothaus, H. V., Krivosheina, I. V., and Viollier, R. (eds) (2011). "Physics beyond the standard models of particles, cosmology and astrophysics," in *Proceedings of the Fifth International Conference – Beyond 2010*, (Singapore: World Scientific Publishing).

Kobayashi, M., Takeda, M., Sato, T., Yamazaki, Y., Kaneko, K., Ito, K., et al. (1999). In vivo imaging of spontaneous ultraweak photon emission from a rat's brain correlated with cerebral energy metabolism and oxidative stress. *Neurosci. Res.* 34, 103–113. doi: 10.1016/s0168-0102(99)00040-1

Kubo, M., Odai, K., Sugimoto, T., and Ito, E. (2001). Quantum chemical study of agonist-receptor vibrational interactions for activation of the glutamate receptor. *J. Biochem.* 129, 869–874. doi: 10.1093/oxfordjournals.jbchem.a002931

Kubo, M., Shiomitsu, E., Odai, K., Sugimoto, T., Suzuki, H., and Ito, E. (2003). Agonist-specific vibrational excitation of glutamate receptor. *J. Mol. Struct.* 639, 117–128. doi: 10.1016/j.theochem.2003.07.003

Kuhlmann, M., Lyre, H., and Wayne, A. (eds) (2002). *Ontological Aspects of Quantum Field Theory*. Singapore: World Scientific Publishing.

Lamme, V. A. F. (2006). Towards a true neural stance on consciousness. *Trends Cogn. Sci.* 10, 494–501. doi: 10.1016/j.tics.2006.09.001

Levine, J. (1983). Materialism and qualia: the explanatory gap. *Pac. Philos. Q.* 64, 354–361.

Marshall, T. W. (1963). Random electrodynamics. *Proc. R. Soc. London A* 276, 475–491. doi: 10.1098/rspa.1963.0220

Marshall, T. W. (1965). Statistical electrodynamics. *Proc. Camb. Phil. Soc.* 61, 537–546. doi: 10.1017/S0305004100004114

McFadden, J. (2002a). Synchronous firing and its influence on the brain's electromagnetic field: evidence for an electromagnetic field theory of consciousness. *J. Conscious. Stud.* 9, 23–50.

McFadden, J. (2002b). The conscious electromagnetic information (cemi) field theory: the hard problem made easy? *J. Conscious. Stud.* 9, 45–60.

McFadden, J. (2013). The cemi field theory: closing the loop. *J. Conscious. Stud.* 20, 153–168.

McFadden, J. (2020). Integrating information in the brain's EM field: the cemi field theory of consciousness. *Neurosci. Conscious.* 2020:niaa016. doi: 10.1093/nc/niaa016

Melloni, L., Molina, C., Pena, M., Torres, D., Singer, W., and Rodriguez, E. (2007). Synchronization of neural activity across cortical areas correlates with conscious perception. *J. Neurosci.* 27, 2858–2865. doi: 10.1523/JNEUROSCI.4623-06.2007

Nagashima, Y. (2014). *Beyond the Standard Model of Elementary Particle Physics*. Weinheim: Wiley-VCH.

Nagel, T. (2012). *Mind and Cosmos: Why the Materialist Neo-Darwinian Conception of Nature is Almost Certainly False*. New York: Oxford University Press.

Nunez, P. L., and Srinivasan, R. (2006). *Electric Fields of the Brain: The Neurophysics of EEG*, Second Edn. New York: Oxford University Press.

Oizumi, M., Albantakis, L., and Tononi, G. (2014). From the phenomenology to the mechanisms of consciousness: integrated information theory 3.0. *PLoS Comput. Biol.* 10:e1003588. doi: 10.1371/journal.pcbi.1003588

Pockett, S. (2000). *The Nature of Consciousness: A Hypothesis*. Lincoln: iUniverse.

Pockett, S. (2002). Difficulties with the electromagnetic field theory of consciousness. *J. Conscious. Stud.* 9, 51–56.

Pockett, S. (2012). The electromagnetic field theory of consciousness: a testable hypothesis about the characteristics of conscious as opposed to non-conscious fields. *J. Conscious. Stud.* 19, 191–223.

Popp, F. A. (2003). "Biophotons — background, experimental results, theoretical approach and applications," in *Integrative Biophysics*, eds F. A. Popp and L. Beloussov (Dordrecht: Springer), 387–438. doi: 10.1007/978-94-017-0373-4_12

Popp, F. A., Gu, Q., and Li, K. H. (1994). Biophoton emission: experimental background and theoretical approaches. *Mod. Phys. Lett. B* 8, 1269–1296. doi: 10.1142/s0217984994001266

Preparata, G. (1995). *QED Coherence in Matter*. Singapore: World Scientific Publishing.

Pribram, K. H., and Meade, S. D. (1999). Conscious awareness: processing in the synaptodendritic web. *New Ideas Psychol.* 17, 205–214. doi: 10.1016/S0732-118X(99)00024-0

Rich, J. (2010). *Fundamentals of Cosmology*, Second Edn. Berlin: Springer.

Riek, C., Seletskiy, D. V., Moskalenko, A. S., Schmidt, J. F., Krauspe, P., Eckart, S., et al. (2015). Direct sampling of electric-field vacuum fluctuations. *Science* 350, 420–423. doi: 10.1126/science.aac9788

Rodriguez, E., George, N., Lachaux, J. P., Martinerie, J., Renault, B., and Varela, F. J. (1999). Perception's shadow: long distance synchronization of human brain activity. *Nature* 397, 430–433. doi: 10.1038/17120

Seager, W. (1999). *Theories of Consciousness: An Introduction and Assessment*. London: Routledge.

Seth, A. K., Izhikevich, E., Reeke, G. N., and Edelman, G. M. (2006). Theories and measures of consciousness: an extended framework. *Proc. Natl. Acad. Sci. U.S. A.* 103, 10799–10804. doi: 10.1073/pnas.0604347103

Shani, I., and Keppler, J. (2018). Beyond combination: how cosmic consciousness grounds ordinary experience. *J. Am. Philos. Assoc.* 4, 390–410. doi: 10.1017/apa.2018.30

Singer, W. (2015). "The ongoing search for the neuronal correlate of consciousness," in *Open MIND*, eds T. Metzinger and J. M. Windt (Frankfurt: MIND Group).

Stewart, C. V., and Plenz, D. (2006). Inverted-u profile of dopamine-NMDA-mediated spontaneous avalanche recurrence in superficial layers of rat prefrontal cortex. *J. Neurosci.* 23, 8148–8159. doi: 10.1523/JNEUROSCI.0723-06.2006

Tang, R., and Dai, J. (2014). Spatiotemporal imaging of glutamate-induced biophotonic activities and transmission in neural circuits. *PLoS One* 9:e85643. doi: 10.1371/journal.pone.0085643

Tononi, G. (2004). An information integration theory of consciousness. *BMC Neurosci.* 5:42. doi: 10.1186/1471-2202-5-42

Tononi, G. (2008). Consciousness as integrated information: a provisional manifesto. *Biol. Bull.* 215, 216–242. doi: 10.2307/25470707

Tononi, G., and Edelman, G. M. (1998). Consciousness and complexity. *Science* 282, 1846–1851. doi: 10.1126/science.282.5395.1846

Van Wijk, E. P. A., Ackerman, J., and Van Wijk, R. (2005). Effect of meditation on ultraweak photon emission from hands and forehead. *Forsch. Komplementärmed. Klass. Naturheilkd.* 12, 107–112. doi: 10.1159/000084028

Van Wijk, R., and Van Wijk, E. P. A. (2005). An introduction to human biophoton emission. *Forsch. Komplementärmed. Klass. Naturheilkd.* 12, 77–83. doi: 10.1159/000083763

Velmans, M. (2007). The co-evolution of matter and consciousness. *Synth. Philos.* 44, 273–282.

Wang, Y. K., and Hioe, F. T. (1973). Phase transition in the Dicke model of superradiance. *Phys. Rev. A* 7, 831–836. doi: 10.1103/PhysRevA.7.831

Zilles, K., and Palomero-Gallagher, N. (2017). Multiple transmitter receptors in regions and layers of the human cerebral cortex. *Front. Neuroanat.* 11:78. doi: 10.3389/fnana.2017.00078

Zinn-Justin, J. (1996). *Quantum Field Theory and Critical Phenomena*. New York: Oxford University Press.

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The Temporally-Integrated Causality Landscape: Reconciling Neuroscientific Theories With the Phenomenology of Consciousness

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In recent years, there has been a proliferation of neuroscientific theories of consciousness. These include theories which explicitly point to EM fields, notably Operational Architectonics and, more recently, the General Resonance Theory. In phenomenological terms, human consciousness is a unified composition of contents. These contents are specific and meaningful, and they exist from a subjective point of view. Human conscious experience is temporally continuous, limited in content, and coherent. Based upon those phenomenal observations, pre-existing theories of consciousness, and a large body of experimental evidence, I derived the Temporally-Integrated Causality Landscape (TICL). In brief, the TICL proposes that the neural correlate of consciousness is a structure of temporally integrated causality occurring over a large portion of the thalamocortical system. This structure is composed of a large, integrated set of neuronal elements (the System), which contains some subsystems, defined as having a higher level of temporally-integrated causality than the System as a whole. Each Subsystem exists from the point of view of the System, in the form of meaningful content. In this article, I review the TICL and consider the importance of EM forces as a mechanism of neural causality. I compare the fundamentals of TICL to those of several other neuroscientific theories. Using five major characteristics of phenomenal consciousness as a standard, I compare the basic tenets of Integrated Information Theory, Global Neuronal Workspace, General Resonance Theory, Operational Architectonics, and the Temporo-spatial Theory of Consciousness with the framework of the TICL. While the literature concerned with these theories tends to focus on different lines of evidence, there are fundamental areas of agreement. This means that, in time, it may be possible for many of them to converge upon the truth. In this analysis, I conclude that a primary distinction which divides these theories is the feature of spatial and temporal nesting. Interestingly, this distinction does not separate along the fault line between theories explicitly concerned with EM fields and those which are not. I believe that reconciliation is possible, at least in principle, among those theories that recognize the following: just as the contents of consciousness are distinctions within consciousness, the neural correlates of conscious content should be distinguishable from but fall within the spatial and temporal boundaries of the full neural correlates of consciousness.

Keywords: consciousness, TICL, phenomenology, EM field, causality

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INTRODUCTION

Consciousness, the subjectivity which manifests in the waking and dreaming brain, is perhaps the greatest mystery in all of science. The scientific method is a system for establishing objective matters of fact by the empirical means of observation and controlled experiment. Up to this point, we have no objective means for establishing the existence or lack of existence of a state of consciousness in any system, the human brain or otherwise. As individual human minds, the contents of experience are self-evident and undeniable. It is within our human minds that scientific experiments and explananda have been contrived. We, the conscious minds of human beings, make observations, derive predictions, test hypotheses, and draw conclusions. It is no simple feat to turn the focus from the materials and forces of the objective world, of which we can make such observations, back upon the observer. Consciousness is a subjective experience itself, and only within such an experience can any observation be made. The challenge faced by neuroscientific theorists in this domain is to establish, upon solid evidence, a relationship between conscious events and objective, physical structures or processes in the brain. Toward that aim, a large and growing body of neuroscience literature is making progress. This includes progress in the elucidation of two major theoretical frameworks: Integrated Information Theory (IIT) and Global Neuronal Workspace Theory (GNW). But, serious attention should be extended to include other established frameworks, such as Operational-Architectonics (O-A) and Temporo-Spatial Theory of Consciousness (TTC). In particular, O-A has been making substantial theoretical progress (Fingelkurts et al., 2019, 2020). Important recent efforts have been made to compare and contrast a wide range of consciousness theories (Northoff and Lamme, 2020). Georg Northoff and his colleagues have been working to establish a new direction in cognitive neuroscience with a focus on spatial-temporal dynamics of brain activity (Northoff et al., 2020). It is my opinion that such a project is of great value for advancing our understanding of consciousness and cognition. Here, I extend the process of bringing the Temporally-Integrated Causality Landscape (TICL) into contact with the larger field. The first article on the TICL focused on a contrast with IIT and GNW (Winters, 2020). Beginning from an exploration of phenomenal human consciousness and its contents, I proposed the TICL as a framework for the full neural correlate of consciousness. Here, I revisit the TICL and the phenomenal features of human consciousness upon which it is based. I expand upon the TICL, by making its grounding in physics more explicit and by expanding upon its implications. Subsequently, I compare the insights of the TICL with a wider scope of established neuroscientific frameworks, including some of those (O-A and General Resonance Theory, GRT) which explicitly invoke electromagnetics (EM). A new consolidation among theoretical frameworks, upon the grounds of reason and evidence, might accelerate the progress toward a true understanding of consciousness as a physical phenomenon in the universe. With that scientific understanding in hand, we will be able to establish, with the force of scientific certainty, the subjectivity or lack of subjectivity inhering in a human brain state or that of any other physical system.

THE TEMPORALLY-INTEGRATED CAUSALITY LANDSCAPE

According to the TICL, a distinction can be made between consciousness as a unified whole and the individual contents which compose the unity. Thus, a distinction is made between the System and its Subsystems, which are understood to be the full neural correlates of consciousness and the content-specific neural correlates of consciousness, respectively. **Figure 1** illustrates the basic structure of the TICL, with the System (A) represented by a large, light gray circle occupying much of the cortex and the thalamus. The System is that component of the thalamocortical brain which exhibits some non-zero level of temporally-integrated causality (TIC) among all its neuronal elements. In **Figure 1**, the level of TIC is shown with the darkness of the color gray. The System (A) contains the Subsystems (B-F) which change over time. **Figure 1** should be understood as an illustration of concepts. The Subsystems (B-F) do not reflect anatomical accuracy. Integration, in the context of TICL, refers to causal influence in both directions. Thus, integrated elements are characterized by having causality upon one another over some timeframe and, therefore, indirect causality upon their own future state. Among a group of integrated elements, the TIC is the amount of causal influence over the time that it takes to achieve it. The System (A) is irreducible in the sense that it only includes those neuronal elements which are contributing causality and are subject to effects under the influence of the other neuronal elements over some period of time. The System alone is insufficient for consciousness. Evidence of this is provided by global synchrony as might occur with certain types of epileptic seizures which co-occur with loss of conscious experience (Blumenfeld, 2011). The TICL explains this by necessitating the existence of Subsystems (B-F) within the System for the consciousness of content. According to the TICL, a Subsystem is a group of neuronal elements within the System which have a higher level of TIC than the System-at-large, shown in **Figure 1** having darker gray colors. This can occur by alteration of the numerator (the amount of causality) or the denominator (the time required) or both. In this way, the activity corresponding to the Subsystem is nested within the time and space of the System. Accordingly, the content which is produced by a Subsystem is nested within the phenomenal time and space produced across the System. The dynamics of Subsystems provide meaningful content from the point of view (the dotted arrows) of the System. These dynamics are illustrated in the figure as changes in the size and grayness of the nested circles (B-F). For example, Subsystem B can be seen to change in size and TIC (grayness), across time. Subsystem E appears only briefly. Subsystem F appears within the pre-existing Subsystem D. The dotted arrows are a crude illustration showing that the System (A) is the point of view upon the Subsystems. Since the Subsystems have higher TIC than the System, they are experienced in specific and meaningful ways. The Subsystemic TIC is intrinsic to the Systemic TIC. In fact, the TICL predicts that the Subsystemic

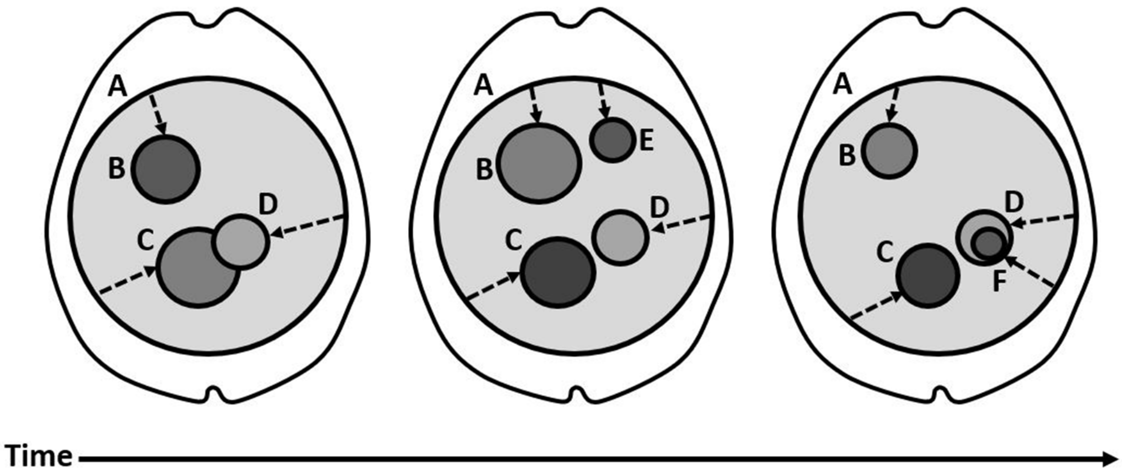

FIGURE 1 | *The Structure of the Temporally-Integrated Causality Landscape*. (A) The large, light gray circle corresponds to the System, which has a non-zero level of TIC and covers a substantial area of the thalamus and cortex. Over time, the System persists with little overall change. The dotted arrows are meant to show that the System is the point of view upon the nested Subsystems. (B–F) The smaller, darker gray circles correspond to Subsystems within the System. (B) This Subsystem shows a change in size and TIC (darkness of color) over time, with less TIC and spatial extent in the third panel relative to the first. (C) This Subsystem shows a change in size and TIC over time, with higher TIC but smaller spatial extent in the third panel than in the first. (D) This Subsystem shows some drift in position relative to Subsystem (C), over the three panels. In the third panel, it comes to contain a smaller Subsystem (F), which has even higher TIC (darker gray). (E) This Subsystem appears briefly in the second panel, then disappears again. F, This small Subsystem appears within the spatial domain of Subsystem D. It has a higher level of TIC (darker gray).

activity is experienced in the form of its geometrical relationship to the System, in space and time. It is thus directly experienced as relational meaning (color, shape, size, pitch, tone, good, bad, painful, strange, scary, sad, interesting, and so on). All neuronal activities in the thalamocortical system which do not contribute to sufficiently high TIC to participate in a Subsystem, are subconscious, background activities. This means that a threshold for consciousness is built-in to the functional organization of the thalamocortical brain.

The brain is a material structure composed of interconnected neurons. Subcellular components, such as axons, dendrites, and pre- and post-synaptic specializations are subject to local causal influences. An important clarification is needed in order to advance the scientific search for consciousness in terms of fundamental physics: Causality requires force. We tend to discuss neuronal function in terms of the movement of charged particles and the interactions of molecules. For example, we understand that sodium, potassium, and chloride ions, moving across the cell membrane, are responsible for the polarization and depolarization of the cell. We know that ion movement across the lipid bilayer requires protein channels, such as voltage-gated sodium channels. However, less discussed in the context of neuronal function is the fundamental force by means of which ions make a difference, namely, the electromagnetic (EM) force (Lorentz Force). There are four fundamental forces in physics: the strong force and the weak force which govern interactions within the atom, the gravitational force, and EM. Ions, biomolecules, and other material substances (composed of atoms) exhibit direct causality upon one another by means of EM forces. Thus, the TICL suggests that the temporally-integrated causality of the System and its Subsystems refers to a complex arrangement of electromagnetic fields. Care should be taken to avoid a naïve conception of nested EM fields in the brain. The thalamocortical brain is a complex system, and human phenomenal consciousness is complex as well. Ultimately, we should expect simple, fundamental principles to underlie consciousness as a phenomenon in the universe. Thus, the study of human consciousness by experimentation poses challenges for deriving those principles. The brain is essentially an EM field system, so the physical measurements we make will inevitably involve the interactions of the EM field. This is the same for all neuroscientific theories. However TIC becomes formulated, in terms of fundamental physics, its empirical verification will be achieved through measurements of EM field properties at a spatial and temporal resolution appropriate to the System and its Subsystems. It would be a mistake to overcommit to a physical formalization of the TICL too early in its theoretical development. Without a doubt, this presents a limitation for distinguishing among frameworks, by experimentation. But, the purpose of this work is not to describe the winning theory in a competition. The purpose is to advance our theoretical understanding of consciousness and to be positively influential in the collaborative process of discovery.

The TICL framework assumes that consciousness of contents is an emergent property of a sufficiently complex system; consciousness of contents requires a unified structure of causality with differentiated structures of causality contained within it. The TICL suggests that a unified (and sustained) thalamocortical EM field structure must co-exist with nested and dynamic Subsystemic EM field structures in order for consciousness to emerge. In contrast to IIT, integration among components of a structure is not predicted to correlate with consciousness, unless there are subsets of components with higher levels of integration to be appreciated by the wider structure. Thus, a physically-nested arrangement is necessary, according to the TICL, for the consciousness of contents. In IIT, consciousness is assumed to be intrinsic to, and limited to, that portion of thalamocortical activity which exhibits maximum causal integration over a discrete timeframe. According to the TICL, there is a distinction between an overarching thalamocortical structure, necessary for consciousness, and embedded thalamocortical structures which are necessary for conscious contents. In IIT, the portion of thalamocortical activity which correlates to consciousness, exists to itself, intrinsically. According to the TICL, the portion of thalamocortical activity which corresponds to conscious content (the Subsystems), exists from the point of view of a larger portion of thalamocortical activity (the System). Subsystemic activities are intrinsic to and meaningful within the System (Winters, 2020). In physical terms, the EM fields which compose Subsystemic structure of causality are nested, in space and time, within the EM field complex which composes the Systemic structure of causality. While this description is reminiscent of dualism, the TICL is explicitly monistic; the contents of consciousness are parts of, or disturbances in, the conscious mind. In an arrangement such as the waking thalamocortical brain, a very large quantity of EM field interactions can occur within the boundaries of the System. The TICL assumes that the integration of causality in time is the key to consciousness. This understanding of causality is not limited to or specific to EM forces. It may be that EM forces are those that are relevant to consciousness as exhibited by the brain, but, in principle, any structure of causality exhibiting both a System and Subsystems could be conscious. The TICL is an attempt to account for consciousness as emergent from the human brain, but it does not rule out consciousness in other systems instantiating the same principles.

THE PHENOMENOLOGY OF HUMAN CONSCIOUSNESS

A robust theory of human consciousness should provide an explanation for the self-evident characteristics of human experience. Again, Nagel defined being conscious as "there is something that it is like to be" (Nagel, 1974). So, what is it like? Phenomenologically, human consciousness is: (1) unified and compositional; its contents are (2) specific and meaningful; and (3) they exist from a subjective point of view. Human consciousness is (4) temporally continuous; and (5) limited and coherent.

Consciousness Is a Unified Composition of Contents

First, consciousness is a unified composition of contents (Koch, 2004). Human consciousness always has content. This is what distinguishes conscious states from nonconscious ones. Even if one is totally confused, the particular quality of that confusion of thoughts or sensations is content. Any given experience contains lots of different identifiable contents, such as a visual scene composed of objects arranged in space, sounds and smells, thoughts and feelings. From a subjective point of view, all of these occur in a common, unified experience. We know that auditory and visual stimuli, language comprehension, and feelings of pressure or vibration on the skin, are all processed by different networks in the cerebral cortex. Moreover, the sense of self can be disrupted or made absent pharmacologically, while preserving a unified composition of contents (Millière et al., 2018; Fingelkurts et al., 2020). The neural correlates of conscious unity are thought to involve functional integration, synchrony, or rapid communication in the thalamocortical system, encompassing a range of cortical regions involved in specialized areas of sensory and cognitive conscious contents.

Conscious Contents Are Specific and Meaningful

Second, conscious contents are specific and meaningful (Koch, 2004; Koch et al., 2016). A certain sound is different from another sound. A certain thought or feeling is different from any other thought or feeling. Green is different from blue, etc. In the scheme of conscious contents, some things are more alike than others. When we say that consciousness is the fact that "it is like something", we are referring to the specific and meaningful contents of experience (Nagel, 1974). Since individual contents are distinguishable and, at least in principle, describable, a complete theory of human consciousness must explain the differentiation among structures or processes that makes this possible. The neural correlates of specific conscious contents are thought to involve differentiation of thalamocortical network functions, occurring during conscious states. These differentiated, modular activities should be nested within the spatial boundaries of the full neural correlate of consciousness.

Conscious Contents Exist From a Subjective Point of View

Third, conscious contents exist from a point of view. This is subjectivity. Whatever content is being experienced, it is only being experienced within that conscious entity, from that point of view. If there is no point of view to observe content, then there is no consciousness. This is directly related to unity. If no common structure or process integrates the contents, then there is no common point of view, and thus, no conscious entity. From the point of view of the conscious subject, contents exist and have meaning. Interestingly, even absent a concept of self, the point of view is implied by the existence of content experiences under high-dose psychedelics (Millière et al., 2018; Fingelkurts et al., 2020). This is also true in the case of illusions involving disembodiment or autoscopy (Blanke and Metzinger, 2009). The point of view should, therefore, not be confused with self-consciousness.

The subjective nature of consciousness is currently inexplicable to experimentation, and thus requires a philosophical consideration in addition to an empirical one. This is in evidence in the "Unfolding Argument", which makes the case that any recurrent computation (input-output relationship) can be achieved by a different, larger feedforward computation (Doerig et al., 2019). Thus, the authors argue that causal structure theories such as ITT (and the TICL) are either falsified or non-scientific. Falsification would occur if causal structure theorists allowed that feedforward structures of causality could be conscious (Doerig et al., 2019). Given that Doerig et al. limit the scientific evidence for consciousness to the subjective report of content, it appears to be impossible to determine whether any other person or thing is conscious. Rene Descartes grounded his philosophy in the undeniable fact of his own consciousness. Descartes wrote, "…this truth, I think hence I am, was so certain and of such evidence, that no ground of doubt, however extravagant, could be alleged by the skeptics capable of shaking it, I concluded that I might, without scruple accept it as the first principle of the philosophy of which I was in search" (Descartes, 1912). Citing Descartes, Tononi and colleagues suggest, axiomatically, that conscious experience exists intrinsically, which is to say it exists to itself (Tononi et al., 2016). In my opinion, this is a misunderstanding that leads to errors in IIT. In describing himself as a "thinking thing", Descartes is not necessitating that he, the thing with thoughts, and the thoughts which he is thinking are one and the same thing. It seems apparent to me, following Descartes, that the thoughts are intrinsic to the thinker, or "thinking thing" that is conscious. Descartes infers his own existence from that of his thoughts. In fact, he does not exist to himself. Rather, his thoughts exist to him. In recognition of this, the TICL posits that the Systemic TIC is aware of the existence of its Subsystemic TICs. The latter are intrinsic to the former. Thus, we see and feel and think about contents, but we can only infer our own existence from those contents. It is rare for neuroscientific theories of consciousness to explicitly address the point of view. However, ultimately, the point of view is what we are seeking to explain.

Consciousness Is Temporally Continuous

Fourth, consciousness is temporally continuous (Wittmann, 2011; Winters, 2020; Kent and Wittmann, 2021). John Searle defined consciousness as "those states of sentience and awareness that typically begin when we awake from a dreamless sleep and continue until we go to sleep again, or fall into a coma or die or otherwise become unconscious" (Searle, 1997). Phenomenologically, we experience no borders between subsequent experiences. In "The Principles of Psychology" (1890) William James said, "Consciousness does not appear to itself chopped up in bits. Such words as "chain" or "train" do not describe it fitly as it presents itself in the first instance. It is nothing jointed; it flows. A "river" or a "stream" are the metaphors by which it is most naturally described. In talking of it hereafter, let us call it the stream of thought, of consciousness, or of subjective life". James recognized that, within a conscious experience, we observe change occurring in a non-discrete, but continuous manner. This may reflect the nestedness of qualitative contents occurring at different temporal scales (Fingelkurts et al., 2010). Whether this necessitates a non-discrete mechanistic correlate in the brain remains a matter of contention (Fingelkurts et al., 2010; Kent et al., 2019; Winters, 2020; Kent and Wittmann, 2021). Nevertheless, contents are dynamic and consciousness seems to flow over an extended sense of the present (Poppel, 1997; Kent et al., 2019).

Consciousness Is Limited and Coherent

Finally, consciousness is limited and coherent. At any given time, most things that could be conscious are not. While the conscious composition contains many simultaneous contents, incoming sensory data streams are mostly unnoticed. Thus, only limited content is subjectively accessible (Dehaene and Changeux, 2011). The contents of consciousness are limited to a subset, and this suggests a threshold for perception. Furthermore, only a single interpretation of contents exists from our point of view at any one time (Blake and Logothetis, 2002; Tsuchiya and Koch, 2005; Imamoglu et al., 2012). This is well demonstrated by visual illusions such as the Necker cube, and by binocular rivalry. The neural correlates of limited conscious content are studied using contrastive analysis at liminal thresholds for perception.

These five phenomenal aspects are derived from human consciousness. We have no way of knowing whether they are fundamental to consciousness itself. The TICL attempts to explain human phenomenal consciousness as a landscape of nested EM field structures. The neural correlates of human consciousness have evolved over millennia, and do not provide insight into the simplest, most primitive, modes of conscious being. Further, there is debate among theorists as to what the key phenomenal features of human consciousness are. The five axioms of IIT overlap with those presented here, but they are distinguishable at least in the case of intrinsicality and exclusion (Tononi et al., 2016; Winters, 2020). With respect to intrinsicality, an area of contention among current frameworks, often implicitly, is the view that consciousness is one thing altogether and intrinsic to itself (Tononi et al., 2016) rather than one thing containing many nested things intrinsic to and differentiated within it (Fingelkurts et al., 2010, 2013; Northoff and Huang, 2017; Winters, 2020). It is my view, that the latter is a closer approximation to the phenomenal human experience. It is often unclear where a theoretical framework falls on this question. The TICL explicitly accounts for the point of view as being that of the wider, integrated System upon its internal dynamics (Winters, 2020). With respect to exclusion, IIT posits that conscious experience has one, definite spatial and temporal grain (Tononi et al., 2016), which contrasts with the view that human consciousness is temporally continuous with dynamic contents nested within it (Fingelkurts et al., 2010, 2013; Wittmann, 2011; Northoff and Huang, 2017; Winters, 2020; Kent and Wittmann, 2021).

My goal in developing the TICL was to establish a framework in which the phenomenal aspects of human consciousness are in parsimonious agreement with their neural (and ultimately physical) correlates. I suggest that the five fundamental features of human consciousness named above require a general physical model of consciousness to take the form of a single, integrated thalamocortical structure corresponding to the state of consciousness, within which differentiated neural activities are nested in space and time, with the limitation and coherence of conscious contents depending on the perceived distinction between background and the differentiated ensembles from the point of view of the unified structure, and with the meaning being intrinsic to the relationship among neural activities from that point of view (Winters, 2020).

The TICL posits a general explanation for the five fundamental aspects of phenomenal consciousness I have presented. Human consciousness is a unified composition of contents because the Subsystems occur within the unified (physically integrated) System. The contents of consciousness are specific because the Subsystems are composed of specific neuronal elements and their specific TIC. They are meaningful because of their relationship to one another and to the System. The contents exist from the point of view of the System. The System remains largely unchanged in spatial and temporal terms, but it persists in time (temporal continuity) as Subsystems appear, change, and disappear within it, in their own time. Finally, the TICL is limited by the necessity of Subsystems to have a higher level of TIC than the System, making them distinguishable from background noise, and thus meaningful to the System. Coherence is achieved because Subsystems cannot have more than one form (meaning) at the same time, from the Systemic point of view. Like other leading neuroscientific theories, the TICL is consistent with a large body of experimental evidence.

THE NEURAL CORRELATES OF CONSCIOUSNESS IN BRIEF REVIEW

The mammalian brain sustains states of consciousness during wakefulness and dreaming sleep, but these are abbreviated by states of nonconsciousness during non-dreaming sleep. This state-change requires enabling factors centered in the brainstem and acting widely across the rest of the brain (Parvizi and Damasio, 2001). During conscious states, whether waking or dreaming, cortical EEG shows asynchronous, high-frequency activity (Siclari et al., 2017). Spontaneous oscillations in the cortical EEG occur when a large number of neurons are acting in concert (Steriade et al., 1990). These EEG rhythms are classically distinguished as delta (1–3 Hz), theta (4–8 Hz), alpha (9–12 Hz), beta (13–30 Hz), and gamma (>30 Hz). It has been suggested that synchronization of neuronal activity, in the gamma frequency band, enables temporal coordination between the large number of inputs and the resulting outputs (Fries, 2015). Such synchronized oscillations co-exist in the brain with arrhythmic scale-free activities in which subsets of neurons fire in synchrony but not in a periodic fashion (Freeman, 2005; Thivierge and Cisek, 2008; Milstein et al., 2009). The scale-free dynamics of human brain activity, in EEG, are characterized by considerable nesting of frequencies (He et al., 2010). The phase of lower frequencies modulates the amplitude of higher frequency neuronal activities (He et al., 2010) in a manner known as cross-frequency coupling, in which small, local populations of neurons are influenced by the low-frequency oscillations occurring over larger populations (Bragin et al., 1995; Canolty et al., 2006; Canolty and Knight, 2010; Aru et al., 2015). Cross-frequency coupling has been suggested to be involved in information exchange and cognitive processes (Tort et al., 2009; Axmacher et al., 2010; Canolty and Knight, 2010; Lisman and Jensen, 2013).

The contents of consciousness are generally understood to be generated by activity limited to a large portion of the cerebral cortex and the thalamus (Koch et al., 2016; Tononi et al., 2016). Primary cortical structures, such as V1, do not directly contribute to consciousness (Weiskrantz, 1996; Lamme and Roelfsema, 2000; He and MacLeod, 2001; Jiang et al., 2007). The cortex is very complex, but it is orderly, with hierarchical processing of incoming data streams from primary modules to higher, association modules. Network modules are subsets of neurons or neuronal groups that are highly connected to one another (Bassett and Sporns, 2017). These overlapping and non-overlapping subsets of nodes in the network are strongly connected to one another but only weakly connected to the wider network (Sporns and Betzel, 2016). Highly connected brain networks along the midline have been described as connector hubs with widespread regional connections by means of cortico-cortical axonal pathways (Hagmann et al., 2008). Modulation across different anatomical networks is arranged hierarchically (Sadaghiani et al., 2010). Dynamic changes in synchrony might drive the capacity for groups of neurons to coalesce into functionally connected ensembles (Fries, 2015). Interestingly, a hierarchy of timescales has been described, noting that association areas, further along a sensory pathway become selectively activated with stimuli that are coherent over longer time periods (Hasson et al., 2008; Murray et al., 2014). In the spatial domain, such hierarchies are apparent in the visual system, in which receptive field sizes increase along the visual pathway. A hierarchy of timescales may be involved in functional specialization across the cortex (Buzsáki and Draguhn, 2004; Murray et al., 2014). Often no direct structural connection is apparent between populations, though they function coherently with one another (Honey et al., 2009). Accordingly, long-range relationships among spatially distributed regions, have been discovered (Sporns and Betzel, 2016). Examples include the frontoparietal control network and the default mode network (Power et al., 2011). States of nonconsciousness are characterized by reduced functional connectivity across the cerebral cortex and a loss in the diversity of connected configurations (Mashour and Hudetz, 2018).

Christof Koch distinguishes the full neural correlates of consciousness (NCC) and the content-specific neural correlates of consciousness (content-specific NCC; Crick and Koch, 1998; Koch et al., 2016). The former (NCC) are the total necessary and sufficient activities in the brain for the production of consciousness, without regard to particular contents. The content-specific NCC refers to the total necessary and sufficient neural activities for the production of consciousness with a given piece of content (Koch et al., 2016). Distributed neural activities across the cerebral cortex are unified by means of functional integration (Massimini et al., 2005; Boly et al., 2012; Hudetz, 2012; King et al., 2013; Monti et al., 2013; Marinazzo et al., 2014; Tagliazucchi and Laufs, 2014; Tononi et al., 2016; Mashour and Hudetz, 2018). This has been proposed to depend on re-entry, recurrent loops or feedback communication between cortical regions (Tononi and Edelman, 1998; Lamme and Roelfsema, 2000; Dehaene and Naccache, 2001; Supèr et al., 2001; Dehaene and Changeux, 2011; Oizumi et al., 2014). An alternative mechanism for integration is EM resonance (Hunt and Schooler, 2019).

Ongoing neural activity across the thalamocortical system occurs at a range of spatial and temporal scales (Sadaghiani et al., 2010). Distinct frequency bands are modulated over time with a predominance of slow-wave activity (Leopold et al., 2003; Nir et al., 2008). Higher frequency activity is nested into the infra-slow fluctuations, which occur at less than 0.1 Hz (He et al., 2010). These especially slow oscillations occur over long cortical distances with wide spatial coherence even across cerebral hemispheres (Leopold et al., 2003; Nir et al., 2008). Ongoing, slow fluctuations have also been observed in fMRI, with coherence across wide ranges providing evidence for functional connectivity (Shmuel and Leopold, 2008).

The content-specific NCC can be studied in laboratory settings using controlled, sensory stimuli. It has largely been accomplished utilizing report-based visual paradigms and has identified the involvement of both frontal and parietal regions (Breitmeyer and Ogmen, 2000; Blake and Logothetis, 2002; Tsuchiya and Koch, 2005; Imamoglu et al., 2012). Similar studies which avoid overt reports of perception suggest that the content-specific NCC are limited to only posterior cortical regions (Frässle et al., 2014; Tsuchiya et al., 2015). The matter is far from settled and probably depends upon experimental approaches and phenomenal definitions as much as it does upon contradictory evidence. The results of transcranial magnetic stimulation studies with EEG in conscious and non-conscious subjects are strongly suggestive of differential oscillations across space being a specific feature of the conscious state (Massimini et al., 2005; Sarasso et al., 2015). The idea that both large-scale integration and smaller-scale differentiation are necessary for the consciousness of content may have first been recognized in the Dynamic Core Hypothesis (Tononi and Edelman, 1998). Neuronal oscillations temporally link neurons into ensembles by means of synchrony (Buzsáki and Draguhn, 2004). Local synchrony at high frequencies may bind features of conscious percepts together but it also occurs among groups of neurons in cases where stimuli are not consciously perceived (Ray and Maunsell, 2010; Pitts et al., 2014; Hermes et al., 2015). Temporo-spatial nestedness has been proposed to correlate with the neural predisposition to the consciousness of stimuli (Northoff and Huang, 2017).

Experiments have shown that increased phase synchrony over long distances, in the cortex, correlates with conscious perception of stimuli (Gross et al., 2004; Gaillard et al., 2009). Localized increases in gamma power and synchrony are seen even with stimuli that are not consciously perceived, particularly within the first 200 ms (Melloni et al., 2007; Ray and Maunsell, 2010). Despite this, most theoretical frameworks for consciousness limit the temporal aspects of consciousness to a few hundred ms timescales (Northoff and Lamme, 2020; Kent and Wittmann, 2021). Phenomenologically, it has been suggested that the experienced present moment is actually occurring over a wider temporal window in which the contents of consciousness are integrated (Poppel, 1997; Kent et al., 2019; Kent and Wittmann, 2021). A large number of studies have shown that the brain's spontaneous activity during conscious states, prior to an experimental stimulus, is relevant to the resulting conscious content (Northoff and Huang, 2017). With weak stimuli (just at threshold), the presentation of which will sometimes result in perception and sometimes not, within the same subject, baseline, or resting state, activity as measured by fMRI, positively correlates with conscious perception (Boly et al., 2007; Hesselmann et al., 2008; Ploner et al., 2010; Qin et al., 2016). Furthermore, the phase of the cortical alpha rhythm, measured by EEG is also predictive of whether a stimulus will be perceived, with significantly lower detection of the stimulus during the trough of the alpha band than during the peak (Mathewson et al., 2009). It was shown, using magnetoencephalography (MEG), that pre-stimulus alpha fluctuations predict the capacity to visually discriminate (Van Dijk et al., 2008). These findings are consistent with the idea that temporal alignment between background oscillations and stimulus-driven activities determines whether stimuli are consciously perceived (Northoff and Huang, 2017). A further temporal feature of conscious perception is informed by visual studies on "masking". Brief visual stimuli which, presented by themselves, are perceived by the subject, can be rendered unperceived by spatially and temporally adjacent stimuli ("masks") even when they are presented after the initial stimulus (Breitmeyer and Ogmen, 2000; Dehaene and Changeux, 2011). This suggests that conscious contents are not evaluated in immediate sequence, but according to a wider temporal window (Kent and Wittmann, 2021).

Rather than disputing the credibility of these experimental results, theories of consciousness differ in their interpretation of them and preferentially address certain areas of evidence. I described five aspects of phenomenology that characterize human consciousness. I said that human phenomenal consciousness is: (1) unified and compositional; its contents are (2) specific and meaningful; and (3) they exist from a subjective point of view. Consciousness is (4) temporally continuous; and (5) limited and coherent. Thus, differing theoretical frameworks can be distinguished by their particular explanations for these phenomenal features. A variety of theoretical frameworks have proliferated recently, and different aspects of consciousness explored using different experimental methods might account, in large part, for the discrepancies among them (Northoff and Lamme, 2020). Neuroscientific theories of consciousness contrast along multiple dimensions. For better or worse, the recent proliferation of theories has often meant differing vocabularies to describe overlapping or identical concepts. It is, thus, worth attempting to distill the fundamental ideas presented by the theorists in order to undertake their comparison. This leads to an imperfect but useful mapping of the relations among concepts that make up the theories. Entrenched theorists risk talking past one another. It is my hope that following the expansion of theoretical models, an evidence-based convergence will ultimately take hold as the field matures. Therefore, I will take a reconciliatory approach as well as a discriminating one, in this discussion.

THE FUNDAMENTALS OF NEUROSCIENTIFIC THEORIES OF CONSCIOUSNESS

Integrated Information Theory

Integrated Information Theory (IIT) begins with a set of axioms, or self-evident phenomenal facts about consciousness, and derives postulates about the physical substrate of consciousness. In brief, these are the axiom of intrinsicality, the axiom of composition, the axiom of information, the axiom of integration, and the axiom of exclusion (Tononi et al., 2016). There is considerable overlap between these axioms and the five aspects of consciousness that I have highlighted in the present article. Reasoning from these axioms, IIT predicts that the physical substrate of consciousness must be the maximum of intrinsic cause-effect power in the thalamocortical system (Tononi et al., 2016). According to IIT, conscious entities are not temporally or spatially nested structures. Rather consciousness is intrinsic to the system of elements across which the maximum of cause-effect power is occurring, given a time constant, at or around 200 ms (Tononi et al., 2016). Thus, for IIT, the unified conscious mind is a single, discrete structure of integrated information with the content of the whole specified by the structure (Tononi et al., 2016). Dynamic, nested Subsystems are excluded from consciousness, though more than one conscious entity might share the brain at a given time in a non-spatially-overlapping arrangement (Oizumi et al., 2014). I predict that the maximal cause-effect power over a set of neuronal elements at a given timescale in the thalamocortical system might correspond to its most salient content at the moment of measurement, rather than capturing consciousness with all of its ongoing content.

Global Neuronal Workspace Theory

Global Neuronal Workspace (GNW) posits that "conscious access" is a means by which information is widely spread through the cerebral cortex (Dehaene and Changeux, 2011). This is suggested to occur by means of delayed amplification of sensory network activity, which leads to long-range synchronization in beta and gamma frequencies (Dehaene and Changeux, 2011). Once access has been achieved and communication is occurring across the "global workspace", information becomes unified into a common conscious mind (Seth et al., 2005). According to GNW, cortical pyramidal neurons and their related thalamocortical loops are functionally interconnected to form a "global workspace". Reciprocal connections among local, specialized modules enable contents to be united into a common structure (Baars, 2005; Dehaene and Changeux, 2011). GNW theorists call this communication a broadcast because it spreads information from, for example, parietal and temporal modules to prefrontal cortical ones, and subsequently makes cognitive recognition and verbal report possible (Dehaene and Naccache, 2001; Dehaene and Changeux, 2011). "Conscious access" provides a threshold mechanism for unconscious neural events to be made conscious. It would appear that this may be consistent with nestedness in space and time, even if the idea has not been claimed explicitly.

General Resonance Theory

According to General Resonance Theory (GRT), shared resonance, an idea related to functional coherence, combines micro-conscious entities into macro-conscious ones (Hunt and Schooler, 2019). Despite the panpsychist framing of GRT, the existence of micro-conscious entities is not dissimilar from the claim, made by IIT theorists, that structures which exhibit some measure of integrated information, no matter how small its manifestation, may have some level of consciousness (Tononi and Koch, 2015). Similarly, the concept of "conscious access", in GNW, while not explicitly an answer to the combination problem, points to a parallel problem of unified consciousness (Dehaene et al., 2014). How do distal networks communicate across the brain, toward the production of conscious contents? The answer, for GRT, lies in the synchronization of their activities into a common system. Its proponents suggest that the brain's EM fields make this resonance possible (Hunt and Schooler, 2019). They point to a hierarchy of resonances in the brain, in accordance with varying oscillations in the brain occurring on a background of non-oscillating, low-frequency activity (Steinke and Galan, 2011). Resonance, or synchrony, among neural populations is proposed to be driven by electrical fields. Despite this mechanistic novelty, the GRT says that "dominant consciousness", the conscious entity exhibited as the human mind, is unified by synchrony into a single system (Hunt and Schooler, 2019). It follows that the contents of "dominant consciousness" are intrinsic to it, much as the maximum of the cause-effect power structure of IIT. Hunt and Schooler propose that a phase transition occurs to facilitate the efficient, high-speed flow of information, reminiscent of the "ignition" discussed in GNW. The content of consciousness is spatially determined by the set of neurons which are in resonance. Even though the theory allows for nested micro-conscious entities occurring at multiple causal speeds, it is unclear if GRT allows for multiple different resonances to co-exist in the "dominant consciousness". I have been arguing that the contents of consciousness are nested within the conscious System, with independent Subsystemic dynamics and independent Subsystemic synchronies. If GRT lacks multiple-resonance-frequency dynamics, this idea appears to contrast with GRT as completely as it does with IIT.

Operational Architectonics

Operational Architectonics (A-O) purports that unified consciousness is achieved by means of a dynamic, nested hierarchy of electromagnetic fields in the brain (Fingelkurts et al., 2010, 2019). An internal physical space-time (IPST) reorganizes and processes signals from the outside world, external physical space-time (EPST), turning those streams of data into dynamic, volumetric spatial-temporal patterns of local extracellular electric fields (Fingelkurts et al., 2010). These EM fields, or operational modules, exhibit intrinsic phenomenal character. This amounts to a virtual world for the subject known as phenomenal space-time (PST; Fingelkurts et al., 2019). Short–term patterns of integrated activity occur within the IPST and become unified within the PST (Fingelkurts et al., 2010). This framework is undeniably one of nestedness. Assemblies of neurons take in energy over time, which is suggested to suddenly offload entropy by means of a rapid transitional process, which then reorganizes the whole system and allows the intermittent emergence of new content in PST (Fingelkurts et al., 2013). There is a recognition of dynamic content occurring within a wider frame of nested assemblies (thus nested EM fields), which suggests a high degree of reconcilability with the TICL.

Temporo-spatial Theory of Consciousness

The Temporo-spatial Theory of Consciousness (TTC) frames the problem of consciousness in terms of four dimensions, or aspects, and offers a set of solutions (Northoff and Huang, 2017). These are: (1) the level or state of consciousness; (2) the content or form of consciousness; (3) phenomenology or experience; and (4) cognitive processing and report. First, the level or state of consciousness is a predisposition to the consciousness of content which corresponds with temporo-spatial nestedness or neural activity. This, of course, is directly relevant to the current discussion and relies upon a large body of evidence reviewed, in part, above. According to the TTC, nestedness in space and time is critical to the state of being conscious. It represents a readiness for stimuli to become consciously perceived (Northoff and Huang, 2017). The authors relate temporo-spatial nestedness to the "dynamic repertoire", which refers to the temporal and spatial range of neural reactions that occurs in conscious states but is substantially reduced in non-conscious states (Hudetz et al., 2015). The contents of consciousness (dimension 2) are related to temporo-spatial nestedness in terms of alignment between stimulus time and strength with the underlying oscillations. It is referred to as the neural prerequisite of consciousness (Northoff and Huang, 2017). Slow-wave activities are hypothesized to provide a temporal window in which the network is receptive to the integration of stimulus-induced activity (Hasson et al., 2008). With respect to phenomenology or experience, TTC connects this to the spatial and temporal expansion of stimulus-induced activities (Northoff and Huang, 2017). The stimulus-driven activity becomes integrated across the brain but is differentiated in terms of its spatial and temporal configuration (Northoff and Huang, 2017). Dimension 4 of the TTC deals with cognitive processing and report and thus reflects delayed stimulus-driven effects (Northoff and Huang, 2017).

COMPETING THEORIES OFFER DIFFERENT EXPLANATIONS FOR PHENOMENAL FEATURES OF HUMAN CONSCIOUSNESS

What Unifies Consciousness?

Since human consciousness is composed of contents of various types which manifest as a unity, it is necessary for a theory of consciousness to explain how this is accomplished in the brain. **Figure 2** shows three different models which broadly represent the different theoretical ways of handling unity. According to IIT, unity occurs by means of network integration in the maximal cause-effect structure over a precise spatial and temporal frame (Tononi et al., 2016). This is a kind of causal integration, assumed to occur among neuronal elements by means of mutual influence. In that sense, it is very similar to the assumptions of the TICL, which unifies the contents of consciousness within a common structure of causality, in a nested way. The unity for IIT, however, is proposed to be quite limited in spatial and temporal breadth, as in **Figure 2A**. Like in **Figure 1**, the degree of integrated causality, information exchange, or functional synchrony is represented by the darkness of the gray color. In **Figure 1A**, we see a single, highly integrated structure (dark gray), as proposed to be the physical substrate of consciousness in IIT. According to GNW, The global workspace unifies the content by making information widely available (Dehaene and Naccache, 2001). This idea is mechanistically distinct but still seems to allow that the communication of information across a common, integrated structure is key to unifying the content. The spatial location in the brain where this takes place is understood in GNW to include prefrontal cortical structures, and the timing with respect to stimulus-onset to conscious perception is late relative to IIT. In a previous article, I criticized GNW as potentially situating the conscious "global workspace" separately in space from the cortical networks responsible for the content (Winters,

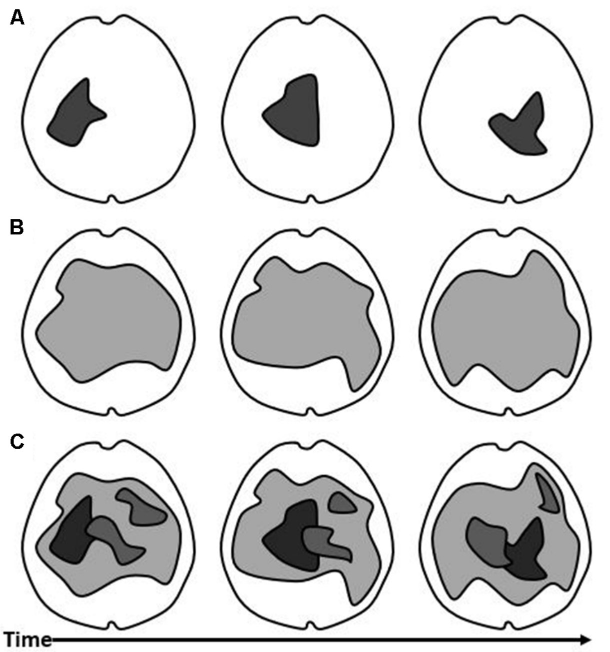

FIGURE 2 | *Models of Consciousness. The thalamocortical substrate of consciousness, proposed by different theories can be generally mapped onto these models*. TIC is represented as the darkness of the color gray. **(A)** In this model, the substrate of consciousness is a single, highly integrated network in the thalamocortical system. Over time, its spatial character and position in the brain changes (different shapes at different positions in the three panels). **(B)** In this model, the substrate of consciousness is a single, large, and integrated or resonant network in the thalamocortical system. Its elemental make-up changes over time (gray shape over three panels). **(C)** In this third model, the substrate of consciousness consists of a large, integrated network in the thalamocortical system (light gray), which can undergo some elemental change across time (shape across panels). Nested within this network are smaller networks with higher TIC (darker colors).

2020). This interpretation would have GNW being represented by **Figure 2A**, like IIT. The difference would be that, for GNW, the substrate of consciousness would be situated further toward the front of the cortex. While that interpretation of the "global workspace" might be incompatible with the TICL, reconciliation could be had by understanding that the "global workspace" consists of the posterior cortical networks producing content as well as the frontal cortical workspace neurons, as long as they are in sufficient communication. In the latter case, GNW might look more like **Figure 2C**, wherein content-producing networks would be nested within the "global workspace". For GRT, spatially widespread synchronization by means of EM fields, unifies consciousness. Those neuronal constituents which are part of the "dominant consciousness" make up its unified content (Hunt and Schooler, 2019). This might be best illustrated by **Figure 2B**, wherein the spatial domain of the "dominant consciousness" is larger than IIT's maximum of cause-effect power. In O-A, phenomenal space-time is a subjective "virtual world" in which nested, local EM field activity self-presents (Fingelkurts et al., 2010). This is best represented by **Figure 2C**. The latter is more consistent with the TICL, in that the neuronal ensembles responsible for content are nested in space and time within a common EM field. The difference is one of explicit terminology regarding consciousness in the brain as an integrated structure of electromagnetism vs. an integrated structure of causality. Reconciliation between theories is possible, once we recognize that EM forces are necessarily the mechanism of causality instantiated in the brain, in the TICL, or any other neuroscientific theory. According to TTC, spatial-temporal nestedness of integrated activity occurring upon the brain's spontaneous activity, as in cross-frequency coupling, unites the contents of consciousness (Northoff and Huang, 2017). Again, this model is consistent with **Figure 2C**. This proposal satisfies the claims of the TICL framework but explores the spatial and temporal mechanisms of integration much more specifically. **Figure 2C** is an appropriate model for how the TICL accounts for the unity of conscious contents. In **Figures 2A,B**, the structure of consciousness is one thing altogether. By contrast, **Figure 2C** allows for the spatial and temporal nesting of content-producing neural structures within a hierarchical arrangement. Notably, the dark gray shape appearing in **Figure 2A** is contained within the larger, light gray shape in **Figure 2C**. This reflects that, in the TICL, the maximum cause-effect structure is a Subsystem contained within a larger System (Winters, 2020).

What Specifies the Content?

The contents of consciousness are specific and qualitatively distinguishable. They tend to arise in correlation with localized cortical functions in a hierarchical arrangement. According to IIT, the specificity of content is given by the constituent elements of the substrate of consciousness and their causal power. The contents are built into the maximal cause-effect structure (Tononi et al., 2016). Thus, **Figure 2A** shows a single structure in the brain corresponding to a high level of integrated causality. The precise structure of cause and effect which currently composes the maximum, is unique and different from any other configuration, allowing for unimaginable variety (Tononi et al., 2016). According to the GNW, specific contents occur due to the sustained activity of a fraction of thalamocortical neurons which are broadcast to, or "accessed" by the "global workspace" (Dehaene and Naccache, 2001; Dehaene and Changeux, 2011). Put side-by-side, this is not so different from IIT, in principle. Which neurons are integrated or in communication, determines the qualitative character of consciousness, in both models. The TICL is roughly compatible with this. In the TICL, a Subsystem is a subset of neuronal elements within the spatially and temporally wider integrated System, which is even more causally-integrated over a shorter timeframe than the whole System (Winters, 2020). The specificity of content is given by the composition of Subsystems which exist at a given moment, and how they are changing. In **Figure 2C**, the darker shapes within the lighter gray shape, correspond, in simplified form, to a set of Subsystems. For GRT, the contents are specified by the particular constituent neurons in the resonant structure (Hunt and Schooler, 2019). Thus, in **Figure 2B**, there are no separate shapes distinguished within the single, common neural substrate of consciousness. In O-A, local extracellular EM fields are highly structured in space-time. This structure determines the content of PST (Fingelkurts et al., 2010). The combinatorial power within and among operational modules enables near infinitely diverse qualitative contents (Benedetti et al., 2010). The operational modules are similar to the concept of Subsystems, and they appear something like the image in **Figure 2C**. According to TTC, the stimulus-induced high-frequency activity becomes expanded, similar to "conscious access" in GNW. This integrates the nested activity within the context of the brain's spontaneous activity (Massimini et al., 2005; Northoff and Huang, 2017). The specificity comes from its spatial-temporal configuration within the integrated brain (Northoff and Huang, 2017). This is well illustrated in **Figure 2C**. Each in its own terms, these frameworks come to fairly similar conclusions about specificity. In the thalamocortical system, a large variety of functional configurations are possible at any given time. One way or another, this enables a wide range of contents.

What Is the Point of View?

According to IIT, consciousness is intrinsic to itself. It is identical to the collected content and the point of view upon it (Tononi et al., 2016). A conceptual difficulty for this viewpoint is that consciousness cannot be continuous if its substrate is not the same thing from instance to instance (**Figure 2A** across time). In fact, it seems to me that a conscious being would be a brief moment of existence, with an endless stream of new conscious beings existing one after another. This is at odds with phenomenology. In GRT, "Dominant consciousness" must be intrinsic to itself, as well. If **Figure 2B** is a fair representation of the spatial domain of the resonant structure, it must provide its own intrinsic point of view. Like in IIT, the structure of consciousness must be understood to exist to itself. By contrast, for GNW, the "global workspace" must provide the point of view upon the content to which it has access. This is more like the TICL, in which the System has a point of view upon the character and dynamics of its subsystems (Winters, 2020). The point of view is understood to be the thing which contains the content. This insight reverses the normal perspective of feeling as if we look out upon the world since the phenomenal world occurs *within* consciousness. The caveat for GNW is the one which I mentioned above; the "global workspace" which achieves the nesting of contents within consciousness must include the cortical regions which produce the content. If it does this, then the "global workspace" can provide the point of view upon the contents which occur with the sustained, but limited, thalamocortical activity which is being accessed in consciousness. Thus, GNW might look something like **Figure 2A** except that the structure of consciousness would have a more stable anatomical shape and would be situated more frontally. Alternatively, as suggested above, GNW might be interpreted closer to what is seen in **Figure 2C**, in which the point of view is that larger, lighter gray structure containing the smaller, darker ones. In O-A, PST is a highly abstract self-presentation of operational spatial-temporal patterns (Fingelkurts et al., 2010). It follows that the PST is the point of view upon those operational patterns. As long as that is the understanding, then the framing provided in the TICL is perfectly amenable to O-A, with the larger, lighter shape providing the point of view upon its contents (**Figure 2C**). While not stated explicitly in the TTC literature, it might be that the point of view is the widest spatial-temporal integrated structure, as in the TICL. For TTC, the brain's intrinsic space and time are given by the spatial extension and temporal duration of neural activities (Northoff and Huang, 2017). If the authors' viewpoint is consistent with the TICL, then the wider extension in space and time corresponds to the System of TICL and the theories are compatible (Winters, 2020). For the TICL, the System (lighter gray) contains specific Subsystems (darker gray shapes), the activities of which it experiences from its own, larger point of view.

How Is Conscious Continuity Understood?

According to IIT, consciousness is a sequence of discrete instances, each replacing the former, not continuous (Tononi et al., 2016). This has been criticized as a difficulty for IIT because the theory begins with a set of self-evident axioms without acknowledging temporal continuity (Wittmann, 2011; Winters, 2020; Kent and Wittmann, 2021). We see that in **Figure 2A**, across the three points in time, the physical substrate of consciousness has changed substantially. For IIT, this is not a gradual morphing, but a sequence of structures gaining ascendency. By contrast, GNW supports this feature of phenomenal consciousness. According to GNW, the sustained activity of thalamocortical neurons should allow a period of continuity for cognitive utilization, even for seconds after the disappearance of the immediate stimulus activity (Dehaene and Naccache, 2001; Baars, 2005). The information which is globally available should be updated as a continuous stream (Dehaene and Changeux, 2005). The integration of experience, for GNW, occurs both at a point in time and across time (Mashour et al., 2020). In GRT, the borders of the "dominant consciousness" are continually changing as activities come into resonance with them, by undergoing phase transition (Hunt and Schooler, 2019). However, the dynamics of conscious content must be encoded spatially because there is no difference in temporal character; they are synchronous (McFadden, 2020). This is what we see in **Figure 2B** over the three time points. In O-A, dynamic content exhibits intermittence because of the suggested rapid transitional process and subsequent restructuring (Fingelkurts et al., 2013). But, phenomenal space time consists of spatially and temporally nested content (Fingelkurts et al., 2010). This implies that O-A is capable of supporting both temporal continuity of the conscious state as well as dynamic contents within conscious experience. This is illustrated in **Figure 2C**, in which the networks responsible for content are changing across time. According to TTC, temporal receptive windows are arranged hierarchically (Northoff and Huang, 2017). This theory also exhibits temporal continuity with overlapping and nested contents in time. In **Figure 2C** across the time points, we see changes in the nested content-producing networks as well as spatial overlap. Thus, IIT stands alone among these theories in insisting upon a discrete timeframe for the entire conscious experience. The TICL, as well as O-A and TTC in particular, proposes continuous consciousness with nested contents in space and time. For the TICL, **Figure 2C** shows that the System is continuous across time, even as it may undergo some spatial change as elements enter and exit the integrated structure. Meanwhile, Subsystems can arise, change, and disappear. Notice that the Subsystems are always shown in darker gray to reflect that they must have a higher level of TIC than the System in which they are embedded. Also, notice that the most highly integrated Subsystem (darkest gray object) is that which appears in **Figure 2A**. The structure which IIT purports to be the whole substrate of consciousness should correspond to a high-TIC Subsystem for TICL, contained within the lower-TIC, but spatially and temporally larger, System.

How Is Consciousness Limited?

In IIT, contents are only possible where their underlying elemental activities are within the spatio-temporal borders of the maximally irreducible cause-effect structure (Tononi et al., 2016). This means that most neurons in the integrated thalamocortical system are not producing content at a given time. Thus, in **Figure 2A**, most of the brain is shown in white. Similarly, in GRT, the borders of the "dominant consciousness" are limited in accordance with the neurons which are resonant or synchronized (Hunt and Schooler, 2019). This is roughly what is shown in **Figure 2B**, with much of the thalamocortical system in "dominant consciousness". In GNW, long-range synchronization facilitates "conscious access" by the "global workspace" (Dehaene and Changeux, 2011). Only a limited fraction of thalamocortical neurons are "ignited" and sustained, providing internal coherence, while the rest are inhibited (Dehaene et al., 2003; Dehaene and Changeux, 2011). According to O-A, local extracellular EM fields are perceivable as nested within the wider EM field (Fingelkurts et al., 2019). Presumably, a threshold is determined by the strength of local extracellular EM fields, such that too weak a field is unperceivable. TTC proposes a mechanism of alignment between stimulus time with phase preference to the underlying spontaneous activity and a threshold driven by resulting neural amplitude (Northoff and Huang, 2017). For the TICL, the presence or absence of a Subsystem depends upon the subset of neuronal elements which would make it up having a higher degree of TIC than the larger System does (Winters, 2020). The content is limited to the Subsystems which exist at a given time. Any subset of neurons which is exhibiting causality in the integrated System, but not to a greater degree than the System, is buried in the noise, unmeaningful, and not experienced (**Figure 2C** in light gray).

CONCLUSIONS

The TICL makes claims that distinguish it in the field of theoretical frameworks. The TICL builds its foundation upon five phenomenal aspects of human consciousness, with the assumption that the most parsimonious explanation for these phenomenal aspects will be an arrangement of physical structure and interactions (anatomy and physiology) which mirror them. Descartes wrote, "…this truth, I think hence I am, was so certain and of such evidence, that no ground of doubt, however extravagant, could be alleged by the skeptics capable of shaking it, I concluded that I might, without scruple accept it as the first principle of the philosophy of which I was in search." (Descartes, 1912). Thus, he observed content and inferred that he must exist. He asked himself what he is and concluded that he is a "thinking thing", a thing with thoughts (and perceptions). Whatever conscious being is, it is a point of view upon contents. With this undeniable fact in mind, we can make observations about the contents of consciousness, from which we note that they are specific, limited, and meaningful, and that they are continually changing. They are specific and meaningful in that we can distinguish among them (sound vs. image, left vs. right, blue vs. red). They are limited in that we do not experience all of the potential contents all the time. And, they are dynamic. The point of view persists as the contents change. This results in a model in which the unified mind (and therefore integrated brain function; a System) contains phenomenal contents within it (differentiated Subsystems). Descartes' dualism made the assumption that the contents were real things (physical stuff) and that consciousness was a separate real thing (mental stuff). A physical, scientific account of phenomenal consciousness must reject this separation. By nesting the content-specific NCC within the full NCC, we arrive at a common structure of which the point of view must be that of the full NCC upon the content-specific NCC (**Figure 1**). The neural correlate of the point of view which contains the content-specific NCC must be not only spatially larger but also temporally longer. By this means, the point of view can bear witness to changing content. According to the TICL, consciousness is a complex structure of integrated causality in time. Causality necessitates force, and EM (Lorentz force) is almost certainly the force at play. The distinctions I wish to highlight among the theories discussed here are not drawn between those which are explicitly network-based (IIT, GNW, TCC) and those which are explicitly EM field-based (GRT and O-A). Rather, the critical distinction is between those theories in which the content-specific NCC are nested within the full NCC and those which conflate the two. In my general analysis, the TICL, O-A, and the TTC best exemplify this distinction. Critically, these explicit mechanisms for the neural correlates of consciousness ultimately collapse into a common implicit mechanism: some arrangement of EM interactions. Recognizing this will enable theoretical neuroscience to escape the bounds of biological and psychological thinking and place our deepest problem (the problem of consciousness) firmly within the purview of physics, where an explanation, after all, will be elucidated.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

The author confirms being the sole contributor of this work and has approved it for publication.

REFERENCES

Aru, J., Aru, J., Priesemann, V., Wibral, M., Lana, L., Pipa, G., et al. (2015). Untangling cross-frequency coupling in neuroscience. *Curr. Opin. Neurobiol.* 31, 51–61. doi: 10.1016/j.conb.2014.08.002

Axmacher, N., Henseler, M. M., Jensen, O., Weinreich, I., Elger, C. E., and Fell, J. (2010). Cross-frequency coupling supports multi-item working memory in the human hippocampus. *Proc. Natl. Acad. Sci. U S A* 107, 3228–3233. doi: 10.1073/pnas.0911531107

Baars, B. J. (2005). Global workspace theory of consciousness: toward a cognitive neuroscience of human experience. *Prog. Brain Res.* 150, 45–53. doi: 10.1016/S0079-6123(05)50004-9

Bassett, D. S., and Sporns, O. (2017). Network neuroscience. *Nat. Neurosci.* 20, 353–364. doi: 10.1038/nn.4502

Benedetti, G., Marchetti, G., Fingelkurts, A. A., and Fingelkurts, A. A. (2010). Mind operational semantics and brain operational architectonics: a putative correspondence. *Open Neuroimag. J.* 4, 53–69. doi: 10.2174/1874440001004020053

Blake, R., and Logothetis, N. K. (2002). Visual competition. *Nat. Rev. Neurosci.* 3, 13–21. doi: 10.1038/nrn701

Blanke, O., and Metzinger, T. (2009). Full-body illusions and minimal phenomenal selfhood. *Trends Cogn. Sci.* 13, 7–13. doi: 10.1016/j.tics.2008.10.003

Blumenfeld, H. (2011). Epilepsy and the consciousness system: transient vegetative state? *Neurol. Clin.* 29, 801–823. doi: 10.1016/j.ncl.2011.07.014

Boly, M., Balteau, E., Schnakers, C., Degueldre, C., Moonen, G., Luxen, A., et al. (2007). Baseline brain activity fluctuations predict somatosensory perceptions in humans. *Proc. Natl. Acad. Sci. U S A* 104, 12187–12192. doi: 10.1073/pnas.0611404104

Boly, M., Moran, R., Murphy, M., Boveroux, P., Bruno, M.-A., Noirhomme, Q., et al. (2012). Connectivity changes underlying spectral EEG changes during propofol-induced loss of consciousness. *J. Neurosci.* 32, 7082–7090. doi: 10.1523/JNEUROSCI.3769-11.2012

Bragin, A., Jandó, G., Nádasdy, Z., Hetke, J., Wise, K., and Buzsáki, G. (1995). Gamma (40–100 Hz) oscillation in the hippocampus of the behaving rat. *J. Neurosci.* 15, 47–60. doi: 10.1523/JNEUROSCI.15-01-00047.1995

Breitmeyer, B. G., and Ogmen, H. (2000). Recent models and findings in visual backward masking: a comparison, review, and update. *Percept. Psychophys.* 62, 1572–1595. doi: 10.3758/bf03212157

Buzsáki, G., and Draguhn, A. (2004). Neuronal oscillations in cortical networks. *Science* 304, 1926–1929. doi: 10.1126/science.1099745

Canolty, R. T., and Knight, R. T. (2010). The functional role of cross-frequency coupling. *Trends Cogn. Sci.* 14, 506–515. doi: 10.1016/j.tics.2010.09.001

Canolty, R. T., Edwards, E., Dalal, S. S., Soltani, M., Nagarajan, S. S., Kirsch, H. E., et al. (2006). High gamma power is phase-locked to theta oscillations in human neocortex. *Science* 313, 1626–1628. doi: 10.1126/science.1128115

Crick, F., and Koch, C. (1998). Feature article consciousness and neuroscience. *Cereb. Cortex* 8, 97–107. doi: 10.1016/bs.pbr.2019.03.031

Dehaene, S., and Changeux, J. P. (2005). Ongoing spontaneous activity controls access to consciousness: a neuronal model for inattentional blindness. *PLoS Biol.* 3:e141. doi: 10.1371/journal.pbio.0030141

Dehaene, S., and Changeux, J.-P. (2011). Experimental and theoretical approaches to conscious processing. *Neuron* 70, 200–227. doi: 10.1016/j.neuron.2011.03.018

Dehaene, S., Charles, L., King, J. R., and Marti, S. (2014). Toward a computational theory of conscious processing. *Curr. Opin. Neurobiol.* 25, 76–84. doi: 10.1016/j.conb.2013.12.005

Dehaene, S., and Naccache, L. (2001). Towards a cognitive neuroscience of consciousness: basic evidence and a workspace framework. *Cognition* 79, 1–37. doi: 10.1016/s0010-0277(00)00123-2

Dehaene, S., Sergent, C., and Changeux, J.-P. (2003). A neuronal network model linking subjective reports and objective physiological data during conscious perception. *Proc. Natl. Acad. Sci. U S A* 100, 8520–8525. doi: 10.1073/pnas.1332574100

Descartes, R. (1912). *A Discourse on Method: Meditations and Principles (First publ).* London: Everyman's Library.

Doerig, A., Schurger, A., Hess, K., and Herzog, M. H. (2019). The unfolding argument: why IIT and other causal structure theories cannot explain consciousness. *Conscious. Cogn.* 72, 49–59. doi: 10.1016/j.concog.2019.04.002

Fingelkurts, A. A., Fingelkurts, A. A., and Kallio-Tamminen, T. (2020). Selfhood triumvirate: from phenomenology to brain activity and back again. *Conscious. Cogn.* 86:103031. doi: 10.1016/j.concog.2020.103031

Fingelkurts, A. A., Fingelkurts, A. A., and Neves, C. F. H. (2010). Natural world physical, brain operational and mind phenomenal space-time. *Phys. Life Rev.* 7, 195–249. doi: 10.1016/j.plrev.2010.04.001

Fingelkurts, A. A., Fingelkurts, A. A., and Neves, C. F. H. (2013). Consciousness as a phenomenon in the operational architectonics of brain organization: criticality and self-organization considerations. *Chaos Solitons Fractals* 55, 13–31. doi: 10.1016/j.chaos.2013.02.007

Fingelkurts, A. A., Fingelkurts, A. A., Neves, C. F. H., and Kallio-Tamminen, T. (2019). Brain-mind operational architectonics: at the boundary between quantum physics and Eastern metaphysics. *Phys. Life Rev.* 31, 122–133. doi: 10.1016/j.plrev.2018.11.001

Frässle, S., Sommer, J., Jansen, A., Naber, M., and Einhäuser, W. (2014). Binocular rivalry: frontal activity relates to introspection and action but not to perception. *J. Neurosci.* 34, 1738–1747. doi: 10.1523/JNEUROSCI.4403-13.2014

Freeman, W. J. (2005). A field-theoretic approach to understanding scale-free neocortical dynamics. *Biol. Cybern.* 92, 350–359. doi: 10.1007/s00422-005-0563-1

Fries, P. (2015). Communication through coherence (CTC 2.0). *Neuron* 88, 220–235. doi: 10.1016/j.neuron.2015.09.034

Gaillard, R., Dehaene, S., Adam, C., Clemenceau, S., Hasboun, D., Baulac, M., et al. (2009). Converging intracranial markers of conscious access. *PLoS Biol.* 7, 472–492. doi: 10.1371/journal.pbio.1000061

Gross, J., Schmitz, F., Schnitzler, I., Kessler, K., Shapiro, K., Hommel, B., et al. (2004). Modulation of long-range neural synchrony reflects temporal limitations of visual attention in humans. *Proc. Natl. Acad. Sci. U S A* 101, 13050–13055. doi: 10.1073/pnas.0404944101

Hagmann, P., Cammoun, L., Gigandet, X., Meuli, R., Honey, C. J., Van Wedeen, J., et al. (2008). Mapping the structural core of human cerebral cortex. *PLoS Biol.* 6, 1479–1493. doi: 10.1371/journal.pbio.0060159

Hasson, U., Yang, E., Vallines, I., Heeger, D. J., and Rubin, N. (2008). A hierarchy of temporal receptive windows in human cortex. *J. Neurosci.* 28, 2539–2550. doi: 10.1523/JNEUROSCI.5487-07.2008

He, S., and MacLeod, D. I. A. (2001). Orientation-selective adaptation and tilt after-effect from invisible patterns. *Nature* 411, 473–476. doi: 10.1038/35078072

He, B. J., Zempel, J. M., Snyder, A. Z., and Raichle, M. E. (2010). The temporal structures and functional significance of scale-free brain activity. *Neuron* 66, 353–369. doi: 10.1016/j.neuron.2010.04.020

Hermes, D., Miller, K. J., Wandell, B. A., and Winawer, J. (2015). Stimulus dependence of gamma oscillations in human visual cortex. *Cereb. Cortex* 25, 2951–2959. doi: 10.1093/cercor/bhu091

Hesselmann, G., Kell, C. A., and Kleinschmidt, A. (2008). Ongoing activity fluctuations in hMT+ bias the perception of coherent visual motion. *J. Neurosci.* 28, 14481–14485. doi: 10.1523/JNEUROSCI.4398-08.2008

Honey, C. J., Sporns, O., Cammoun, L., Gigandet, X., Thiran, J. P., Meuli, R., et al. (2009). Predicting human resting-state functional connectivity from structural connectivity. *Proc. Natl. Acad. Sci. U S A* 106, 2035–2040. doi: 10.1073/pnas.0811168106

Hudetz, A. G. (2012). General anesthesia and human brain connectivity. *Brain Connect.* 2, 291–302. doi: 10.1089/brain.2012.0107

Hudetz, A. G., Liu, X., and Pillay, S. (2015). Dynamic repertoire of intrinsic brain states is reduced in propofol-induced unconsciousness. *Brain Connect.* 5, 10–22. doi: 10.1089/brain.2014.0230

Hunt, T., and Schooler, J. W. (2019). The easy part of the hard problem: a resonance theory of consciousness. *Front. Hum. Neurosci.* 13:378. doi: 10.3389/fnhum.2019.00378

Imamoglu, F., Kahnt, T., Koch, C., and Haynes, J.-D. (2012). Changes in functional connectivity support conscious object recognition. *NeuroImage* 63, 1909–1917. doi: 10.1016/j.neuroimage.2012.07.056

Jiang, Y., Zhou, K., and He, S. (2007). Human visual cortex responds to invisible chromatic flicker. *Nat. Neurosci.* 10, 657–662. doi: 10.1038/nn1879

Kent, L., and Wittmann, M. (2021). Special Issue: consciousness science and its theories Time consciousness: the missing link in theories of consciousness. *Neurosci. Conscious.* 2021:niab011. doi: 10.1093/nc/niab011

Kent, L., Van Doorn, G., and Klein, B. (2019). Systema temporis: a time-based dimensional framework for consciousness and cognition. *Conscious. Cogn.* 73:102766.doi: 10.1016/j.concog.2019.102766

King, J.-R., Sitt, J. D., Faugeras, F., Rohaut, B., El Karoui, I., Cohen, L., et al. (2013). Information sharing in the brain indexes consciousness in noncommunicative patients. *Curr. Biol.* 23, 1914–1919. doi: 10.1016/j.cub.2013.07.075

Koch, C. (2004). *The Quest for Consciousness: A Neurobiological Approach.* Englewood: Roberts and Company Publishers.

Koch, C., Massimini, M., Boly, M., and Tononi, G. (2016). Neural correlates of consciousness: progress and problems. *Nat. Rev. Neurosci.* 17, 307–321. doi: 10.1038/nrn.2016.22

Lamme, V., and Roelfsema, P. (2000). The distinct modes of vision offered by feedforward and recurrent processing. *Trends Neurosci.* 23, 571–579. doi: 10.1016/s0166-2236(00)01657-x

Leopold, D. A., Murayama, Y., and Logothetis, N. K. (2003). Very slow activity fluctuations in monkey visual cortex: implications for functional brain imaging. *Cereb. Cortex* 13, 422–433. doi: 10.1093/cercor/13.4.422

Lisman, J. E., and Jensen, O. (2013). The θ-γ neural code. *Neuron* 77, 1002–1006. doi: 10.1016/j.neuron.2013.03.007

Marinazzo, D., Gosseries, O., Boly, M., Ledoux, D., Rosanova, M., Massimini, M., et al. (2014). Directed information transfer in scalp electroencephalographic recordings: insights on disorders of consciousness. *Clin. EEG Neurosci.* 45, 33–39. doi: 10.1177/1550059413510703

Mashour, G. A., and Hudetz, A. G. (2018). Neural correlates of unconsciousness in large-scale brain networks. *Trends Neurosci.* 41, 150–160. doi: 10.1016/j.tins.2018.01.003

Mashour, G. A., Roelfsema, P., Changeux, J. P., and Dehaene, S. (2020). Conscious processing and the global neuronal workspace hypothesis. *Neuron* 105, 776–798. doi: 10.1016/j.neuron.2020.01.026

Massimini, M., Ferrarelli, F., Huber, R., and Esser, S. K. (2005). Breakdown of cortical effective connectivity during sleep—supporting material. *Science* 309, 2228–2233. doi: 10.1126/science.1117256

Mathewson, K. E., Gratton, G., Fabiani, M., Beck, D. M., and Ro, T. (2009). To see or not to see: prestimulus α phase predicts visual awareness. *J. Neurosci.* 29, 2725–2732. doi: 10.1523/JNEUROSCI.3963-08.2009

McFadden, J. (2020). Integrating information in the brain's EM field: the cemi field theory of consciousness. *Neurosci. Conscious.* 2020:niaa016. doi: 10.1093/nc/niaa016

Melloni, L., Molina, C., Pena, M., Torres, D., Singer, W., and Rodriguez, E. (2007). Synchronization of neural activity across cortical areas correlates with conscious perception. *J. Neurosci.* 27, 2858–2865. doi: 10.1523/JNEUROSCI.4623-06.2007

Millière, R., Carhart-Harris, R. L., Roseman, L., Trautwein, F. M., and Berkovich-Ohana, A. (2018). Psychedelics, meditation, and self-consciousness. *Front. Psychol.* 9:1475. doi: 10.3389/fpsyg.2018.01475

Milstein, J., Mormann, F., Fried, I., and Koch, C. (2009). Neuronal shot noise and brownian 1/f2 behavior in the local field potential. *PLoS One* 4:e4338. doi: 10.1371/journal.pone.0004338

Monti, M. M., Lutkenhoff, E. S., Rubinov, M., Boveroux, P., Vanhaudenhuyse, A., Gosseries, O., et al. (2013). Dynamic change of global and local information processing in propofol-induced loss and recovery of consciousness. *PLoS Comput. Biol.* 9:e1003271. doi: 10.1371/journal.pcbi.1003271

Murray, J. D., Bernacchia, A., Freedman, D. J., Romo, R., Wallis, J. D., Cai, X., et al. (2014). A hierarchy of intrinsic timescales across primate cortex HHS Public Access Author manuscript. *Nat. Neurosci.* 17, 1661–1663. doi: 10.1038/nn.3862

Nagel, T. (1974). What is it like to be a bat? *Philos. Rev.* 83, 435–450. doi: 10.2307/2183914

Nir, Y., Mukamel, R., Dinstein, I., Privman, E., Harel, M., Fisch, L., et al. (2008). Interhemispheric correlations of slow spontaneous neuronal fluctuations revealed in human sensory cortex. *Nat. Neurosci.* 11, 1100–1108. doi: 10.1038/nn.2177

Northoff, G., and Huang, Z. (2017). How do the brain's time and space mediate consciousness and its different dimensions? Temporo-spatial theory of consciousness (TTC). *Neurosci. Biobehav. Rev.* 80, 630–645. doi: 10.1016/j.neubiorev.2017.07.013

Northoff, G., and Lamme, V. (2020). Neural signs and mechanisms of consciousness: is there a potential convergence of theories of consciousness in sight? *Neurosci. Biobehav. Rev.* 118, 568–587. doi: 10.1016/j.neubiorev.2020.07.019

Northoff, G., Wainio-Theberge, S., and Evers, K. (2020). Is temporo-spatial dynamics the "common currency" of brain and mind? In Quest of "Spatiotemporal Neuroscience". *Phys. Life Rev.* 33, 34–54. doi: 10.1016/j.plrev.2019.05.002

Oizumi, M., Albantakis, L., and Tononi, G. (2014). From the phenomenology to the mechanisms of consciousness: integrated information theory 3.0. *PLoS Comput. Biol.* 10:e1003588. doi: 10.1371/journal.pcbi.1003588

Parvizi, J., and Damasio, A. (2001). Consciousness and the brainstem. *Cognition* 79, 135–160. doi: 10.1016/s0010-0277(00)00127-x

Pitts, M. A., Padwal, J., Fennelly, D., Martinez, A., and Hillyard, S. A. (2014). Gamma band activity and the P3 reflect post-perceptual processes, not visual awareness. *NeuroImage* 101, 337–350. doi: 10.1016/j.neuroimage.2014.07.024

Ploner, M., Lee, M. C., Wiech, K., Bingel, U., and Tracey, I. (2010). Prestimulus functional connectivity determines pain perception in humans. *Proc. Natl. Acad. Sci. U S A* 107, 355–360. doi: 10.1073/pnas.0906186106

Poppel, E. (1997). A hierarchical model of temporal perception. *Trends Cogn. Sci.* 1, 56–61. doi: 10.1016/S1364-6613(97)01008-5

Power, J. D., Cohen, A. L., Nelson, S. M., Wig, G. S., Barnes, K. A., Church, J. A., et al. (2011). Functional network organization of the human brain. *Neuron* 72, 665–678. doi: 10.1016/j.neuron.2011.09.006

Qin, P., Grimm, S., Duncan, N. W., Fan, Y., Huang, Z., Lane, T., et al. (2016). Spontaneous activity in default-mode network predicts ascription of self-relatedness to stimuli. *Soc. Cogn. Affect. Neurosci.* 11, 693–702. doi: 10.1093/scan/nsw008

Ray, S., and Maunsell, J. H. R. (2010). Differences in gamma frequencies across visual cortex restrict their possible use in computation. *Neuron* 67, 885–896. doi: 10.1016/j.neuron.2010.08.004

Sadaghiani, S., Hesselmann, G., Friston, K. J., and Kleinschmidt, A. (2010). The relation of ongoing brain activity, evoked neural responses and cognition. *Front. Syst. Neurosci.* 4:20. doi: 10.3389/fnsys.2010.00020

Sarasso, S., Boly, M., Napolitani, M., Gosseries, O., Charland-Verville, V., Casarotto, S., et al. (2015). Consciousness and complexity during unresponsiveness induced by propofol, xenon, and ketamine. *Curr. Biol.* 25, 3099–3105. doi: 10.1016/j.cub.2015.10.014

Searle, J. R. (1997). *The Mystery of Consciousness.* 1st Edn. New York, NY: The New York Review of Boos.

Seth, A. K., Baars, B. J., and Edelman, D. B. (2005). Criteria for consciousness in humans and other mammals. *Conscious. Cogn.* 14, 119–139. doi: 10.1016/j.concog.2004.08.006

Shmuel, A., and Leopold, D. A. (2008). Neuronal correlates of spontaneous fluctuations in fMRI signals in monkey visual cortex: implications for functional connectivity at rest. *Hum. Brain Mapp.* 29, 751–761. doi: 10.1002/hbm.20580

Siclari, F., Baird, B., Perogamvros, L., Bernardi, G., LaRocque, J. J., Riedner, B., et al. (2017). The neural correlates of dreaming. *Nat. Neurosci.* 20, 872–878. doi: 10.1038/nn.4545

Sporns, O., and Betzel, R. F. (2016). Modular brain networks. *Annu. Rev. Psychol.* 67, 613–640. doi: 10.1146/annurev-psych-122414-033634

Steinke, G. K., and Galan, R. F. (2011). Brain rhythms reveal a hierarchical network organization. *PLoS Comput. Biol.* 7:e1002207. doi: 10.1371/journal.pcbi.1002207

Steriade, M., Gloor, P., Llinás, R. R., Lopes da Silva, F. H., and Mesulam, M.-M. (1990). Basic mechanisms of cerebral rhythmic activities. *Electroencephalogr. Clin. Neurophysiol.* 76, 481–508. doi: 10.1016/0013-4694(90)90001-z

Supèr, H., Lamme, V. A. F., and Spekreijse, H. (2001). Two distinct modes of sensory processing oberved in monkey primary visual cortex (V1). *Nat. Neurosci.* 4, 304–310. doi: 10.1038/85170

Tagliazucchi, E., and Laufs, H. (2014). Decoding wakefulness levels from typical fMRI resting-state data reveals reliable drifts between wakefulness and sleep. *Neuron* 82, 695–708. doi: 10.1016/j.neuron.2014.03.020

Thivierge, J. P., and Cisek, P. (2008). Nonperiodic synchronization in heterogeneous networks of spiking neurons. *J. Neurosci.* 28, 7968–7978. doi: 10.1523/JNEUROSCI.0870-08.2008

Tononi, G., Boly, M., Massimini, M., and Koch, C. (2016). Integrated information theory: from consciousness to its physical substrate. *Nat. Rev. Neurosci.* 17, 450–461. doi: 10.1038/nrn.2016.44

Tononi, G., and Edelman, G. M. (1998). Consciousness and complexity. *Science* 282, 1846–1851. doi: 10.1126/science.282.5395.1846

Tononi, G., and Koch, C. (2015). Consciousnesse here, there and everywhere. *Philos. Trans. R. Soc. Lond. B Biol. Sci.* 370:20140167. doi: 10.1098/rstb.2014.0167

Tort, A. B. L., Komorowski, R. W., Manns, J. R., Kopell, N. J., and Eichenbaum, H. (2009). Theta-gamma coupling increases during the learning of item-context associations. *Proc. Natl. Acad. Sci. U S A* 106, 20942–20947. doi: 10.1073/pnas.0911331106

Tsuchiya, N., and Koch, C. (2005). Continuous flash suppression reduces negative afterimages. *Nat. Neurosci.* 8, 1096–1101. doi: 10.1038/nn1500

Tsuchiya, N., Wilke, M., Frässle, S., and Lamme, V. A. F. (2015). No-report paradigms: extracting the true neural correlates of consciousness. *Trends Cogn. Sci.* 19, 757–770. doi: 10.1016/j.tics.2015.10.002

Van Dijk, H., Schoffelen, J.-M., Oostenveld, R., and Jensen, O. (2008). Prestimulus oscillatory activity in the alpha band predicts visual discrimination ability. *J. Neurosci.* 28, 1816–1823. doi: 10.1523/JNEUROSCI.1853-07.2008

Weiskrantz, L. (1996). Blindsight revisited. *Curr. Opin. Neurobiol.* 6, 215–220. doi: 10.1016/s0959-4388(96)80075-4

Winters, J. J. (2020). The temporally-integrated causality landscape: a theoretical framework for consciousness and meaning. *Conscious. Cogn.* 83:102976. doi: 10.1016/j.concog.2020.102976

Wittmann, M. (2011). Moments in time. *Front. Integr. Neurosci.* 5:66. doi: 10.3389/fnint.2011.00066

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The Slowest Shared Resonance: A Review of Electromagnetic Field Oscillations Between Central and Peripheral Nervous Systems

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Young A, Hunt T and Ericson M (2022) The Slowest Shared Resonance: A Review of Electromagnetic Field Oscillations Between Central and Peripheral Nervous Systems. Front. Hum. Neurosci. 15:796455. doi: 10.3389/fnhum.2021.796455

Electromagnetic field oscillations produced by the brain are increasingly being viewed as causal drivers of consciousness. Recent research has highlighted the importance of the body's various endogenous rhythms in organizing these brain-generated fields through various types of entrainment. We expand this approach by examining evidence of extracerebral shared oscillations between the brain and other parts of the body, in both humans and animals. We then examine the degree to which these data support one of General Resonance Theory's (GRT) principles: the Slowest Shared Resonance (SSR) principle, which states that the combination of micro- to macro-consciousness in coupled field systems is a function of the slowest common denominator frequency or resonance. This principle may be utilized to develop a spatiotemporal hierarchy of brain-body shared resonance systems. It is predicted that a system's SSR decreases with distance between the brain and various resonating structures in the body. The various resonance relationships examined, including between the brain and gastric neurons, brain and sensory organs, and brain and spinal cord, generally match the predicted SSR relationships, empirically supporting this principle of GRT.

Keywords: resonance, interoception, consciousness, EEG, embodied cognition, coupled oscillators

INTRODUCTION

A nested hierarchy of electromagnetic (EM) fields spans the entire human physiology, encompassing the cortex, deep brain structures, and an extracerebral network throughout the body (Hales, 2017; Klimesch, 2018). This system of EM fields appears to synchronize, in various ways and to varying degrees, neural activity in peripheral neural clusters, such as the stomach and heart, to the brain's rhythms, maintaining a generally steady state, during waking consciousness, of "electromagnetic homeostasis" (De Ninno and Pregnolato, 2017). All of this EM field activity supervenes upon a neuroanatomical backbone that is as stable as the fields are dynamic.

This review summarizes the current research on shared electromagnetic field resonance among (1) the human brain and its peripheral nervous system; (2) similar activity observed in other animals; and (3) the implications of these interactions for electromagnetic field theories of consciousness, specifically the General Resonance Theory (GRT) of consciousness (Hunt, 2011, 2020; Hunt and Schooler, 2019). GRT postulates that all matter resonates and has some iota of associated consciousness. Shared resonance is achieved when matter resonates in proximity with other matter at the same frequency, or harmonics thereof, over a sufficient duration, resulting in the combination of micro-consciousnesses into larger, more complex macro-consciousness. GRT is a proposed solution to the Combination Problem (Hunt and Schooler, 2019), which is often leveled as a critique of panpsychist approaches to consciousness. A key motivation of GRT is the transformation of panpsychism from a philosophical position into an empirical theory of consciousness.

EM field theories of consciousness, of which GRT is one type, often posit that neuronally generated EM fields (Buzsáki et al., 2012; Hales, 2017; Chiang et al., 2019) are the primary seat of consciousness. GRT suggests a shared resonance between various nested EM fields and the specific kinds of information processing made possible with resonating EM fields is necessary and sufficient for mammalian consciousness. It differs in this respect from Integrated Information Theory (Oizumi et al., 2014), a widely discussed theory of consciousness, that suggests information processing and its integration are necessary and sufficient for consciousness. We can measure the dynamics of these EM fields by, for example, distinguishing five primary EEG frequency bands: delta (0.2–3 Hz), theta (3–8 Hz), alpha (8–12 Hz), beta (12–27 Hz), and gamma (27–100 Hz) (Fields, 2020), and then measuring their strength and interactions throughout the brain. It is not arbitrary that there are five main bands because recent data supports the view that the mammalian brain often achieves, particularly during times of high performance, a binary (harmonic) hierarchical relationship between each band (Klimesch, 2018; Rassi et al., 2019; Rodriguez-Larios et al., 2020). For example, the middle range of theta is twice that of delta, and also for alpha in relation to theta, etc. This binary hierarchy supports the notion that the EM fields generated by the brain are indeed causal rather than epiphenomenal (Klimesch, 2018; Rassi et al., 2019). The heart-brain, gastric-brain, and retinal-brain shared resonance relationships surveyed in the current paper appear to, in some manner, entrain cerebral EM fields, and vice versa (all physical reactions are necessarily bi-directional).

"Consciousness" will be defined here for clarity as the "what it is to be like" (subjective feeling) of the EM field system produced by the brain and peripheral nervous system (Hales et al., 2021, in progress). While Nagel (1974) asked "What is it like to be a bat," we reframe this as: "What is it like to be the EM field system produced by the brain of that bat?"

Theories of embodied cognition propose an inherent capacity of the body to constrain, regulate, and distribute cognitive processes across the organism (Thompson and Varela, 2001; Fuchs, 2009; Foglia and Wilson, 2013). We follow this tradition by suggesting that cognitive processes and endogenous rhythms are tightly coupled and are the pathways through which the body regulates an agent's cognitive activity over both space and time. The structuring of the neuronally generated cerebral fields by the oscillatory activity of distant neural clusters is one such manifestation of this interconnected network of embodied cognition. Similar theories argue that the experienced "self" emerges from the constant stream of afferent signals the brain receives from the various bodily organs (Park and Tallon-Baudry, 2014).

The alignment of EM field oscillations, or oscillatory integration windows, between the brain and other organs seems to be a key part of the conditions that allow a unified consciousness to emerge (Strogatz, 2012; Riddle et al., 2021, in progress). Gupta et al. (2016) provides evidence of preferred windows of oscillation cycles in locust Kenyon cells that more effectively integrate information and separate signal from noise. We also review various brain-body shared resonances in rats and octopi, and these data provides at least preliminary evidence that extracerebral shared resonance is not solely a human or mammalian phenomenon.

In fact, if we follow in the embodied cognition tradition, we hypothesize that the embodied mind, represented here by various brain-body shared resonances in organizing a unified organismic consciousness, must have been present in terrestrial organisms as early as the Cambrian explosion (Trestman, 2013), and probably far earlier. This suggests that embodied cognition may have emerged at roughly the same time as the ancestral bilaterian, the first animal with an organization for left and right, top and bottom, front and back (Godfrey-Smith, 2013). Embodied cognition and brain-body coupling is likely present in many, if not all, modern organisms, from the highly centralized nervous systems of *Homo sapiens* to the highly decentralized, split-brain-esque nervous system of the *Octopus vulgaris* (Godfrey-Smith, 2020).

Our analysis seeks to shed light on GRT's SSR principle: that the shared resonance frequency between neural clusters decreases with the spatial distance separating them (Hunt, 2020). The slowest common denominator frequency, or Slowest Shared Resonance (SSR), accordingly, defines the boundaries of each conscious entity in each moment. The inverse relationship between frequency of the SSR and distance between neural clusters is due to the physics of wave propagation. Lower frequencies travel faster (Dehaene, 2014), thus information to the brain will be carried upon increasingly lower frequency signals as the distance between the two clusters increases.

Cross-frequency coupling (CFC), the modulation of a faster frequency by a slower rhythm through harmonics or phase-amplitude coupling, is a mechanism by which functional systems may be integrated across varying spatiotemporal scales (Canolty and Knight, 2010) and a necessary component of the spatiotemporal relations underlying the combination of consciousness that is suggested by GRT (for a review of the relationship between disordered states of consciousness and altered cross-frequency couplings as supportive of the causality conferred to CFC, see Cai et al., 2020).

The evidence reviewed is largely supportive of GRT's SSR prediction. Further research is needed, however, both in improving our understanding of the various spatial and temporal causal hierarchies present, as well as for its application in clinical settings, if we are to succeed in our effort to make GRT a mature and empirically founded theory of consciousness.

THE OSCILLATORY HIERARCHY OF BRAIN AND BODY RHYTHMS

The trend toward considering EM field oscillations as causal rather than epiphenomenal has been gradual, as new evidence has come to light and new paradigms developed. Here, we will review several recent studies that speak to the causal role of cerebral fields in cognition and consciousness.

One such method of testing the cognitive role of certain neural oscillations has been through the application of artificial oscillatory stimulation using rhythmic transcranial magnetic stimulation (rTMS), transcranial alternating current stimulation (tACS), and transcranial direct current stimulation (tDCS)—collectively termed transcranial brain stimulation (TBS).

Klimesch et al. (2003) applied rTMS to subjects' frontal and parietal regions (specifically P6 and Fz cortical sites) at their individual alpha frequencies which was found to increase cognitive performance in mental rotation tasks by influencing the dynamics of their alpha desynchronization. Similarly, Wilsch et al. (2018) fortified cortical entrainment to the speech envelope at 3–8 Hz (Fujii and Wan, 2014), successfully modulating sentence comprehension. In a broad review of neurostimulation studies, Thut et al. (2011) supports the efficacy of the modality in modulating cognitive behaviors through the alteration of cortical oscillatory networks. It's application on the clinical end has found substantial success directly treating the neural networks associated with disordered consciousness in Alzheimer's disease (Nardone et al., 2015; Chang et al., 2018), anxiety (Kar and Sarkar, 2016), post-traumatic stress disorder (PTSD), and obsessive-compulsive disorder (Freire et al., 2020) to name a few among many psychopathologies.

Other empirical methods include observing the spontaneous, yet organized, coupling and decoupling of various brain waves during cognitive tasks. Rodriguez-Larios et al. (2020) recorded the enhanced transient occurrence of 2:1 (binary) harmonic cross-frequency coupling between alpha and theta when subjects engaged in effortful cognition. The same study also recorded a decrease (as compared to resting state) in alpha-theta coupling during a "mind emptiness" meditation task, an experimental condition opposite that of effortful cognition.

Samaha and Postle (2015) utilized flicker-fusion rate as a measure of visual experience in order to investigate the relationship between cortical alpha frequencies and temporal resolution. Subject's individual alpha frequency predicted temporal resolution of visual perception (Samaha and Postle, 2015). A slower alpha frequency would process both flashes in a single oscillatory integration window with which the subject would report a fusion of the two flashes. A faster alpha frequency showed the two flashes were processed in different oscillatory windows and the subject reported the visual experience of two flashes. These results were taken as evidence that the alpha wave underlies the temporal granularity of visual perception, defining what was presented to the subject's consciousness in each moment.

Başar (2008) describes the body as a unified network of oscillatory activity between the brain, spinal cord, and peristaltic organs—a system whose foundation is built on a frequency band hierarchy. The hierarchy proposed contained three tiers organized by frequency in descending order: the high frequency band (above 40 Hz), EEG frequencies, and the ultra-slow oscillations. Integrating results from Ruskin et al. (1999) and Allers et al. (2000, 2002), Başar (2008) hypothesized that the ultra-slow oscillations (0.001–1 Hz) originating from various elements of the autonomic nervous system (ANS) have the potential to organize the propagation and synchronization of neural oscillations in higher frequency bands. ANS feedback signals to the brain carry the input for bodily experience, contributing to the feelings of energy, fatigue, and relaxation (Başar, 2008). Barman and Gebber (1993) and Barman et al. (1995) recordings of sympathetic nerves in decerebrated cats demonstrated 10 Hz discharges between both subcortical structures and cardiac neurons. Başar (2008) concludes that these data support the presence of oscillatory links between the brain, spinal cord, and organs of the body.

Klimesch's (2018) "binary hierarchy brain body oscillation theory" suggests that the frequency of body oscillations can be predicted from brain oscillations, and vice versa, and that these different frequency domains fall on a predictable pattern across 11 or more "frequency domains." He suggests that brain-body coupling is governed by either harmonic phase-to-phase coupling or phase-to-envelope coupling. The six endogenous rhythms that Klimesch focuses on are presented in **Figure 1**, which reproduces Figure 5 from Klimesch (2018), in descending order of frequency: (1) brain rhythms; (2) heart rate; (3) breathing frequency (BF); (4) blood pressure (BP); (5) gastric neuron basal rhythms; and (6) blood oxygen level dependent (BOLD measured with fMRI) signal. These rhythms generally remain coupled to brain wave frequency bands during waking states but become decoupled in sleep, although the body rhythms remain coupled to each other in binary integer ratios even in sleep (Rassi et al., 2019).

Another pattern not included sufficiently in Başar's and Klimesch's work is a shared resonance between cerebral EM fields, represented by interactions between the five brain wave frequency bands, and the various organs of the body, including gastric, retinal, and cardiac neurons (Klimesch does discuss gastric/cerebral resonance, as **Figure 1** shows, but not the other resonance relationships we discuss below). We discuss four such shared resonance relationships in laying the groundwork for additional research into brain-body oscillatory links that have not yet been explored sufficiently, but are predicted by both Başar's (2008) globally coupled oscillators model and Klimesch's (2018) binary hierarchy brain body oscillation theory.

Gastric-Brain Shared Resonance

Measured with the electrogastrogram (EGG), the peristaltic organs, primarily the stomach, emit a central frequency of 0.05 Hz (about one cycle every 20 s), an ultra-slow oscillation (Başar, 2008). This oscillation, the gastric basal rhythm, is emitted by the interstitial cells of Cajal—specialized cells in the stomach's

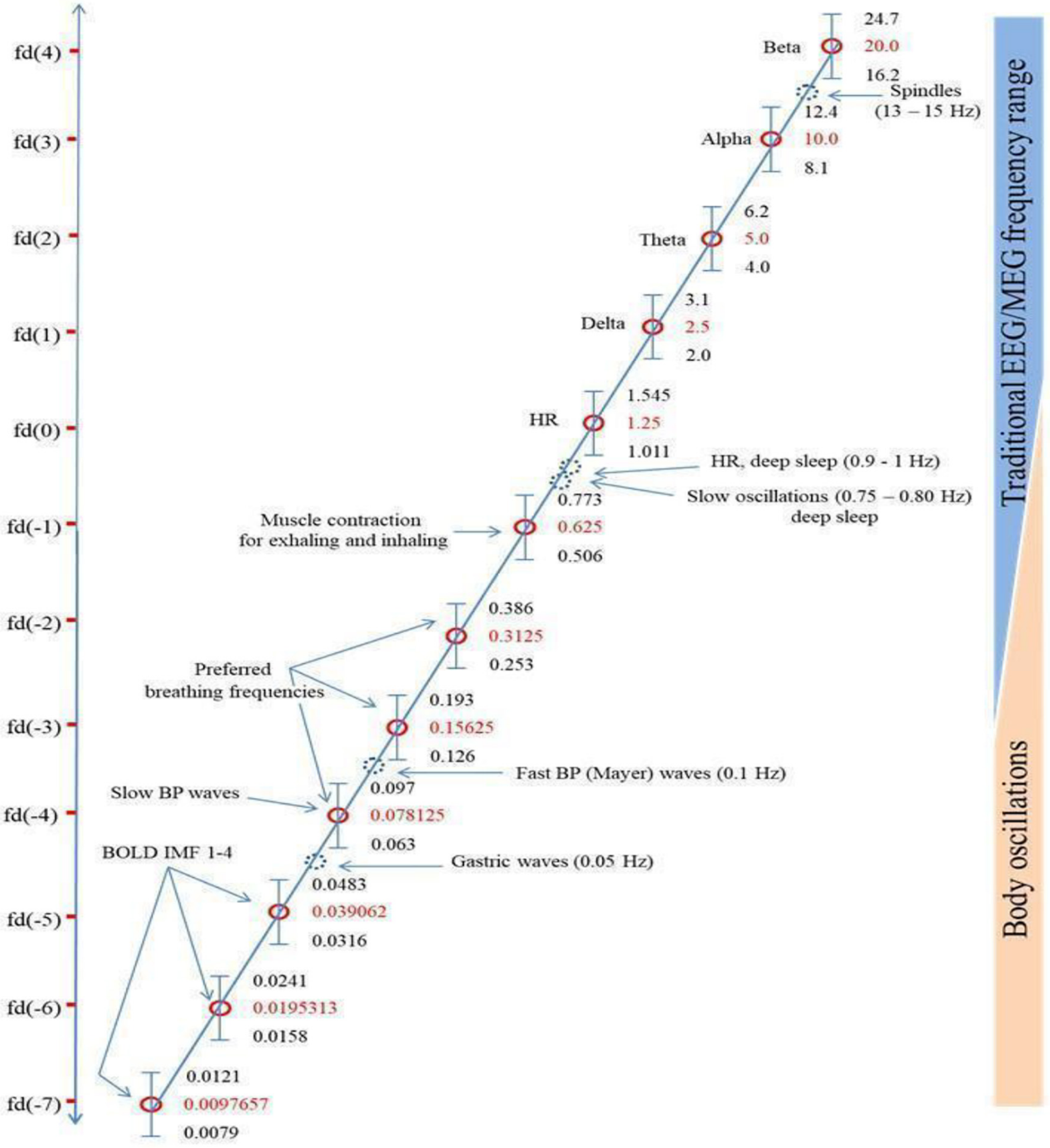

FIGURE 1 | Klimesch's (2018) figure illustrating the Binary Hierarchy Brain Body Oscillation Theory frequency architecture. Frequency bands, calculated according to the "golden mean rule" (see Klimesch, 2018), are depicted as vertical bars (bandwidths relative to the *y*-axis are not to scale). Frequencies lying outside the predicted bands are represented as dashed blue circles and are considered falling outside the binary hierarchy.

wall (Takaki, 2003). Richter et al. (2017) reported a stomach-brain resonance relationship by which EEG frequencies were phase amplitude coupled (PAC) to the gastric basal rhythm. PAC evaluates changes in the amplitude of a high frequency oscillation according to the phase of a lower frequency oscillation—a relationship that usually presents between distant neural clusters (Richter et al., 2017). This study provided evidence for a directional relationship between the 0.05 Hz ultra-slow oscillations of the stomach and the 8–12 Hz oscillations of the brain's alpha waves, suggestive of a framework by which slow organ oscillations can, in fact, couple to the brain's higher frequency waves. Richter notes that the relationship is primarily ascending with the greatest information transfer from stomach to brain due to the intrinsic nature of the stomach's emitted pulses.

Rebollo et al. (2018) expanded on Richter's gastric-alpha work by establishing oscillatory links between the stomach-brain interaction and the BOLD signal in resting state networks (RSN). This relationship arises due to the following dynamics: (1) the stomach's extensive connections to cortical structures through neuroanatomical pathways (primarily Vagus nerve) and EM field resonance; (2) the gastric basal rhythms falling within the BOLD signal's range of fluctuations (0.0079–0.0483 Hz; Klimesch, 2018); and (3) the PAC of alpha-gastric basal rhythm (Richter et al., 2017). The network is represented by synchronized fluctuations in BOLD signal in brain structures known to be coupled to the gastric basal rhythm, extrapolated from Richter's earlier work. Rebollo et al. (2018) "identifies BOLD regions that go faster when the stomach goes faster, and slower when the stomach goes slower."

Rebollo et al.'s (2018) study revealed a novel RSN by which two endogenous rhythms, BOLD and gastric basal rhythms, are phase-amplitude-coupled, but only partially (up to ∼17 percent maximum) to the brain's alpha waves. The relationship is argued to be bi-directional in establishing an interoceptive sense (Huizinga, 2017, per the entrainment of cortical oscillations in the insular cortex) and maintaining homeostasis, but Rebollo agrees with Richter that there is a significant ascending influence of the stomach on the brain. The vagus nerve (VN), a significant carrier of information between the brain and the GI tract, is composed of eighty percent afferent fibers and twenty percent efferent fibers (Bonaz et al., 2018). This division in the VN validates Rebollo and Richter's proposition of a significant ascending influence but in no way rules out descending influence. This gastric-brain shared EM field resonance is defined by the ultra-slow oscillations of the 0.05 Hz gastric basal rhythm partially resonating with the brain's alpha wave. This is the slowest of the shared resonance relationships examined here, and the stomach's neural cluster is farthest, of the organs examined herein, from the brain.

Cardiac-Brain Shared Resonance

The heart is implicated in embodied cognition frameworks, specifically in its influence on emotional experience. For example, fear signals are judged as more fearful when the stimulus appears during a heartbeat as opposed to between beats (Garfinkel and Critchley, 2016). In fact, the resting state heartbeat induces phase synchronization between cortical regions in the theta frequency (3–8 Hz) comprising a five-module network known as the heartbeat-induced network (Kim and Jeong, 2019). Increased synchronization correlated with more positive mood as well as an inverse relationship with negative mood.

McCraty et al. (2009) sought to uncover a coherent heart-brain system of interaction by correlating emotional states with psychophysiological changes, citing the heart as the most powerful generator of endogenous rhythms in the body. The study identified six psychophysiological states to measure cardiac-brain resonance: mental focus, psychophysiological incoherence, psychophysiological coherence, relaxation, extreme negative emotion, and emotional quiescence. The state of psychophysiological coherence was specifically noted as a shared resonance state between brain and heart oscillations (McCraty et al., 2009). This state, which entails the global coupling of body rhythms to cardiac oscillations, is hypothesized to be causal in increasing performance and overall well-being (or the converse through desynchronization or dysregulation).

The study demonstrates, unsurprisingly, a bidirectional relationship between the heart and the brain, wherein emotional states are reflected in the heart rate variability (HRV) and the cognitive processes that shape emotion are modulated by HRV. The 0.1 Hz (10 s cyles) central heart resonant EM field frequency (measured with EKG), represented by a distinct high amplitude peak in the HRV power spectrum, synchronizes with alpha (derived from Wölk and Velden, 1987, 1989; replicated by McCraty et al., 2009) and beta (per McCraty et al., 2009) bands in the brain in psychophysiological coherent states. These 0.1 Hz oscillations reappear in PTSD patients undergoing Somatic Experiencing (SE) trauma resolution therapy when a threat response is successfully re-negotiated and constricted energy is subsided (Whitehouse and Heller, 2008).

The cardiac-brain shared resonance is defined by the 0.1 Hz heart resonant frequency with shared resonance occurring between alpha and beta EEG bands. In developing the ongoing pattern in this paper, the SSR for cardiac-brain shared resonance occurs at a frequency twice as fast as the 0.05 Hz of the gastric basal rhythm underlying gastric-brain shared resonance, and supports the SSR prediction that SSR will increase inversely with distance between neural clusters.

Retinal-Brain Shared Resonance

Several studies provide evidence for oscillatory links between the retina and brain (Leszczynski and Schroeder, 2019; Leszczynski et al., 2020). Saccadic eye movements are generated rhythmically at 3–4 Hz by the observer to place the fovea—the area of the retina containing the densest concentration of photoreceptors—on a target. Saccadic rhythms reset the alpha phase (8–12 Hz) in the occipital lobe and theta phase (4–7 Hz) in the medial temporal lobe (Leszczynski and Schroeder, 2019). The rhythmic nature of the saccadic phase reset generates an entrainment, the largely uni-directional coupling of one oscillator to another (Lakatos et al., 2019), of alpha and theta EEG bands.

The alpha-theta entrainment aligns cerebral oscillatory integration windows to the flow of the rhythmic visual input from the retina, an exchange termed active visual sensing (Leszczynski et al., 2020). Active sensing is defined as fovea relocation through saccadic eye movements and sampling of different bits of visual information many times a second. The entrainment of alpha and theta to saccade onset rhythms amplifies neuronal responses to the incoming visual stream, thus lowering perceptual thresholds (Leszczynski and Schroeder, 2019). This hypothesis about the mechanism for these connections was confirmed in a later study (Leszczynski et al., 2020). In this sense, just as gastric-brain shared resonance appears to underlie interoception and cardiac-brain shared resonance contributes to emotional experience, retinal-brain shared resonance enacts a functional relationship to engage in active sensing.

The 3–4 Hz saccadic rhythm serves as the SSR for this retinal-brain shared resonance relationship with the alpha and theta brain waves. As a neural cluster significantly closer to the brain than either the stomach or heart, its SSR is a significantly faster frequency than the two previously discussed shared resonance relationships.

Corticospinal Shared Resonance

The spinal cord, an important part of the central nervous system, engages in large-scale coherent neuronal firing with the brain's motor cortex during movement. Using reaction time tasks, Schoffelen et al. (2005) manipulated hazard rates of the go-cue peri-task to measure "readiness" and the corticospinal interaction that underpin it. The hazard rate of an event is the conditional probability of the event occurring if it has not yet occurred. Readiness was represented by the subject's response times (Riehle et al., 1997; Trillenberg et al., 2000). Measuring the left motor cortex neuronal group directly with magnetoencephalography (MEG) and the corresponding spinal neuronal group indirectly through the right musculus extensor carpi radialis longus with electromyogram (EMG), Schoffelen recorded beta (12–27 Hz) and gamma (27–100 Hz) coherence between the spinal cord and motor cortex. The experimental paradigm was split into two conditions: UP- and DOWN-schedule, referring to the hazard rate of the go-cue. Corticospinal gamma band coherence increased with the hazard rate in UP-schedule trials and decreased in DOWN-schedule trials. Corticospinal coherence in the beta band was present through every trial regardless of schedule. Results demonstrated corticospinal coherence in the gamma band and tightly coupled readiness-to-respond. Gamma band coherence was increased when the subject expected a physical movement.

This corticospinal to brain shared resonance with beta and gamma bands appears to underlie mechanical motion (van Wijk et al., 2012). However, differing from the other shared resonance systems surveyed, the evidence is inconclusive in establishing an entraining rhythm by the spinal cord to ground the corticospinal shared resonance, as discussed above for gastric basal rhythm (0.05 Hz), heart resonant frequency (0.1 Hz), or retinal saccadic rhythm (3–4 Hz). Although the preliminary evidence is promising, further research is needed to define the SSR of this particular system and integrate corticospinal shared resonance into the GRT spatiotemporal hierarchy.

PRINCIPLES OF SPATIAL COUPLING

Research discussed above supports the presence of oscillatory links between the brain and the heart, stomach, retina, and spinal cord. Subsequent studies will be needed to expand the framework to include shared resonances between the brain and neural clusters in the genitals, lungs, olfactory centers, and any combination thereof.

The pattern predicted by GRT's SSR principle—distance inversely affects shared resonance frequency bands—is generally supported by current findings (**Table 1**). The retina, as the most proximal neural cluster to the brain, emits the highest frequency SSR (3–4 Hz), in the form of a saccade and associated neural activity resonating with theta and alpha EEG bands (Leszczynski and Schroeder, 2019; Leszczynski et al., 2020). The heart's primary EM field rhythm, the heart resonant frequency at 0.1 Hz, resonates with alpha and beta brain waves (McCraty et al., 2009). The stomach, the organ most distant from the brain (of the organs reviewed herein), emits the slowest frequency SSR at 0.05 Hz gastric basal rhythm, resonating with the brain's alpha rhythms (Richter et al., 2017; Rebollo et al., 2018). While research is suggestive of corticospinal shared resonance (Schoffelen et al., 2005), the evidence is inconclusive in establishing an SSR frequency underlying the observed resonance. We also include preliminary data on olfactory center and brain shared resonance as a plausible addition to the developing hierarchy.

TABLE 1 | Slowest Shared Resonance (SSR) between coupled neural clusters.

Coupled system	Slowest Shared Resonance (SSR)	Estimated distance**
Retinal-brain	3–4 Hz	5 cm
Olfactory-brain*	0.16–0.33 Hz	7–10 cm
Cardiac-brain	0.1 Hz	30 cm
Gastric-brain	0.05 Hz	50 cm
Corticospinal-brain	N/A	15–50 cm (wide range due to length of spinal cord)

**Tentative placement.*
***Rough estimate provided in normal stature adult human, provided for illustration only. Additional research is required to provide better estimates.*

Zelano et al. (2016) findings are suggestive of links between nasal respiration rates and delta, theta, and beta waves in the human piriform cortex (PC), and limbic-related brain areas. Intracranial EEG recordings paired with concomitant nasal respiration recordings indicated cortical entrainment to the 0.16–0.33 Hz rhythm of the human respiratory cycle. This BF is hypothesized to act as an electrical pacemaker synchronizing activity in the PC, amygdala, and hippocampus. These results determined this entrainment to be functional in modulating emotional experience and memory. Fearful faces are identified with faster reaction times when presented during nasal inspiratory phase, but not surprised faces. Recognition tasks in memory tests find enhanced retrieval of stimuli when prompted during nasal inspiratory phase versus expiration. These findings are in line with those of Klimesch (2018), such that BF appears to be one of the primary organizing endogenous rhythms. Corcoran et al. (2018) echoes this view, hypothesizing respiration-brain coupling to constitute a global rhythm that structures higher-frequency brain activity. However, what differs from the previously discussed shared resonances is that olfactory-brain shared resonance does not appear to have an entraining neural rhythm apart from the entraining physiological rhythm. Giving credence to Zelano's findings, the 0.16–0.33 rhythm of human nasal respiration (the olfactory-brain SSR) would place the shared resonance appropriately above cardiac-brain and gastric-brain, and just below retinal-brain shared resonance properly fitting in our developing spatial hierarchy (**Table 1**).

ENTRAINMENT AND SHARED RESONANCE

The internal resonance properties of the cerebral field system, as the brain is entrained by and responds to external stimuli, supports the notion that EM field resonance is causal with respect to the dynamics of consciousness (Başar et al., 1975). The entrainment of cortical oscillations through the application of rhythmic auditory (Chatrian et al., 1960) and visual (Adrian and Matthews, 1934) stimuli is a deeply researched and well-substantiated tool in clinical settings for treating disordered states of consciousness (Siever and Collura, 2017), as well as a common method of laboratory paradigms for correlating neural oscillations with conscious and cognitive behaviors (Young, 2021, in press). This section surveys empirical examples in which resonance between the central and peripheral neural clusters, specifically between the heart and the brain, is driven by external stimuli.

The conscious control that can be exercised over respiration makes it unique among the fundamental rhythms. Breathing at a rate of 6 breaths per minute (0.17 Hz) evokes synchrony among cardiac measures (Shaffer et al., 2014) and induces coherence in the 0.1 Hz oscillations of the heart resonant frequency (Schwerdtfeger et al., 2020). The range of "coherent" or "resonance" breathing is between 4.5 (0.22 Hz) and 6.5 (0.15 Hz) breaths per minute depending on the cardiovascular disposition of the individual but all values fall within BF ranges of Klimesch's brain-body frequency architecture (**Figure 1**; Klimesch, 2018). This breathing mode, in evoking the heart resonant frequency, affects the physiological and psychological regulation of negative affect (Schwerdtfeger et al., 2020). This is one avenue through which an ascending influence of HRV may partially entrain the brain's endogenous rhythms and regulate cognition.

The bidirectional nature of the cardiac-brain correspondence is exemplified by the downward influence the brain's EM oscillations exercises over the heart in audiovisual entrainment (AVE) studies. As referenced above, auditory and visual stimuli, separately or in combination, reliably entrain cortical oscillations. Francesco et al. (2013) administered alpha frequency AVE and, in doing so, increased HRV, a sign of positive cardiac health (van Ravenswaaij-Arts et al., 1993). McConnell et al. (2014), in a similar study, administered theta frequency binaural beats to individuals post-exercise. The measures of HRV recorded no significant change but the AVE-stimulated group reported greater feelings of relaxation. An acute influence over low and high frequency components of HRV were concluded. We may speculate that the greater success of Francesco et al.'s (2013) stimulation was due to the targeted frequency. Alpha, but not theta, resonates with the HRV signal (McCraty et al., 2009) and the manipulation of one end of the correspondence will alter the other.

SHARED RESONANCE IN OTHER ANIMALS

Cerebral and extracerebral EM field oscillations, as reviewed above, are not a phenomenon specific to humans. The frequency hierarchy we inherited from our distant evolutionary ancestors is, in many cases, very similar to that which humans and other mammals possess today (Buzsáki et al., 2013). Despite the increase in human brain volume, the frequency hierarchy that characterizes neural oscillations in the brain and body has been largely conserved across species. Animal cerebral oscillatory interaction is assumed to be equally causal as appears to be in humans. Animal studies are often conducted as suitable stand-ins for the usually invasive testing procedures and the findings extended to explain human oscillatory dynamics (Roelfsema et al., 1997; Tallon-Baudry et al., 2004; Paulk et al., 2013). This section will review an integrative example of similar extracerebral shared resonance to support additional research into non-human brain-body oscillatory links.

Tort et al. (2018) examined nasal respiratory entrained rhythms in rodents, in a system similar to the speculated olfactory-brain shared resonance in humans. Rodent respiration cycles can occur at frequencies as low as 1 Hz during rest/sleep and as high as 14 Hz during sniffing, making these rhythms indistinguishable from delta and theta oscillations in the rodent brain if not measured concomitantly (Wesson et al., 2008; Rojas-Líbano et al., 2014). When differentiating the respiration rhythms from low frequency brain waves, respiration-gamma coupling is observable in several regions of the brain. During immobility and active behaviors, the respiration-gamma coupling is recorded in the olfactory bulb (OB), medial prefrontal cortex (mPFC), and hippocampus. This coupling ceases if the rodent diverts breathing to the trachea or the OB is surgically removed. The mechanism is unknown, but Tort hypothesized the respiration-gamma coupling serves as a means of integrating gamma activity across distant regions given that slow oscillations, such as that of the respiratory cycles, remain coherent while traveling longer spatial distances.

Tsukahara et al. (1973), in observing neural oscillations from an anesthetized *O. vulgaris* retina, serendipitously recorded retinal oscillations resonating with respiration. Spontaneous oscillations appeared as bursts at approximately 0.2 Hz during the measurement of retinal oscillations under illumination. The spontaneous bursts ceased when the octopus breathing was interrupted. Similar in kind to speculated olfactory shared resonance, the neural oscillations commenced at inspiration and somewhat ceased at expiration. This is likely evidence for a shared resonance relationship between the octopus's neural and physiological rhythms.

Shared resonance between the central and peripheral nervous system, as well as in other organs, is likely not isolated to humans. Beginning with physiological entrainment of neural rhythms, a similar frequency hierarchy of resonating brain-body oscillations presumably awaits discovery in other animal species.

DISCUSSION

Taken together, our developing model supposes functional links between endogenous neural rhythms throughout the brain and body. The peripheral nervous clusters in the organs can be regarded in some manner as extensions of the brain itself, and the consciousness associated with the activity of the cerebral brain can likewise be extended to encompass the entire organism, although in a more rudimentary manner. This is exemplified in the gastric influence on interoception, the heart on emotional processing, and the rhythms of the eye and retina in active visual sensing. This is supplemented by corticospinal shared resonance in locomotion and respiration-gamma coupling in emotional processes. The similarities with animal neural-physiological synchronization indicates a probable universality of the oscillatory substrates of consciousness. Theories of embodied cognition are congruent;

the timeline of development suggests all modern organisms are likely to exhibit some manner of brain-body coupling and the included discussion on respiration-neural coupling in rats and octopi would support it.

The spatiotemporal hierarchy depicted in **Table 1** generally supports GRT's predictions and closely aligns with Klimesch's (2018) similar binary hierarchy brain body oscillation theory shown in **Figure 1**. Data supports the suggested inverse relationship between resonating frequencies and the spatial distance separating the resonating clusters.

For clinical applications this model presents a novel path by which the documentation and treatment of neuropsychiatric conditions may be extrapolated to the whole organism. Findings of bodily illness coinciding with cognitive conditions are well documented and, in some cases, bi-directional. A pathological reduction of HRV is associated with PTSD (Whitehouse and Heller, 2008), Alzheimer's Disease (Zulli et al., 2005), and anxiety disorders (Chalmers et al., 2014). Trauma disorders are frequently comorbid with functional gastro-intestinal disorders (Kolacz et al., 2019) and chronic gut inflammation is linked to the development and progression of AD (Santiago and Potashkin, 2021). To assume disruption of the underlying synchrony architecture that may influence the trajectory and symptomatology of a disorder in such cases is not so great a leap of faith. In fact, Richter et al.'s (2017) findings of gastric-alpha coupling prompted some authors to consider this synchrony link as a viable route by which the gut microbiota, implicated in a number of disorders (Rees, 2014; Latalova et al., 2017; Sochocka et al., 2019), may be able to influence cognitive processes (Palacios-García and Parada, 2020). The benefits of this model as compared to previous efforts is the quantifiable nature by which the strength of brain-body coupling may be examined through the use of already developed phase-to-phase and phase-amplitude quantification techniques. With proper development, the spatiotemporal hierarchy of brain-body shared resonance may be utilized in illustrating a more comprehensive picture of holistic health, and to provide the means by which treatments based on correcting out of sync brain and body rhythms may be administered as an effective adjunct to prevailing treatments.

Subsequent efforts should be directed at further developing the hierarchy of brain-body neural resonances. Başar and Klimesch's foundational works suggest coupling between the brain and all of the body's organs. Corticospinal and olfactory-brain shared resonance relationships require further development to integrate into the model. A related venture is the examination of environmental EM influence, such as geomagnetic activity (Bureau and Persinger, 1992; Cherry, 2002, 2003) or anthropogenic sources more generally (Becker et al., 1985), upon this network of resonating structures.

AUTHOR CONTRIBUTIONS

AY produced the manuscript. TH and ME advised and edited. All authors contributed to the article and approved the submitted version.

REFERENCES

Adrian, E. D., and Matthews, B. H. (1934). The Berger rhythm: potential changes from the occipital lobes in man. *Brain* 57, 355–385. doi: 10.1093/brain/awp324

Allers, K. A., Kreiss, D. S., and Walters, J. R. (2000). Multisecond oscillations in the subthalamic nucleus: effects of apomorphine and dopamine cell lesion. *Synapse* 38, 38–50. doi: 10.1002/1098-2396(200010)38:1<38::AID-SYN5>3.0.CO;2-V

Allers, K. A., Ruskin, D. N., Bergstrom, D. A., Freeman, L. E., Ghazi, L. J., Tierney, P. L., et al. (2002). Multisecond periodicities in basal ganglia firing rates correlate with theta bursts in transcortical and hippocampal EEG. *J. Neurophysiol.* 87, 1118–1122. doi: 10.1152/jn.00234.2001

Barman, S. M., and Gebber, G. L. (1993). Lateral tegmental field neurons play a permissive role in governing the 10-Hz rhythm in sympathetic nerve discharge. *Am. J. Physiol. Regul. Integr. Comp. Physiol.* 265, R1006–R1013. doi: 10.1152/ajpregu.1993.265.5.R1006

Barman, S. M., Orer, H. S., and Gebber, G. L. (1995). A 10-Hz rhythm reflects the organization of a brainstem network that specifically governs sympathetic nerve discharge. *Brain Res.* 671, 345–350. doi: 10.1016/0006-8993(94)01402-4

Başar, E. (2008). Oscillations in "brain–body–mind"—a holistic view including the autonomous system. *Brain Res.* 1235, 2–11. doi: 10.1016/j.brainres.2008.06.102

Başar, E., Gönder, A., Özesmi, C., and Ungan, P. (1975). Dynamics of brain rhythmic and evoked potentials. *Biol. Cybern.* 20, 145–160.

Becker, R. O., Selden, G., and Bichell, D. (1985). *The Body Electric: Electromagnetism And The Foundation Of Life*. New York, NY: Quill.

Bonaz, B., Bazin, T., and Pellissier, S. (2018). The vagus nerve at the interface of the microbiota-gut-brain axis. *Front. Neurosci.* 12:49. doi: 10.3389/fnins.2018.00049

Bureau, Y. R., and Persinger, M. A. (1992). Geomagnetic activity and enhanced mortality in rats with acute (epileptic) limbic lability. *Int. J. Biometeorol.* 36, 226–232. doi: 10.1007/BF02726403

Buzsáki, G., Anastassiou, C. A., and Koch, C. (2012). The origin of extracellular fields and currents—EEG, ECoG, LFP and spikes. *Nat. Rev. Neurosci.* 13, 407–420. doi: 10.1038/nrn3241

Buzsáki, G., Logothetis, N., and Singer, W. (2013). Scaling brain size, keeping timing: evolutionary preservation of brain rhythms. *Neuron* 80, 751–764. doi: 10.1016/j.neuron.2013.10.002

Cai, L., Wang, J., Guo, Y., Lu, M., Dong, Y., and Wei, X. (2020). Altered inter-frequency dynamics of brain networks in disorder of consciousness. *J. Neural Eng.* 17:036006. doi: 10.1088/1741-2552/ab8b2c

Canolty, R. T., and Knight, R. T. (2010). The functional role of cross-frequency coupling. *Trends Cogn. Sci.* 14, 506–515. doi: 10.1016/j.tics.2010.09.001

Chalmers, J. A., Quintana, D. S., Abbott, M. J., and Kemp, A. H. (2014). Anxiety disorders are associated with reduced heart rate variability: a meta-analysis. *Front. Psychiatry* 5:80. doi: 10.3389/fpsyt.2014.00080

Chang, C. H., Lane, H. Y., and Lin, C. H. (2018). Brain stimulation in Alzheimer's disease. *Front. Psychiatry* 9:201. doi: 10.3389/fpsyt.2018.00201

Chatrian, G. E., Petersen, M. C., and Lazarte, J. A. (1960). Responses to clicks from the human brain: some depth electrographic observations. *Electroencephalogr. Clin. Neurophysiol.* 12, 479–489. doi: 10.1016/0013-4694(60)90024-9

Cherry, N. (2002). Schumann resonances, a plausible biophysical mechanism for the human health effects of Solar. *Nat. Hazards* 26, 279–331.

Cherry, N. J. (2003). Human intelligence: the brain, an electromagnetic system synchronised by the schumann resonance signal. *Med. Hypotheses* 60, 843–844. doi: 10.1016/s0306-9877(03)00027-6

Chiang, C. C., Shivacharan, R. S., Wei, X., Gonzalez-Reyes, L. E., and Durand, D. M. (2019). Slow periodic activity in the longitudinal hippocampal slice can self-propagate non-synaptically by a mechanism consistent with ephaptic coupling. *J. Physiol.* 597, 249–269. doi: 10.1113/JP276904

Corcoran, A. W., Pezzulo, G., and Hohwy, J. (2018). Commentary: respiration-entrained brain rhythms are global but often overlooked. *Front. Syst. Neurosci.* 12:25. doi: 10.3389/fnsys.2018.00025

De Ninno, A., and Pregnolato, M. (2017). Electromagnetic homeostasis and the role of low-amplitude electromagnetic fields on life organization. *Electromagn. Biol. Med.* 36, 115–122. doi: 10.1080/15368378.2016.1194293

Dehaene, S. (2014). *Consciousness And The Brain: Deciphering How The Brain Codes Our Thoughts*. London: Penguin.

Fields, R. D. (2020). *Electric Brain: How The New Science Of Brainwaves Reads Minds, Tells Us How We Learn, And Helps Us Change For The Better*. Dallas, TX: BenBella Books Inc.

Foglia, L., and Wilson, R. A. (2013). Embodied cognition. *Wiley Interdiscip. Rev.* 4, 319–325.

Francesco, C., Vincenza, L., Sergio, C., Maria, P., Antonio, F., Orlando, T., et al. (2013). Alpha-rhythm stimulation using brain entrainment enhances heart rate variability in subjects with reduced HRV. *World J. Neurosci.* 3, 213–220. doi: 10.4236/wjns.2013.34028

Freire, R. C., Cabrera-Abreu, C., and Milev, R. (2020). Neurostimulation in anxiety disorders, post-traumatic stress disorder, and obsessive-compulsive disorder. *Anxiety Disord.* 1191, 331–346. doi: 10.1007/978-981-32-9705-0_18

Fuchs, T. (2009). Embodied cognitive neuroscience and its consequences for psychiatry. *Poiesis Praxis* 6, 219–233. doi: 10.1007/s10202-008-0068-9

Fujii, S., and Wan, C. Y. (2014). The role of rhythm in speech and language rehabilitation: the SEP hypothesis. *Front. Hum. Neurosci.* 8:777. doi: 10.3389/fnhum.2014.00777

Garfinkel, S. N., and Critchley, H. D. (2016). Threat and the body: how the heart supports fear processing. *Trends Cogn. Sci.* 20, 34–46. doi: 10.1016/j.tics.2015.10.005

Godfrey-Smith, P. (2013). Cephalopods and the evolution of the mind. *Pacific Conserv. Biol.* 19, 4–9. doi: 10.1071/pc130004

Godfrey-Smith, P. (2020). *Metazoa: Animal Life And The Birth Of The Mind*. New York, NY: Farrar, Straus and Giroux.

Gupta, N., Singh, S. S., and Stopfer, M. (2016). Oscillatory integration windows in neurons. *Nat. Commun.* 7, 1–10. doi: 10.1038/ncomms13808

Hales, C. G. (2017). "The origins of the brain's endogenous electromagnetic field and its relationship to provision of consciousness," in *Biophysics Of Consciousness: A Foundational Approach*, eds J. A. Tuszynski, R. R. Poznanski, and T. E. Feinberg (Singapore: World Scientific Publishing Company Pte Limited), 295–354. doi: 10.1142/S0219635214400056

Hales, C. G., Ericson, M., and Hunt, T. (2021). All theories of consciousness are electromagnetic field theories of consciousness. *Front. Hum. Neurosci.*

Huizinga, J. D. (2017). Commentary: phase-amplitude coupling at the organism level: the amplitude of spontaneous alpha rhythm fluctuations varies with the phase of the infra-slow gastric basal rhythm. *Front. Neurosci.* 11:102. doi: 10.3389/fnins.2017.00102

Hunt, T. (2011). Kicking the psychophysical laws into Gear a new approach to the combination problem. *J. Conscious. Stud.* 18, 96–134.

Hunt, T. (2020). Calculating the boundaries of consciousness in general resonance theory. *J. Conscious. Stud.* 27, 55–80.

Hunt, T., and Schooler, J. W. (2019). The easy part of the hard problem: a resonance theory of consciousness. *Front. Hum. Neurosci.* 13:378. doi: 10.3389/fnhum.2019.00378

Kar, S. K., and Sarkar, S. (2016). Neuro-stimulation techniques for the management of anxiety disorders: an update. *Clin. Psychopharmacol. Neurosci.* 14:330. doi: 10.9758/cpn.2016.14.4.330

Kim, J., and Jeong, B. (2019). Heartbeat induces a cortical theta-synchronized network in the resting state. *Eneuro* 6, 1–11. doi: 10.1523/ENEURO.0200-19.2019

Klimesch, W. (2018). The frequency architecture of brain and brain body oscillations: an analysis. *Eur. J. Neurosci.* 48, 2431–2453. doi: 10.1111/ejn.14192

Klimesch, W., Sauseng, P., and Gerloff, C. (2003). Enhancing cognitive performance with repetitive transcranial magnetic stimulation at human individual alpha frequency. *Eur. J. Neurosci.* 17, 1129–1133. doi: 10.1046/j.1460-9568.2003.02517.x

Kolacz, J., Kovacic, K. K., and Porges, S. W. (2019). Traumatic stress and the autonomic brain-gut connection in development: polyvagal theory as an integrative framework for psychosocial and gastrointestinal pathology. *Dev. Psychobiol.* 61, 796–809. doi: 10.1002/dev.21852

Lakatos, P., Gross, J., and Thut, G. (2019). A new unifying account of the roles of neuronal entrainment. *Curr. Biol.* 29, R890–R905. doi: 10.1016/j.cub.2019.07.075

Latalova, K., Hajda, M., and Prasko, J. (2017). Can gut microbes play a role in mental disorders and their treatment? *Psychiatr. Danub.* 29, 28–30. doi: 10.24869/psyd.2017.28

Leszczynski, M., and Schroeder, C. E. (2019). The role of neuronal oscillations in visual active sensing. *Front. Integr. Neurosci.* 13:32. doi: 10.3389/fnint.2019.00032

Leszczynski, M., Staudigl, T., Chaieb, L., Enkirch, S. J., Fell, J., and Schroeder, C. E. (2020). Saccadic modulation of neural activity in the human anterior thalamus during visual active sensing. *bioRxiv* [Preprint] doi: 10.1101/2020.07.17.209387

McConnell, P. A., Froeliger, B., Garland, E. L., Ives, J. C., and Sforzo, G. A. (2014). Auditory driving of the autonomic nervous system: listening to theta-frequency binaural beats post-exercise increases parasympathetic activation and sympathetic withdrawal. *Front. Psychol.* 5:1248. doi: 10.3389/fpsyg.2014.01248

McCraty, R., Atkinson, M., Tomasino, D., and Bradley, R. T. (2009). The coherent heart heart-brain interactions, psychophysiological coherence, and the emergence of system-wide order. *Integral Rev.* 5, 10–115.

Nagel, T. (1974). What is it like to be a bat. *Read. Philos. Psychol.* 1, 159–168. doi: 10.1111/1468-5930.00141

Nardone, R., Höller, Y., Tezzon, F., Christova, M., Schwenker, K., Golaszewski, S., et al. (2015). Neurostimulation in Alzheimer's disease: from basic research to clinical applications. *Neurol. Sci.* 36, 689–700. doi: 10.1007/s10072-015-2120-6

Oizumi, M., Albantakis, L., and Tononi, G. (2014). From the phenomenology to the mechanisms of consciousness: integrated information theory 3.0. *PLoS Comput. Biol.* 10:e1003588. doi: 10.1371/journal.pcbi.1003588

Palacios-García, I., and Parada, F. J. (2020). Measuring the brain-gut axis in psychological sciences: a necessary challenge. *Front. Integr. Neurosci.* 13:73. doi: 10.3389/fnint.2019.00073

Park, H. D., and Tallon-Baudry, C. (2014). The neural subjective frame: from bodily signals to perceptual consciousness. *Philos. Trans. R. Soc. B* 369:20130208. doi: 10.1098/rstb.2013.0208

Paulk, A. C., Zhou, Y., Stratton, P., Liu, L., and van Swinderen, B. (2013). Multichannel brain recordings in behaving *Drosophila* reveal oscillatory activity and local coherence in response to sensory stimulation and circuit activation. *J. Neurophysiol.* 110:1703–1721. doi: 10.1152/jn.00414.2013

Rassi, E., Dorffner, G., Gruber, W., Schabus, M., and Klimesch, W. (2019). Coupling and decoupling between brain and body oscillations. *Neurosci. Lett.* 711:134401. doi: 10.1016/j.neulet.2019.134401

Rebollo, I., Devauchelle, A. D., Béranger, B., and Tallon-Baudry, C. (2018). Stomach-brain synchrony reveals a novel, delayed-connectivity resting-state network in humans. *Elife* 7:e33321. doi: 10.7554/eLife.33321

Rees, J. C. (2014). Obsessive–compulsive disorder and gut microbiota dysregulation. *Med. Hypotheses* 82, 163–166. doi: 10.1016/j.mehy.2013.11.026

Richter, C. G., Babo-Rebelo, M., Schwartz, D., and Tallon-Baudry, C. (2017). Phase-amplitude coupling at the organism level: the amplitude of spontaneous alpha rhythm fluctuations varies with the phase of the infra-slow gastric basal rhythm. *NeuroImage* 146, 951–958. doi: 10.1016/j.neuroimage.2016.08.043

Riddle, J., Irgen-Gioro, S., and Schooler, J. W. (2021). *Nested Observer Windows (NOW): A Theory of Scale-free Cognition*. Tucson, AZ: The Science of Consciousness.

Riehle, A., Grün, S., Diesmann, M., and Aertsen, A. (1997). Spike synchronization and rate modulation differentially involved in motor cortical function. *Science* 278, 1950–1953. doi: 10.1126/science.278.5345.1950

Rodriguez-Larios, J., Faber, P., Achermann, P., Tei, S., and Alaerts, K. (2020). From thoughtless awareness to effortful cognition: alpha-theta cross-frequency dynamics in experienced meditators during meditation, rest and arithmetic. *Sci. Rep.* 10, 1–11. doi: 10.1038/s41598-020-62392-2

Roelfsema, P. R., Engel, A. K., König, P., and Singer, W. (1997). Visuomotor integration is associated with zero time-lag synchronization among cortical areas. *Nature* 385, 157–161. doi: 10.1038/385157a0

Rojas-Líbano, D., Frederick, D. E., Egaña, J. I., and Kay, L. M. (2014). The olfactory bulb theta rhythm follows all frequencies of diaphragmatic respiration in the freely behaving rat. *Front. Behav. Neurosci.* 8:214. doi: 10.3389/fnbeh.2014.00214

Ruskin, D. N., Bergstrom, D. A., and Walters, J. R. (1999). Multisecond oscillations in firing rate in the globus pallidus: synergistic modulation by D1 and D2 dopamine receptors. *J. Pharmacol. Exp. Ther.* 290, 1493–1501.

Samaha, J., and Postle, B. R. (2015). The speed of alpha-band oscillations predicts the temporal resolution of visual perception. *Curr. Biol.* 25, 2985–2990. doi: 10.1016/j.cub.2015.10.007

Santiago, J. A., and Potashkin, J. A. (2021). The impact of disease comorbidities in Alzheimer's disease. *Front. Aging Neurosci.* 13:38. doi: 10.3389/fnagi.2021.631770

Schoffelen, J. M., Oostenveld, R., and Fries, P. (2005). Neuronal coherence as a mechanism of effective corticospinal interaction. *Science* 308, 111–113. doi: 10.1126/science.1107027

Schwerdtfeger, A. R., Schwarz, G., Pfurtscheller, K., Thayer, J. F., Jarczok, M. N., and Pfurtscheller, G. (2020). Heart rate variability (HRV): from brain death to resonance breathing at 6 breaths per minute. *Clin. Neurophysiol.* 131, 676–693. doi: 10.1016/j.clinph.2019.11.013

Shaffer, F., McCraty, R., and Zerr, C. L. (2014). A healthy heart is not a metronome: an integrative review of the heart's anatomy and heart rate variability. *Front. Psychol.* 5:1040. doi: 10.3389/fpsyg.2014.01040

Siever, D., and Collura, T. (2017). "Audio–visual entrainment: physiological mechanisms and clinical outcomes," in *Rhythmic Stimulation Procedures in Neuromodulation*, eds J. R. Evans and R. Turner (Cambridge, MA: Academic Press), 51–95. doi: 10.1016/b978-0-12-803726-3.00003-1

Sochocka, M., Donskow-Łysoniewska, K., Diniz, B. S., Kurpas, D., Brzozowska, E., and Leszek, J. (2019). The gut microbiome alterations and inflammation-driven pathogenesis of Alzheimer's disease—a critical review. *Mol. Neurobiol.* 56, 1841–1851. doi: 10.1007/s12035-018-1188-4

Strogatz, S. H. (2012). *Sync: How Order Emerges From Chaos In The Universe, Nature, And Daily Life*. London: Hachette.

Takaki, M. (2003). Gut pacemaker cells: the interstitial cells of Cajal (ICC). *J. Smooth Muscle Res.* 39, 137–161. doi: 10.1540/jsmr.39.137

Tallon-Baudry, C., Mandon, S., Freiwald, W. A., and Kreiter, A. K. (2004). Oscillatory synchrony in the monkey temporal lobe correlates with performance in a visual short-term memory task. *Cereb. Cortex* 14, 713–720. doi: 10.1093/cercor/bhh031

Thompson, E., and Varela, F. J. (2001). Radical embodiment: neural dynamics and consciousness. *Trends Cogn. Sci.* 5, 418–425. doi: 10.1016/s1364-6613(00)01750-2

Thut, G., Schyns, P., and Gross, J. (2011). Entrainment of perceptually relevant brain oscillations by non-invasive rhythmic stimulation of the human brain. *Front. Psychol.* 2:170. doi: 10.3389/fpsyg.2011.00170

Tort, A. B., Brankačk, J., and Draguhn, A. (2018). Respiration-entrained brain rhythms are global but often overlooked. *Trends Neurosci.* 41, 186–197. doi: 10.1016/j.tins.2018.01.007

Trestman, M. (2013). The Cambrian explosion and the origins of embodied cognition. *Biol. Theory* 8, 80–92. doi: 10.1007/s13752-013-0102-6

Trillenberg, P., Verleger, R., Wascher, E., Wauschkuhn, B., Wessel, K. (2000). CNV and temporal uncertainty with "ageing" and "non-ageing" S1–S2 intervals. *Clin. Neurophysiol.* 111, 1216–1226. doi: 10.1016/s1388-2457(00)00274-1

Tsukahara, Y., Tamai, M., and Tasaki, K. (1973). Oscillatory potentials of the octopus retina. *Proc. Jpn. Acad.* 49, 57–62. doi: 10.2183/pjab1945.49.57

van Ravenswaaij-Arts, C. M., Kollee, L. A., Hopman, J. C., Stoelinga, G. B., and van Geijn, H. P. (1993). Heart rate variability. *Ann. Intern. Med.* 118, 436–447.

van Wijk, B., Beek, P. J., and Daffertshofer, A. (2012). Neural synchrony within the motor system: what have we learned so far? *Front. Hum. Neurosci.* 6:252. doi: 10.3389/fnhum.2012.00252

Wesson, D. W., Donahou, T. N., Johnson, M. O., and Wachowiak, M. (2008). Sniffing behavior of mice during performance in odor-guided tasks. *Chem. Senses* 33, 581–596. doi: 10.1093/chemse/bjn029

Whitehouse, B., and Heller, D. P. (2008). Heart rate in trauma: patterns found in somatic experiencing and trauma resolution. *Biofeedback* 36, 24–29.

Wilsch, A., Neuling, T., Obleser, J., and Herrmann, C. S. (2018). Transcranial alternating current stimulation with speech envelopes modulates speech comprehension. *NeuroImage* 172, 766–774. doi: 10.1016/j.neuroimage.2018.01.038

Wölk, C., and Velden, M. (1987). Detection variability within the cardiac cycle: toward a revision of the "baroreceptor hypothesis.". *J. Psychophysiol.* 1, 61–65.

Wölk, C., and Velden, M. (1989). "Revision of the baroreceptor hypothesis on the basis of the new cardiac cycle effect," in *Psychobiology: Issues And Applications*, eds N. W. Bond and D. A. T. Siddle (Amsterdam: Elsevier Science Publishers B.V), 371–379.

Young, A. (2021). Altered states of consciousness induced by exogenous audio signals: toward a better understanding of the oscillatory correlates of consciousness. *Resonance* 3.

Zelano, C., Jiang, H., Zhou, G., Arora, N., Schuele, S., Rosenow, J., et al. (2016). Nasal respiration entrains human limbic oscillations and modulates cognitive function. *J. Neurosci.* 36, 12448–12467. doi: 10.1523/JNEUROSCI.2586-16.2016

Zulli, R., Nicosia, F., Borroni, B., Agosti, C., Prometti, P., Donati, P., et al. (2005). QT dispersion and heart rate variability abnormalities in Alzheimer's disease and in mild cognitive impairment. *J. Am. Geriatr. Soc.* 53, 2135–2139. doi: 10.1111/j.1532-5415.2005.00508.x

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frontiers in Human Neuroscience

HYPOTHESIS AND THEORY
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What Neuroscientists Think, and Don't Think, About Consciousness

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The approach the majority of neuroscientists take to the question of how consciousness is generated, it is probably fair to say, is to ignore it. Although there are active research programs looking at correlates of consciousness, and explorations of informational properties of what might be relevant neural ensembles, the tacitly implied mechanism of consciousness in these approaches is that it somehow just happens. This reliance on a "magical emergence" of consciousness does not address the "objectively unreasonable" proposition that elements that have no attributes or properties that can be said to relate to consciousness somehow aggregate to produce it. Neuroscience has furnished evidence that neurons are fundamental to consciousness; at the fine and gross scale, aspects of our conscious experience depend on specific patterns of neural activity – in some way, the connectivity of neurons computes the features of our experience. So how do we get from knowing that some specific configurations of cells produce consciousness to understanding why this would be the case? Behind the voltages and currents electrophysiologists measure is a staggeringly complex system of electromagnetic fields – these are the fundamental physics of neurons and glia in the brain. The brain is entirely made of electromagnetism (EM) phenomena from the level of the atoms up. The EM field literally manifests the computations, or signaling, or information processing/activities performed by connected cellular ensembles that generate a 1st-person perspective. An investigation into the EM field at the cellular scale provides the possibility of identifying the outward signs of a mechanism in fundamental terms (physics), as opposed to merely describing the correlates of our mental abstractions of it.

Keywords: consciousness, electromagnetism, information, neural signals, computation

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> *To the theoretical question, Can you design a machine to do whatever a brain can do? The answer is this: If you will specify in a finite and unambiguous way what you think a brain does do with information, then we can design a machine to do it. Pitts and I have proven this construction. But can you say what you think brains do?*
>
> McCulloch (1965)

NEUROSCIENTISTS AND THE NEUROSCIENCE OF CONSCIOUSNESS

Neuroscience research, led by the funding that supports it, is dominated by research into disorders of the nervous system. The pursuit of treatments and cures (and the research efforts into understanding the normal function of the brain) builds on decades of discovery into all levels of neural organization – seemingly none of it reliant on knowing very much at all about consciousness.

Studies of how consciousness is generated, and why it has the characteristics it does, is nevertheless a focus of considerable interest and effort. There is no consensus about how it is generated, or how best to approach the question, but all investigations start with the incontrovertible premise that consciousness comes about from the action of the brain.

A key driver of a general understanding of how the nervous system works are the discoveries relating to how signals are combined and transmitted by neurons. From Golgi's and Ramon-y-Cajal's insights that neurons are morphologically specialized to form extensive interconnectivity (Glickstein, 2006), a sample of Nobel prizes provides an effective summary of the progress in our understanding of how neurons perform the functions of the nervous system: to Eccles, Hodgkin, and Huxley for "discoveries concerning the ionic mechanisms involved in excitation and inhibition in the peripheral and central portions of the nerve cell membrane"; to Katz, von Euler, and Axelrod for "discoveries concerning the humoral transmitters in the nerve terminals and the mechanism for their storage, release and inactivation," and to Neher and Sakmann for "discoveries concerning the function of single ion channels in cells." These discoveries were crucial for understanding how neurons generate, transmit and integrate biological signals and have had an understandably huge impact across all of neuroscience (Eccles, 1982; Valenstein, 2002; Augustine and Kasai, 2007; Reyes, 2019). Central to this understanding is the deep insight of how the biophysics of ionic movement across the neuronal membrane expresses the action potential. The significance and influence of this discovery is captured admirably in McComas' history "Galvani's Spark":

> *"The nerve impulse is the mechanism by which the brain conducts its affairs, the currency for all its transactions"*
>
> McComas (2011)

Another immensely significant and influential discovery points directly to how the action of neuronal circuits identifies features in the visual scene that form elements of visual perception. By mapping the adequate stimuli of receptive fields in the visual system, Hubel and Wiesel [see Constantine-Paton (2008) and Wurtz (2009) for review] discovered that the connectivity between neurons along the pathway dictates that the receptive fields in visual cortex are tuned to features such as edges and boundaries. Neuronal receptive fields are a product of the inputs they receive so it seems very reasonable to consider that the neurons of the visual pathway, by virtue of their signaling configuration, compute (in some sense) features of the perceptual experience.

In its generalized recent form, what has become "computation by synaptic connectivity" is accepted as the basis of nervous system function. This has convergent support from formal computing. In recent times, digital computers implementing artificial neural networks show that the simple learning rules that define an optimization process cause (for example) convolution kernels to converge from an initial random configuration to a collection of filters that are optimally activated by various oriented edges and simple luminance distributions that comprise the features of the images (Linsker, 1986a,b,c; Olshausen and Field, 1996; Gregor and LeCun, 2010). Deeper layers of these networks become maximally activated by more abstract features of images. These properties, as well as the reliance of learning (network adaptation) through interaction with stimuli, and the lack of explicit specified initial connectivity (and their eventual accuracy), seem to embody many attributes of biological visual systems. This understanding of the brain has become a powerful driver of modern progress in artificial intelligence (LeCun et al., 2015; O'Shea and Nash, 2015; Schmidhuber, 2015).

It is probably difficult to overstate the influence that the rapid development and exploration of formal computation (and especially digital computing) has had on our ideas about how the brain works. Rather than taking formal computation as a metaphor, it is not at all uncommon to hear present day brain scientists ask not *whether* the brain is any sort of computer but rather, *what sort* of computer is it.[1] For example, the recent enterprise of connectomics assumes not only that the computational aspects of the brain are sufficiently represented in the connectome, but also that the revealed connectome will provide the best possibility of answering questions about how the brain works. The claim that "*Neuroscience would be much easier if we had a detailed circuit diagram of the brain*" (Martin, 2006) may be true, but it is not so clear that the connectome's explanatory power would extend to how the brain generates consciousness.

What is interesting is that a scientific account of consciousness need form no explicit part of what motivated the cited progress in neuroscience. Indeed, attention to consciousness has woven a history of considerable scientific-cultural controversy into it. Neuroscience is a relative late comer to the question of how consciousness arises, and it is only in the last decades that this topic obtained a level of legitimacy within neuroscience research. This transformation can arguably be specifically dated to the 1990 work of Francis Crick (another Nobel Laureate) and Kristoff Koch that gave birth to the (neurobiological) "correlates-of-consciousness" empirical paradigm (Crick and Koch, 1990) and its descendants. By organizing the science around isolation of observational "correlates-of" consciousness, a physical science could finally get permission to deal with consciousness without its related funding application being tainted by a historically "career-limiting" direct attack on what was then a taboo explanandum in the physical sciences: the 1st-person perspective (1PP) (Wallace, 2000).

This transition of the science of consciousness into the physical sciences is now entering its fourth successful decade of relief from a long era of explicit-funding-pariah-hood in the physical sciences (Koch, 2019; Seth, 2021). The centuries of prior history of attempts to explain consciousness, in ways too numerous to address here, have been swamped by the knowledge delivered by the 30 years of neuroscience's active presence in the area. This has occurred despite it being successfully ignored by

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[1] For example, Computational Models of Cognition, Center for Brains Minds + Machines: Summer Course 2018. See https://www.youtube.com/watch?v=TFyAEHk5asY.

the bulk of mainstream neuroscientists. In the "correlates-of" paradigm we all set aside the fact that top-down observational correlates do not reveal principled explanations (Seth, 2009). For three decades we have elected to live with that limitation while making impressive progress in exploring for the outward signs of delivery of consciousness by brain activity. Strategically, the "correlates of" paradigm has been a highly effective way to make progress. What it has not done, however, is conclusively isolate the originating principle that might predict brain material's 1PP.

By its nature, and for good reason, the "correlates-of" paradigm bypasses the true significance of the 1990 event. To see the significance more clearly, consider that producing an abstract "3rd-person-perspective" (3PP) model, that is predictive of observable properties of nature, is the normal, familiar end of the concerns of a physical science. But in 1990 this changed. The ultimate target of the neuroscience of consciousness is an account of "what it is like to be" the studied nature. This is a categorically distinct, novel kind of explanandum. The burden of accounting for the 1PP falls on neuroscience because the human brain's cranial central excitable cell biology somehow delivers the only instance of a 1PP known to science (this excludes the spinal cord and the peripheral nervous system as originators of subjective experience itself). The human brain's 1PP is the reason we have a science of consciousness. This is not a "business-as-usual" scientific context. No other physical science has this confluence of circumstances and obligation. For example, no Perovskite geologist is required to account for "what it is like to be Perovskite." Not so for the neuroscientist and tissue based on excitable cells made of atoms from the same table of elements used in Perovskite.

To deal with this unprecedented explanatory target, the "correlates-of" empirical paradigm was established as an ersatz form of explanation of the 1PP by procedurally rendering it in the familiar, centuries-old 3PP form. It does this in practice by explicitly studying a "correlate of a 1PP *report*." This is the extra distancing from the target that attracts the "correlates-of" moniker. The 1PP itself *is not observed by the attending scientists*. Instead, the "report" is observed as a highly curated form of hearsay evidence. As a successful empirical method, it has resulted in the bourgeoning and sophisticated knowledge of consciousness that has arisen in the last three decades. However, the intrinsic indirectness and non-uniqueness of the evidence undermines, possibly fatally and indefinitely, the goal of understanding how brains produce consciousness.

If neuroscience is to make a contribution to this rather daunting foundational issue, what might be the form of a solution to the origin of a 1PP? Exactly what is it that brain tissue is "being"? The fundamental physics of electromagnetism (EM) is a very attractive candidate but, effectively, an undiscovered country in the life of the mainstream neuroscientist. Excluding explicit attention to the fundamental physics of the brain has clearly not prevented huge advances in neuroscience but may be precluding investigation of how the brain generates consciousness. In this reframing of approach, what is proposed here isn't an EM theory of consciousness (EM ToC) but a case for why a ToC should first be sought, by neuroscience, in the EM phenomena of brains.

ELECTROMAGNETISM AND THE SCIENCE OF CONSCIOUSNESS

The standard model of particle physics is about twice the age of the modern "correlates-of" form of the science of consciousness (Cottingham and Greenwood, 2007; Rich, 2010). In it, physics has already determined what our biosphere and everything in it is made of. It is effectively entirely electromagnetism (electromagnetic fields). This idea applies to anything made of atoms from the table of the elements at a spatiotemporal scale above that of the atomic particles comprising atoms (electrons and nuclei). At the atomic level and above, we and our host environment are defined by three things: space, an EM field system impressed on space (due to subatomic charge and spin content tightly bound up with the subatomic mass), and a gravitational field impressed on space (due to sub-atomic mass, functionally inert in context because it is more than 16 orders of magnitude weaker in force transmission than EM). In rough terms, at the intra-atomic scale, EM fields occupy the space occupied by an atom to the extent of at least 14,999 parts in 15,000. The remaining "1 part" is the interior of electrons and nuclei. When you add in the space between atoms, the proportion of overall spatial occupancy by EM fields is far higher. We humans are nearly entirely EM field objects. In our context of the brain, when we use the words "material" or "physical," these words (abstractions) refer to EM phenomena.

Therefore, the question "What is it that we are 'being'?" has an answer in the standard model: "We are 'being' EM fields from the atomic level up." Brevity demands that we avoid going into a discourse on the details, defending it right down into the subatomic intricacies and across the four fundamental force quadrants of the standard model. The standard model's EM-quadrant/atomic basis of our biosphere is just a basic, well established and proved fact of the physics. More important is how this basic fact impacts a science of consciousness. What is it like to "be" EM fields when the EM fields are configured in the form of a healthy, awake, alert human brain? To be such a configuration of EM fields is, under the right conditions, to be conscious. That is, fundamental physics has already, *prima facie*, determined a bottom-up (fundamental) origin of a 1PP: EM fields. There is literally nothing else there but a functionally irrelevant gravitational field and space. The endogenous EM field expressed by the atomic-level componentry of the brain entirely fills the space occupied by a brain, spilling out from its generating tissue into the surrounding tissue and beyond the skull. An EM ToC merely points out that basic fact and explicitly holds particular aspects of "the brain as an EM field" accountable for a 1PP. As a (bottom-up) claim made with well-established fundamental physics, such a proposal has a clear critical advantage, giving it priority.

What the fundamental physics lacks is an explanation of where EM's potential for a 1PP comes from, and what specific patterning of brain EM is necessary and sufficient to create a 1PP of a specific kind (qualia or "qualitative feel") and specific degree (spatial extension, granular resolution, duration, and intensity). Here we set aside this lack as a secondary issue. In terms of a strategic direction for the science, what matters is the obvious centrality of EM fields as the prime candidate for a route to a full explanation of consciousness in fundamental physics terms yet to be formulated. We are all familiar with the EM field system of the brain. Every measurement ever made in support of any ToC involves accessing and characterizing EM properties of the brain (more on this later).

The EM field system impressed on space by brain tissue is therefore not a side effect of cells made of something else. The entire tissue is a single, unitary EM field system impressed on space with atomic-level resolution. For example, there is no special substance that is a neuron. A neuron is a collection of EM fields "behaving neuron-ly" to an observer made of EM fields. "Chemical" or "chemical reaction," or "chemical pathway" is a reference to EM field activity. "Mechanical" (such as sound propagation/transduction/phonons, or cell deformation) is also an EM phenomenon. "Electro-chemical" is also selecting phenomena entirely comprised of EM. "Quantum mechanics" is not a substance. It is a set of (wave-equation-based) quantizing constraints on EM field expression (such as that determining the electron orbitals in an atom). "Chemical potential" is a population statistic depicting average EM field properties for particular collections of atoms in relation to each other. "Action potentials" are a system of EM field dynamics propagating slowly through space longitudinally following neuronal cell membrane (also an EM field construct). Synapse activity ("electrical" and "chemical") is an EM field phenomenon. The familiar electrophysiological measurements made in brain tissue detect "total field" in the brain that is a result of the vector-field superposition of myriad individual atomic/molecular field sources that superpose to dominate (spatially, temporally, and in intensity) the underlying atomic/molecular EM field "noise" found at any point in space. "Electrical current" is a transit of an EM field system through space. Ultraweak biophoton and thermal (heat) radiation is also an EM field phenomenon originating in the same system of atomic sources. Diffusion is a collection of randomly colliding atomic EM field systems bouncing off each other due to EM field-based repulsion. To "touch something" with your finger is to engage in an interaction between the EM field system of a finger surface and the EM field of the touched entity.

There is nothing left to describe in a brain that is not EM fields until we get into the interior of the subatomic constituents of atoms. This property is not limited merely to the brain. The pancreas and the heart (or any other organ) are also EM field objects from the atomic level up. What distinguishes the brain's EM field system from that of any other organ is that its cells can generate an EM configuration conferring the 1PP for humans. Our "Perovskite" rock (above) is also an EM field object, presumably (we conjecture) lacking the specifics of EM field expression that results in a 1PP for the rock.

We can apply the same considerations to previous attempts to explain consciousness using "top-down" abstractions of aggregations of particular formations of EM fields construed as "information," "signal processing," "computation," "thalamocortical loop," "entropy dynamics," "resonance," "reciprocal loops," "function," "behavior" and many others. These are all "correlates-of" labels applied to refer to the organization and properties of EM fields. It doesn't matter whether such depictions of brain tissue operate at molecular/atomic, subcellular, cell organelle, cellular, cell ensemble, cell population, or whole-tissue level. In every case it is EM fields that literally manifest the observable property hypothesized to originate a 1PP. Locating and describing these top-down field-abstractions as "correlates" has, for 30 years, been held up as a route to an explanation of consciousness. But such abstracted "top-down" features that correlate with aspects of consciousness seem to have no explanatory relevance to, or information concerning, the causal basis for having any form of consciousness. An EM ToC seeks an explanation in a separate fundamental physics account of how "being" (bottom-up) EM fields actually originates a 1PP.

These considerations of the state of the science extend even into the long history of EM field theories of consciousness. For interested readers the history and scope of existing EM ToC can be found through reviews (Jones, 2013, 2017; Pockett, 2013). But the details therein are not germane here. In reality all ToC (EM and otherwise) are actually, ultimately, EM field theories sometimes disguised out of view by a chosen kind of abstraction and then empirically supported by measurements also disguising their ultimate EM basis in tissue. We are proposing that we all collectively converge on the reality that it is actually EM fields that originate the 1PP, and engage with fundamental physics in whatever novel manner is necessary to hold it accountable for the origins of a 1PP.

Notice that no existing theory of consciousness is invalidated by this proposal. It is quite possible that one of the plethora of "correlates" is right! This is not contested here. What this article argues is that the "correlate" can be right and yet deliver no actual explanation (no principled account of the origin of the unique explanandum). This is because the EM basis of the correlate is the actual source of the origin of the claimed correlate's connection to a 1PP.

CONSCIOUSNESS FROM COMPUTATION

We can further explore the utility of EM in providing explanation of the origin of consciousness by consideration of ToC that do not posit any role for EM. If there are no features, other than those related to signaling between its constituent cells, that neurons contribute to how the brain works, a parsimonious explanation for consciousness is that it too is the result of signal processing (a specific form of computation). This is entirely consistent with the accumulated evidence from the history of studying the brain, which has reinforced, at coarse and fine scales, that the details of conscious experience are associated with the details of brain activity. As previously noted, the evident truth of this does not provide an explanation of why it is so.

The idea that consciousness arises from processing signals (of the now well-defined and well-understood neuronal forms) would give rise to the phenomenon of a 1PP can be called "strong emergence" (or "magical emergence") because there is, currently, no reason to hold that such a phenomenon would, should, or could follow from the known properties of the system's constituents (Bedau, 1997; Chalmers, 2006; O'Connor, 2020). This gap in the explanatory sequence has been discussed for as long as the nature of the mind has been considered (Levine, 1983; Van Gulick, 2018), and has more recently been characterized by David Chalmers as the "hard problem": "*Why should physical processing give rise to a rich inner life at all? It seems objectively unreasonable that it should, and yet it does*" (Chalmers, 1995, 1996, 1997).

The computational view renders consciousness either a rather unimportant feature of brain function or a causally inert epiphenomenon inhering in it. If everything the nervous system does is computation, and thus computation does everything, then there would seem to be no need for consciousness. This disconnects the computational or symbolic representation of brain operation from the physics of the system it represents (the EM physics of nervous system signaling). In other science disciplines, digital models or simulations are used to represent the known and hypothesized attributes and relationships between the elements of a system. Sufficiently accurate and comprehensive models (of the 3PP kind discussed earlier) allow prediction that corresponds to the performance/properties of the real systems (the ones being modeled) and can validate assumptions and hypotheses used in the model.

In the brain sciences, however, the models take on a very different expectation: the simulations are doing exactly the same transformations of signals and data that they are representing in the real system, so must display all phenomena of the system being represented. For example, a computer model of combustion might indicate, numerically, how much heat is produced, but it doesn't get hot - the simulation uses abstract representations, not the actual physics of combustion. Neuroscientists are entitled to ask what goes missing, in the sense of the heat in the combustion example, when the physics of brain signaling is thrown out and replaced by the physics of a computer. Is the computer and its model really contacting *all* brain phenomena? If there is something missing, how would we know? What procedure might we use to find out? This is the challenge posed by the McCulloch quote (McCulloch, 1965) at the start of this article.

In brain sciences that study consciousness within the paradigm of computation, there is no perceived need to relate the model's results to the actual physics of brains and neurons. In the current neuroscience paradigm, the physics of brain cells can be entirely ignored once we have sufficient data on activations and connectivity to accurately mimic the signal processing apparently performed by brain signaling physics. This "abstracting away" of the underlying fundamental physics implies that consciousness will emerge from the analogous (or informationally equivalent) simulation of a model of the signal processing that happens in brains. One of the difficulties with accepting this kind of strong emergence as an explanation for consciousness is that it is unclear how to proceed from this position to a deeper understanding of how this happens. "Emergent" as an explanation has the same value as using the term "happens" (Kelly, 1994). Our normal expectation of explanations has been classified as "weak emergence" because they say something about *why* things happen in terms of a mechanistic link between the attributes and actions of the relevant parts and the phenomena they generate. This contrasts with strong emergence, which is literally defined as a form of explanatory failure (Bedau, 1997; Chalmers, 2006; O'Connor, 2020). If consciousness is properly explained, then it would be transformed into weak emergence: a predictable whole resulting from the understood properties of its parts.

But whether the tendency of this "hard problem" to elicit a reliance on strong emergence is seen as a fundamental, or large, or illusory, obstacle to understanding consciousness, it has little bearing on the research being undertaken by neuroscientists working in the standard, albeit tacit, mode of scientific investigation: obtaining 3PP descriptions of nervous system structure and function. Neuroscientists may well suspect that consciousness emerges (somehow) at some higher level of organization to the level of explanation they are pursuing, so a solution is not required of them. This exonerates neuroscientists for being unconcerned about their discipline's ignorance of consciousness, and absolves them from exploring why EM ToC might offer plausible explanations. We pose that EM should not be ignored because it is actually at the heart of all phenomena in the nervous system, and when neuroscientists measure brain phenomena, the action potentials measured as transmembrane voltage, the "local field potential" (LFP), EEG, and MEG, and so forth, are all aspects of the fine-scale EM phenomena that actually underline the brain's signaling systems, our characterization of them, and our stimulation of them when we intervene in brain function. To ignore explicit attention to EM, by subsuming it into simplified measurements applied to an abstraction of it, is to cast an irreversible pall of strong emergence over the explanatory discourse of the science of consciousness.

In recent times it has become possible to see EM field interactions within tissue having a direct effect on neuronal excitation. This new signaling mechanism, "ephaptic transmission" shows the causal power of the brain's endogenous EM fields on its own neural activation. For example, the EM fields associated with neural activity have been shown to generate traveling waves of neuronal excitation in hippocampal pyramidal neurons (Chiang et al., 2019). This characterization of ephaptic transmission in the hippocampus is significant as it implies that EM field propagation can traverse considerable distances in laminated (spatially coherent) and synchronized (temporally coherent) neuronal assemblies - and laminated neuronal assemblies are a fundamental architectural principle across the central nervous system (CNS). This real example of EM fields having a direct effect on neural signaling reveals another advantage inherent in an EM field approach: the provision of a fundamental causal mechanism (via the Lorentz force) within brain signaling. It means that EM ToC offer a plausible physics mechanism linking consciousness to brain causality.

However, even with advantages like this, and like other ToC that identify the informational aspects of neuronal circuits as correlates of consciousness, structures of CNS EM, as an explanation of the origins of consciousness, similarly leaves an explanatory gap (where magical emergence comes in) for how consciousness is generated by EM phenomena. But EM has an aspect that gives it an explanatory future otherwise apparently lacking. Unlike computational ToC, an EM ToC is grounded in the fundamental physics of brain activity.

Even without any claims about which aspects or scales of EM might be relevant for how EM phenomena generate consciousness, it is clear that an EM ToC introduces a significant adjustment to ideas of "substrate independence." An EM ToC claims that consciousness is substrate dependant. Only a substrate of EM fields of the kind expressed by the brain will do the job. Contrast this with a general-purpose computer running software of any kind. The EM field system physics that is a general-purpose computer need have no direct relationship with the EM field system physics of the brain. In the case of the general-purpose computer (regardless of whether it is claimed conscious or not) the EM fields comprising the general-purpose computer can be organized in any way that is consistent with the execution of the software it hosts (from an abacus to a steam computer). The EM basis of the substrate of a general-purpose computer is radically and irreconcilably different to that of the brain. Note that an (inorganic) artificially originated consciousness based on an EM ToC, for example, requires chip components that generate the same EM phenomena that brain cells generate – at the same spatial and temporal scales. That kind of physics replication activity is, so far, completely missing from the set of options used by neuroscience. It would operate with the same EM field substrate as the natural (organic) brain. The interesting potential future that this suggests is one where the equivalence of a brain and a general-purpose computer can be conclusively scientifically tested based on the idea of substrate *dependence* introduced by an EM ToC.

OTHER WAYS OF GETTING CONSCIOUSNESS INTO COMPUTATIONS

If strong emergence is not considered to be a satisfactory explanation of how consciousness arises, then a reasonable alternative might be that, rather than it emerging at some point in a complex system, it was actually present all along – perhaps even as an exotic field or particle or similar component that comprises the fundamental fabric of the universe. Some ToC include a proposal that consciousness in some most elemental or fundamental form, is a currently unrecognized (in that it is missing from the standard model of particle physics) basic constituent of the universe. For example Benjamin Libet's "conscious mental field (CMF)" that "*would not be in any category of known physical fields, such as electromagnetic, gravitational, etc.*" (Libet, 1994). Such proposals recognize that in a more comprehensive appreciation of the nature of the universe's most basic composition we would appreciate consciousness in the same way that we appreciate that the fundamental constituents of the universe we know about have properties such as mass and spin and charge. Variations of this idea either propose that everything is, to some degree, consciousness [panpsychism (Skrbina, 2007; Goff et al., 2018)] or that consciousness emerges in a recognizable form, or reaches a critical threshold, only under certain constructions. Clearly, brains would be one such construction (indeed currently the only such construction known to us), but even then, there needs to be an explanation of why some aspects of nervous system function have consciousness and why some have not.

The Integrated Information Theory (IIT) ToC, another member of this class of ToC, seeks to find an informational criterion (such as the extent to which information is integrated) to define the presence or the amount of consciousness that certain constructions (biological or otherwise) will possess (Balduzzi and Tononi, 2008; Tononi, 2008; Oizumi et al., 2014; Tononi et al., 2016). To ground the information transformations in consciousness, it has been proposed that all information carries with it, or inherits, or is formed from, a most basic and indivisible mote of consciousness, which is, again, implicitly posed as an undiscovered member or property of an upgraded standard model of particle physics (although it is not presented in standard-model terms). The desire to bring information into the fold of fundamental physics is a topic of exploration within physics more broadly (Walker et al., 2017). We note in passing that an interesting connection between IIT and EM fields has been posed twice to date (Barrett, 2014; McFadden, 2020). This may offer IIT a future as an EM field ToC.

Rather than start a ToC that implicitly relies on an undiscovered fundamental entity and engage in implementing whatever radical changes to the standard model are necessitated by it, EM ToC start with and are located within the relevant quadrant of the existing standard model of particle physics. We already know standard-model EM field properties naturally satisfy the necessary basic requirements of an originator of consciousness. The EM fields are large in spatial extent: the electric and magnetic fields of the brain pervade the entire space occupied by the brain, extending out into the space outside it. The EM fields are impressed on space in exquisite detail consistent with the detail we experience in perceptual fields (such as vision). The EM fields originate at the scale of the membrane in thousands of square meters of a huge electric field spanning the 5 nm membrane enclosure of all neurons and astrocytes. This forms the basis of (a kind of blank canvas for) a nested dynamic hierarchical organizational EM field structure with seven or eight orders of magnitude of spatial detail, extending to the cm scale. The endogenous EM fields of the brain are intense in that they dominate, in a signal strength sense, all the underlying chemical "EM noise" produced by the atomic-level structures generating it in its total form (on a scale that systematically influences its own neuronal excitability – see the above notes on ephaptic transmission).

The EM fields are intrinsically unified: the electric and magnetic fields of the brain are each a single object and inexorably present and modulated when any neural activity occurs. This unification provides a natural route to a solution to another well-known but unexplained property of consciousness: it's striking and seamless unification of all the experiential modes of vision, audition, touch, olfaction and gustation, along with all the emotions (Cleeremans and Frith, 2003; Bayne, 2010). Natural field superposition also solves the "combination" problem where emergent "wholes," of a qualitatively unique character can be traced back to its vectorially superadded EM field parts. It facilitates the transformation to weak emergence discussed above. Contents of consciousness delivered by EM fields can enter consciousness merely through the seamless natural integrative superposition (a vector field property) of new field contributions produced by the underlying neural activity originating it. The EM field is also a parsimonious solution to problems related to time, for example, the need for a mechanism that explains how contents of consciousness delivered by EM fields can arrive and leave at the temporal rate and temporal resolution we observe and with the temporal continuity and discontinuity we observe. EM fields have the potential to provide that mechanism. We have already addressed the issue of causality that EM fields uniquely address in well-known physics terms. We will shortly discuss how EM fields naturally possess a potential to address the "symbol grounding/binding" issue. These issues have a long history of prominence in the science of consciousness (Harnad, 1990; Treisman, 1996; Revonsuo and Newman, 1999; Roskies, 1999; Singer, 2001; Chalmers, 2016; Kent and Wittmann, 2021), and EM fields seem naturally suited to potentially offer a solution to them. At least, there is no aspect of these phenomena that seems obviously beyond the scope of EM fields.

However, despite the suitability of EM to potentially account for longstanding, nuanced and unexplained aspects of consciousness, yet again we arrive at the fact that the thing that is missing from an EM field account of consciousness is the troublesome aspect of its delivery: by "being the EM fields." But this, we hold, is actually *our problem*, not a problem for nature. We are the ones that have failed to bring a 1st-person perspective into fundamental physics. The existing standard model of particle physics is empty of all content specifying "what it is like to be" any of the multitude of standard model entities (of "being" a muon or a neutrino or an EM field, for example). The neuroscience of consciousness, and its novel explanandum, have proved (albeit inadvertently) that the EM fields, a standard model entity, can originate a 1PP. Perhaps this deep and persistent evidence anomaly will motivate some attention by physicists to its standard model. It seems that one way or another, the standard model is up for an eventual makeover to formally introduce the 1PP to its otherwise prodigious predictive capacities. This reinforces the need for a future neuroscience/physics collaboration in the science of consciousness. Meanwhile, the recommended low hanging fruit of a convergence on EM fields is good preparation for it.

THE SIMULATION GROUNDING PROBLEM

As well as respecting the fine structure and function of the nervous system components, EM ToC naturally offers neuroscientists the potential to address the symbol binding problem (an issue brain science inherited by adopting paradigms from computer science). "Grounding," in the sense of models of brain or cognitive function, can take on different definitions (Harnad, 1990). Grounding addresses the sense in which symbols can be regarded as having a reliable relationship with the external environmental inputs that evoke the symbol (or other symbolic representation, such as the distributed activation states in an artificial neural network) or with the outputs to the external environment. A simple thermostat can be said to be grounded in this sense, but not (panpsychism excepted) in the sense that there is any meaning to its operation other than the interpretation of its input, output, and setpoint values in a more comprehensive context, such as in the humans employing or examining its structure and function. Symbols in more complex information processing contexts can stand for abstracted properties of the information. In these cases the complexity comes about by, for example, processing large quantities of information, combining it with previously acquired information, and being directed by explicit or generic objectives and so forth. This permits the analogy of these complex information processes with cognitive functions. Invariably, these information processing models are implemented on digital computers.

Variability in the definitions of grounding is presumably a large part of why it is claimed that the symbol grounding problem has been solved, hasn't been (but could be) solved, can't be solved, or isn't a problem (Taddeo and Floridi, 2005; Steels et al., 2007; Cubek et al., 2015). When considering how consciousness arises, we recognize that various cognitive processes are associated with very distinct and stable conscious states (experiences). These experiences literally are the symbol that becomes bound to brain events. Not only do our cognitions produce experienced conscious states (e.g., frustration, excitement, thirst, redness, fatigue, boredom, anger and so forth), but we are not the least bit unaware of their meaning – we don't confuse feeling hungry with feeling short of breath; we are not confused about why these conscious states come and go because we are not observing or witnessing them, we *are* those states. The question of grounding in this context is how does the flow of information from interoceptive and exteroceptive systems give rise to the neural activity that generates these utterly familiar and innately interpretable experiences? Neuroscientists would agree that the brain activity occasioned by those inputs, in interaction with the states of the relevant brain regions when receiving the inputs, would dictate the particular quality of the conscious experience. But neuroscientists would likely be very reluctant to say that such states represented in the brain's activity are grounded by the fact that the signals arise from (for example) vagal afferents from the viscera – if that was true it would not be possible to evoke sensations by stimulation higher up the pathway, and while direct brain stimulation is a very crude and unrealistic substitute for the precise and intricate patterns of activations that occur physiologically, stimulation of the cerebral cortex in awake people can still give rise to conscious experiences appropriate to the modalities known to be present in those cortical regions (Raccah et al., 2021). Phantom limb pathologies also attest to the centrality of cranial brain matter in originating the kind and degree of experiences, resulting in perceptual "grounding" in symbols applied to externalities that do not exist (Giummarra et al., 2007).

If it is held that the origins of meaning can't be found in the ambient energies in the environment that construe adequate stimuli for sensors, and it is also granted that the inherent meaningfulness of conscious experiences means they must be considered to be grounded, it could be proposed that only consciousness can ground representations expressed in brain activity. For neuroscientists engaged in an EM ToC, this means the basis of grounding is intrinsically there to be found in the activity of the brain's signaling physics itself – specifically those aspects of its function that are not those abstracted as the signals for information processes in computational models. This makes a sharp distinction between EM ToC and computational theories: the former claims that the crucial fundamental physics mechanisms are the very phenomena that computational theories discard as irrelevant.

CONCLUSION

What is proposed here isn't an EM ToC but a case for why a ToC should be sought in the EM phenomena of brains. It proposes EM as the answer to the challenge: "*Which electrical property provides the most fruitful explanatory basis for understanding consciousness remains an open question*" (Wu, 2018). In the process we find that neuroscience mixed with EM physics locates the center of the study of consciousness. Engaging this possibility, for neuroscientists, means bringing an end to a long era of abstracting-away EM phenomena. Neuroscientists will be required to embrace fundamental physics at a new level of complexity. Neuroscience and physics communities, connected in a joint need to resolve a troublesome and novel explanandum, are likely to be required to accommodate each other's needs. What the standard model of particle physics might look like after this project is completed, we can only guess at.

Why then, would EM ToC offer an incentive for more neuroscientists to engage with consciousness? The primary reason is that EM fields are the fundamental physics of neurons and glia in the brain. It literally manifests the computations, or signal processing, or information processing/integration activities performed by connected ensembles of cells that we know generate a 1st-person perspective. An EM ToC also has built-in, natural routes to solutions to the thorniest issues of consciousness such as time, unity, binding, combination and causality. Most importantly, it provides the possibility of identifying the outward signs of a mechanism in the normal fundamental terms of EM field physics, as opposed to merely describing the correlates of our mental abstractions of it. A focus on an EM field basis for consciousness does not in any way diminish the role of computation in the operation of the nervous system. Nor does it invalidate any other existing theory of consciousness. Computational activity, or aspects of that activity, will define the particulars of conscious experience, but the computations are not what generates consciousness: that is a deeper level of the fundamental signaling physics originating in the activity of the membrane. That signaling is entirely and only an EM field phenomenon.

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Both authors listed have made a substantial, direct, and intellectual contribution to the work, and approved it for publication.

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REFERENCES

Augustine, G. J., and Kasai, H. (2007). Bernard Katz, quantal transmitter release and the foundations of presynaptic physiology. *J. Physiol.* 578, 623–625. doi: 10.1113/jphysiol.2006.123224

Balduzzi, D., and Tononi, G. (2008). Integrated information in discrete dynamical systems: motivation and theoretical framework. *PLoS Comput. Biol.* 4:e1000091. doi: 10.1371/journal.pcbi.1000091

Barrett, A. (2014). An integration of integrated information theory with fundamental physics. *Front. Psychol.* 5:63. doi: 10.3389/fpsyg.2014.00063

Bayne, T. (2010). *The Unity of Consciousness*. Oxford: Oxford University Press.

Bedau, M. A. (1997). "Weak emergence," in *Philosophical Perspectives: Mind, Causation, and World*, ed. J. Tomberlin (Malden, MA: Blackwell), 375–399. doi: 10.1111/0029-4624.31.s11.17

Chalmers, D. (1997). "Facing up to the hard problem of consciousness," in *Explaining Consciousness: The Hard Problem*, ed. J. Shear (Cambridge: MIT Press), 9–32.

Chalmers, D. J. (1995). Facing up to the problem of consciousness. *J. Conscious. Stud.* 2, 200–219.

Chalmers, D. J. (1996). *The Conscious Mind: In Search of a Fundamental Theory*. New York, NY: Oxford University Press.

Chalmers, D. J. (2006). "Strong and weak emergence," in *The Re-emergence of Emergence: the Emergentist Hypothesis From Science to Religion*, eds P. Clayton and P. Davies (New York, NY: Oxford University Press), 244–254. doi: 10.1093/acprof:oso/9780199544318.003.0011

Chalmers, D. (2016). The combination problem for panpsychism. In Panpsychism: Contemporary Perspectives, G. Bruntrup, and L. Jaskolla, eds. (Oxford University Press), pp. 179-214.

Chiang, C.-C., Shivacharan, R. S., Wei, X., Gonzalez-Reyes, L. E., and Durand, D. M. (2019). Slow periodic activity in the longitudinal hippocampal slice can self-propagate non-synaptically by a mechanism consistent with ephaptic coupling. *J. Physiol.* 597, 249–269. doi: 10.1113/JP276904

Cleeremans, A., and Frith, C. (eds) (2003). *The Unity of Consciousness*. Oxford: Oxford University Press.

Constantine-Paton, M. (2008). Pioneers of cortical plasticity: six classic papers by Wiesel and Hubel. *J. Neurophysiol.* 99, 2741–2744. doi: 10.1152/jn.00061.2008

Cottingham, W. N., and Greenwood, D. A. (2007). *An Introduction to the Standard Model of Particle Physics*. Cambridge: Cambridge university press.

Crick, F., and Koch, C. (1990). Towards a neurobiological theory of consciousness. *Semin. Neurosci.* 2, 263–275.

Cubek, R., Ertel, W., and Palm, G. (2015). "A critical review on the symbol grounding problem as an issue of autonomous agents," in *KI 2015: Advances in Artificial Intelligence. KI 2015. Lecture Notes in Computer Science*, Vol. 9324, eds S. Hölldobler, R. Peñaloza, and S. Rudolph (Cham: Springer), 256–263.

Eccles, J. C. (1982). The synapse: from electrical to chemical transmission. *Annu. Rev. Neurosci.* 5, 325–339. doi: 10.1146/annurev.ne.05.030182.001545

Giummarra, M. J., Gibson, S. J., Georgiou-Karistianis, N., and Bradshaw, J. L. (2007). Central mechanisms in phantom limb perception: the past, present and future. *Brain Res. Rev.* 54, 219–232. doi: 10.1016/j.brainresrev.2007.01.009

Glickstein, M. (2006). Golgi and Cajal: the neuron doctrine and the 100th anniversary of the 1906 Nobel Prize. *Curr. Biol.* 16, R147–R151. doi: 10.1016/j.cub.2006.02.053

Goff, P., Seager, W., and Allen-Hermanson, S. (2018). *Panpsychism. The Stanford Encyclopedia of Philosophy*. Available online at: https://plato.stanford.edu/entries/panpsychism/ (accessed on February 28, 2018).

Gregor, K., and LeCun, Y. (2010). Emergence of complex-like cells in a temporal product network with local receptive fields. *arXiv [Preprint]* Available online at: https://arxiv.org/abs/1006.0448

Harnad, S. (1990). The symbol grounding problem. *Physica D* 42, 335–346.

Jones, M. W. (2013). Electromagnetic-field theories of mind. *J. Conscious. Stud.* 20, 124–149.

Jones, M. W. (2017). Mounting evidence that minds are neural EM fields interacting with brains. *J. Conscious. Stud.* 24, 159–183.

Kelly, K. (1994). *Out of Control: the Rise of Neo-biological Civilization*. Reading, MA: Addison-Wesley.

Kent, L., and Wittmann, M. (2021). Time consciousness: the missing link in theories of consciousness. *Neurosci. Conscious.* 2021:niab011.

Koch, C. (2019). *The Feeling of Life Itself: Why Consciousness is Widespread but Can't be Computed*. Cambridge, MA: MIT Press.

LeCun, Y., Bengio, Y., and Hinton, G. (2015). Deep learning. *Nature* 521, 436.

Levine, J. (1983). Materialism and qualia, the explanatory gap. *Pac. Philos. Q.* 64, 354–361. doi: 10.1111/j.1468-0114.1983.tb00207.x

Libet, B. (1994). A testable field theory of mind-brain interaction. *J. Conscious. Stud.* 1, 119–126. doi: 10.3389/fnhum.2012.00147

Linsker, R. (1986a). From basic network principles to neural architecture: emergence of orientation-selective cells. *Proc. Natl. Acad. Sci. U.S.A.* 83, 8390–8394. doi: 10.1073/pnas.83.21.8390

Linsker, R. (1986b). From basic network principles to neural architecture: emergence of orientation columns. *Proc. Natl. Acad. Sci. U.S.A.* 83, 8779–8783. doi: 10.1073/pnas.83.22.8779

Linsker, R. (1986c). From basic network principles to neural architecture: emergence of spatial-opponent cells. *Proc. Natl. Acad. Sci. U.S.A.* 83, 7508–7512. doi: 10.1073/pnas.83.19.7508

Martin, K. A. C. (2006). Where are the switches on this thing? *Nature* 440, 1113–1114.

McComas, A. (2011). *Galvani's Spark: The Story of the Nerve Impulse*. Oxford: Oxford University Press.

McCulloch, W. S. (1965). *Embodiments of Mind*. Cambridge, MA: MIT Press.

McFadden, J. (2020). Integrating information in the brain's EM field: the cemi field theory of consciousness. *Neurosci. Conscious.* 2020:13. doi: 10.1093/nc/niaa016

O'Connor, T. (2020). "Emergent properties," in *The Stanford Encyclopedia of Philosophy*, ed. E. N. Zalta (Stanford, CA: Stanford University).

Oizumi, M., Albantakis, L., and Tononi, G. (2014). From the phenomenology to the mechanisms of consciousness: integrated information theory 3.0. *PLoS Comput. Biol.* 10:e1003588.

Olshausen, B. A., and Field, D. J. (1996). Emergence of simple-cell receptive field properties by learning a sparse code for natural images. *Nature* 381, 607–609. doi: 10.1038/381607a0

O'Shea, K., and Nash, R. (2015). An introduction to convolutional neural networks. *arXiv [Preprint]* Available online at: https://arxiv.org/abs/1511.08458

Pockett, S. (2013). Field theories of consciousness. *Scholarpedia* 8:4951. doi: 10.4249/scholarpedia.4951

Raccah, O., Block, N., and Fox, K. C. R. (2021). Does the prefrontal cortex play an essential role in consciousness? Insights from intracranial electrical stimulation of the human brain. *J. Neurosci.* 41, 2076–2087. doi: 10.1523/JNEUROSCI.1141-20.2020

Revonsuo, A., and Newman, J. (1999). Binding and consciousness. *Conscious. Cogn.* 8, 123–127. doi: 10.1006/ccog.1999.0393

Reyes, A. D. (2019). A breakthrough method that became vital to neuroscience. *Nature* 575, 38–39. doi: 10.1038/d41586-019-02836-6

Rich, J. (2010). *Fundamentals of Cosmology*. Berlin: Springer-Verlag.

Roskies, A. L. (1999). The binding problem. *Neuron* 24, 7–9.

Schmidhuber, J. (2015). Deep learning in neural networks: an overview. *Neural Netw.* 61, 85–117. doi: 10.1016/j.neunet.2014.09.003

Seth, A. (2009). Explanatory correlates of consciousness: theoretical and computational challenges. *Cogn. Comput.* 1, 50–63. doi: 10.1007/s12559-009-9007-x

Seth, A. (2021). *Being You: A New Science of Consciousness*. New York, NY: Penguin Publishing Group.

Singer, W. (2001). "Consciousness and the binding problem," in *Cajal and Consciousness - Scientific Approaches to Consciousness on the Centennial of Ramon Y Cajal's Textura*, ed. P. C. Marijuan (New York, NY: Annals of the New York Academy of Science), 123–146.

Skrbina, D. (2007). "Panpsychism ," in *Internet Encyclopedia of Philosophy*, (Cambridge, MA: MIT Press).

Steels, L., Loetzsch, M., and Spranger, M. (2007). Semiotic dynamics solves the symbol grounding problem. *Nat. Prec.* 1–15. doi: 10.1038/npre.2007.1234.1

Taddeo, M., and Floridi, L. (2005). Solving the symbol grounding problem: a critical review of fifteen years of research. *J. Exp. Theor. Artif. Intell.* 17, 419–445. doi: 10.1080/09528130500284053

Tononi, G. (2008). Consciousness as integrated information: a provisional manifesto. *Biol. Bull.* 215, 216–242.

Tononi, G., Boly, M., Massimini, M., and Koch, C. (2016). Integrated information theory: from consciousness to its physical substrate. *Nat. Rev. Neurosci.* 17:450.

Treisman, A. (1996). The binding problem. *Curr. Opin. Neurobiol.* 6, 171–178.

Valenstein, E. S. (2002). The discovery of chemical neurotransmitters. *Brain Cogn.* 49, 73–95. doi: 10.1006/brcg.2001.1487

Van Gulick, R. (2018). "Consciousness," in *The Stanford Encyclopedia of Philosophy Spring 2018 Edition*, ed. E. N. Zalta (Berlin: Springer).

Walker, S. I., Davies, P. C. W., and Ellis, G. F. R. (2017). *From Matter to Life: Information and Causality*. Cambridge: Cambridge University Press.

Wallace, B. A. (2000). *The Taboo of Subjectivity: Toward a New Science of Consciousness*. New York, NY: Oxford University Press.

Wu, W. (2018). "The neuroscience of consciousness," in *The Stanford Encyclopedia of Philosophy*, ed. E. N. Zalta (Stanford, CA: Stanford University).

Wurtz, R. H. (2009). Recounting the impact of Hubel and Wiesel. *J. Physiol.* 587, 2817–2823. doi: 10.1113/jphysiol.2009.170209

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From Micro to Macro: The Combination of Consciousness

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Crick and Koch's 1990 "neurobiological theory of consciousness" sparked the race for the physical correlates of subjective experience. 30 years later, cognitive sciences trend toward consideration of the brain's electromagnetic field as the primary seat of consciousness, the "to be" of the individual. Recent advancements in laboratory tools have preceded an influx of studies reporting a synchronization between the neuronally generated EM fields of interacting individuals. An embodied and enactive neuroscientific approach has gained traction in the wake of these findings wherein consciousness and cognition are theorized to be regulated and distributed beyond the individual. We approach this frontier to extend the implications of person-to-person synchrony to propose a process of combination whereby coupled individual agents merge into a hierarchical cognitive system to which they are subsidiary. Such is to say, the complex mammalian consciousness humans possess may not be the tip of the iceberg, but another step in a succeeding staircase. To this end, the axioms and conjectures of General Resonance Theory are utilized to describe this phenomenon of interpersonal resonant combination. Our proposal describes a coupled system of spatially distributed EM fields that are synchronized through recurrent, entraining behavioral interactions. The system, having achieved sufficient synchronization, enjoys an optimization of information flow that alters the conscious states of its merging agents and enhances group performance capabilities. In the race for the neurobiological correlates of subjective experience, we attempt the first steps in the journey toward defining the physical basis of "group consciousness." The establishment of a concrete account of the combination of consciousness at a scale superseding individual human consciousness remains speculation, but our suggested approach provides a framework for empirical testing of these possibilities.

Keywords: resonance, altered states of consciousness, interpersonal synchrony, hyperscanning, human mind, social interaction, neural synchronization

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INTRODUCTION

The Borg of *Star Trek*, Xenomorphs of *Alien*, and Wights of *Game of Thrones* (*A Song of Ice and Fire*) are single conscious entities united across multiple individual bodies often used as a foil to the protagonists' flamboyant individualism. These science fiction terrors constitute a group in which constituent members engage in a combined, supervening consciousness. The horror of the "hive mind" stems from the undying loyalty, lockstep initiative, and the abolition of self that accompanies being one with the collective. A permeated motif of cultural media

(O'Sullivan, 2010), hive minds, or extended consciousness is a topic frequently engaged yet remains shrouded in popular mysticism.

One such example of engagement with mystical undertones is the Global Consciousness Project's longstanding study of global consciousness and random number generation. Their report of the events of September 11th, 2001 gained notoriety when it described attenuation of random number variation as an effect of unified, global consciousness ignited by shared global attention on the terrorist attacks. Another example may be found in a question commonly posed to cognitive scientists: "Does the Internet, currently or in the near future, possess the capacity to constitute a conscious entity?" (O'Gieblyn, 2020; see also Hunt, 2014). The article concludes "Perhaps," allowing the reader's mind to linger on the possibility of a conscious brain to which they are akin to a single neuron. We appear to possess a popular, natural notion of combined consciousness or conscious entities at scales superseding our own.

The natural presupposition of combined consciousness is accompanied by a parallel notion that groups of discrete individuals constitute Gestalts distinct from the sum of its parts. This parallel notion has become operationalized in experimental psychology through such concepts as intergroup emotion theory (Smith et al., 2007; Mackie et al., 2008) and collective intelligence factor (Woolley et al., 2010). Equipped with these recurring themes, we will explore combined consciousness primarily through the lens of cognitive neuroscience. Normally regarded as a fringe topic, we will attempt to explore the possibility of its occurrence while remaining within the confines of accepted scientific method. We ask only that the reader entertains (without endorsing) the possibility of consciousness at scales beyond the individual human level, as we sketch an outline of how this may physically occur, how it may be measured, and what it implies for our understanding of conscious, cognitive systems (Schooler et al., 2018).

There has been a growing trend in the cognitive sciences to look to rhythmic neural oscillations of neuronally generated electromagnetic fields (Anastassiou et al., 2011; Buzsáki et al., 2012; Hales, 2017; Chiang et al., 2019) as the primary seat of consciousness (McFadden, 2013; Jones, 2016; Hunt and Schooler, 2019; Hunt, 2020). In this approach, scientists look to the "oscillatory correlates of consciousness" as the primary physical dynamic for tracking the presence and complexity of consciousness. It is suggested that the dynamics of consciousness may be identical to the dynamics of the various EEG frequency bands from slow oscillations (below 0.2 Hz), to delta (0.2–3 Hz), theta (3–8 Hz), alpha (8–12 Hz), beta (12–27 Hz), through gamma (27–100 Hz), and higher (Fields, 2020).

Not only are these rhythms known to be important dynamics of individual consciousness; over the last two decades, research has revealed that the oscillatory correlates of distinct individuals will often synchronize with the neural oscillations of other individuals of the same species. This phenomenon, coined inter-individual neural synchrony (also referred to as inter-brain coupling, inter-brain synchrony, interpersonal brain coupling, etc., abbreviated here to INS), is a product of shared, recurrent stimulus-to-brain coupling, amidst joint action behavior, whereby the stimulus is produced by the brain of one individual, conveyed by the motor system, and received by the other's sensory system (Hasson et al., 2012). The correlates of joint action are observed at a young age, facilitating social development in children. Infants and their parents/caregivers engage in dyadic activity by utilizing a common visual focus to express shared intentionality (Mundy and Newell, 2007). Both infant and caregiver use this common visual focus to establish a point of reference, aligning their mutual attention to the stimulus (Lachat and George, 2012). By proxy of this shared entrainment, infant and caregiver synchronize their neural activity (Leong et al., 2017).

Inspired by the General Resonance Theory of consciousness (Hunt and Schooler, 2019; Hunt, 2020), we will develop a model of interpersonal resonant combination (a broader framework for INS) that builds upon and extends the implications of joint action findings. This paper attempts to integrate empirical findings of synchronization in the oscillatory correlates of consciousness with GRT's generalized resonance principles of micro-to-macro combination. It is our hope that this framework can extend what is currently only speculation about higher scales of consciousness than the individual scale into a testable framework. It will be stressed here that this is an application solely of General Resonance Theory's framework as there are dissenting opinions, as will be reviewed below, regarding the parameters of extended or combined consciousness.

INTRA-BODY RESONANCE TO INTER-INDIVIDUAL SYNCHRONY

GRT postulates that all matter resonates (the resonance axiom) and that all matter possess, at the very least, a rudimentary capacity for consciousness (the panpsychism axiom). Resonating structures will, when in sufficient proximity to influence one another (Hunt, 2020), resonate at the same frequency with other proximal matter and establish a shared resonance frequency (the coupling axiom). The shared resonance achieves a distinctive phase transition in the speed and/or bandwidth of information processing between the resonating constituents, thereby generating a larger, more complex physical system that has an increased capacity for conscious experience (the shared resonance conjecture). Shared resonance between coupled oscillators, specifically between neuronally generated EM fields (and the information processing made possible with EM fields), is, GRT suggests, necessary and sufficient for mammalian consciousness.

The Huygens clock phenomenon provides an effective illustration of the ontological foundations upon which the remainder of this article will build from. Christiaan Huygens, inventor of the pendulum clock, serendipitously observed that his clocks will, when sharing a medium (physical connection *via* floor or wall), synchronize pendulum swings regardless of their starting position. The one-second pulses of the clock's internal timekeeping mechanisms reverberate through the shared medium to influence the partner clock and, within a sufficient period of time, this bi-directional flow of one-second pulses will couple the two together and synchronize swing cycles (Oliveira and Melo, 2015). This shared resonance between oscillators or systems of oscillators is the mechanism by which micro-conscious entities combine into a new macro-conscious entity. Our micro and macro designations, that will appear often throughout this article, are relative terms used to designate pre- and post-combination units. The two clocks in the above example, in their incorporation into the coupled oscillator system, are micro-systems (clock) that are nested in the supervening macro-system (clock-clock). As we take another step up the staircase of combination, the micro prefix will designate the clock-clock system in their coupling to a partner clock-clock system to form a new macro: group-group system and so on. With each step, though, the system transitions through spatiotemporal scales. We will return to this point following the summary of the brain–body spatiotemporal hierarchy, upon which this current description of interpersonal resonant combination is derived.

As matter evolves into more complex forms so does its capacity for consciousness. The mammalian body displays a number of these shared resonance interactions between the central brain and the organs of the periphery (Young et al., 2022). The oscillatory links merge the distant neural clusters into a unified whole, thereby producing the complex mammalian consciousness that we now enjoy, as a product not only of intra-cerebral shared resonance but also whole-body shared resonance of different types. The three extra-cerebral shared resonances that will briefly be reviewed seem to play functional roles in regulating and distributing cognitive activity throughout the Gestalt organism.

The gastric basal rhythm, a 0.05 Hz frequency emitted by the peristaltic organs, couples to the brain's alpha frequency forming a gastric-brain shared resonance interaction, as measured by a combination of EEG (electroencephalogram) and EGG (electrogastrogram; Richter et al., 2017; Rebollo et al., 2018). This comprises one link in the oscillatory arm of the gut-brain-axis that resonates with the brain to maintain homeostasis and interoceptive sense (Huizinga, 2017; Jena et al., 2020). Within the brain, the BOLD (blood oxygen level-dependent) signal also shares this extra-cerebral resonance, maintaining a positive relationship with the gastric basal rhythm (Rebollo et al., 2018).

Cardiac-brain shared resonance is established through the coupling of the 0.1 Hz heart resonant frequency, a distinctive high amplitude peak in the HRV power spectrum, to the brain's alpha and beta frequencies (McCraty et al., 2009). The resonance relationship functions as a regulator of emotional experience. Coupling is established in post-traumatic stress disorder (PTSD) patients undergoing Somatic Experiencing trauma therapy when a threat response is successfully re-negotiated (Whitehouse and Heller, 2008).

The saccadic rhythm, generated at 3–4 Hz, underlies the retinal-brain shared resonance relationship with cerebral theta and alpha waves (Leszczynski and Schroeder, 2019; Leszczynski et al., 2021). The endogenous rhythm aligns the neural oscillations to the flow of incoming visual information. Retinal-brain shared resonance facilitates our active visual sensing of the external environment.

These shared resonance interactions comprise distinct neural clusters synchronizing and contributing to the larger merged system: the organism. Through a GRT lens, the observer can denote the neat nesting of many micro-conscious combinations that generate the complex, unified human or animal thereof (Young et al., 2022). Each of these merged systems can be defined by the slowest shared resonance (SSR), the GRT principle postulating that the boundary of a conscious system is defined by the slowest common denominator frequency by which shared resonance occurs (the boundary conjecture). The 0.05 Hz gastric basal rhythm defines the gastric-brain system, the 0.1 Hz heart resonance frequency defines the cardiac-brain system, and the 3–4 Hz saccadic rhythm defines the retinal-brain system. The spatialization of consciousness across the distributed nervous system implies a mechanism of information integration across spatiotemporal scales. Cross-frequency coupling (CFC), the modulation of a higher frequency by one that is lower (Canolty and Knight, 2010), represents the synchrony architecture through which the sub-hertz rhythms of the body's organs may influence the higher frequency bands of the EEG. As the distribution of the coupled system increases, the unifying consciousness that encompasses it is constrained by the increasingly slower frequencies that underlie it.

This model can be rearticulated to fit our needs in exploring INS combination. Hyperscanning EEG (Liu et al., 2018; Czeszumski et al., 2020), fNIRI (Scholkmann et al., 2013), and fMRI (Montague et al., 2002) are recent laboratory tools that have made possible the recording of phase synchronization of neural rhythms across groups of individuals. Briefly, the hyperscanning technique simultaneously measures activity between two or more brains for identifying commonalities (Montague et al., 2002). The establishment of such synchrony relies on two factors: mutual attention (Hasson et al., 2012; Koban et al., 2019; Nguyen et al., 2020; Djalovski et al., 2021) and the presence of prior empathetic relationships (close friends, true couple, etc.) within the participant pool (Kinreich et al., 2017; Djalovski et al., 2021). We propose, in line with Hasson et al. (2012), that INS is defined by a shared entraining stimulus. Entrainment, the (mostly) unidirectional coupling of one oscillator to another (Lakatos et al., 2019), to a shared behavioral rhythm facilitates the alignment of neural activity within the entrained group.

The coupled system is defined and limited by the slowest shared resonance to which all group members are entrained. Slow frequencies traverse spatial distances at greater speeds, allowing information to arrive and be incorporated into the oscillatory cycles of constituent group members (Dehaene, 2014). The shared entraining signal, within our model, serves as the SSR of the interpersonal cognitive system. The INS-SSRs we have identified are of ultraslow variety, with the exception of speech, and thus possess the capacity to traverse the spatial distance between group members for their entrainment.

The synchronization between neural clusters of distinct brains can be accomplished via a substitution of direct axonal connections with shared exogenous entrainment of neural rhythms to identical effect. The ultraslow entraining oscillations that inaugurate INS then define the coupled group. Our compiled list of INS-SSRs will be discussed in the following section.

The experience, objective (i.e., task performance), and subjective (self-other merging, feelings of affiliation, etc.) of individuals as they synchronize and become nested in the larger group cognitive system is very much altered from their regular waking consciousness. Some authors have called this experience "group flow" (Kotler and Wheal, 2018). GRT's framework assumes continuation (no extinction) of micro-conscious entities as they merge into a macro-system (the nested consciousness conjecture). Although it is far too early and there is not sufficient evidence to definitively claim the presence of a macro-conscious system, a "group consciousness," within the entrained, synchronized group, we will put forth the proposition that the inter-individual resonance in the oscillatory correlates produces the possibility of such a claim. If it is to be measured, it will likely be through the mapping of the altered states of consciousness in the unextinguished micro-conscious individuals pre-, peri-, and post-combination. The penultimate section will review several feasible experimental paradigms for testing our proposition. This approach must suffice until a proper "psychometer" (Hunt et al., 2021) may be developed for measuring a phenomenal consciousness more complex than our own.

INTER-INDIVIDUAL SSRs

We have compiled a list of INS-SSRs that possess the entraining capacity to serve as the coupling signal underlying synchronized groups. All of these are of social variety in that they may originate from constituent group members to which sender and receiver/s may share in coupling. The coupling signal is dependent on the group's focus of attention and can be transferable in this respect. As aggregate attention on one shared rhythm wanes and is reignited upon another oscillator, the SSR demarcation is thus transferred. Our list of INS-SSRs includes syllabic rate of speech, respiratory cycles, behavioral cue exchange, and interpersonal sexual activity (shared tactile stimulation). These entraining modalities are conveyed at ultraslow frequencies, with exception to speech which is conveyed at slow frequencies. There is some discussion regarding "true" versus "false" interpersonal synchrony (Valencia and Froese, 2020). Reciprocal adjustment of ongoing rhythms is regarded as necessary for true synchrony as opposed to the driving of rhythms by an external source. The behavioral nature of the entraining signals listed below, although external drivers, exhibits a reciprocal adjustment between attending group members (Dumas et al., 2010; Woolley et al., 2010; Nguyen et al., 2020; Loh and Froese, 2021) and thus, in our view, constitute a true synchronization.

Human speech is expressed at the syllabic rate of 3–8 Hz (Fujii and Wan, 2014). In attending speech, the listener is entrained in delta, theta, and gamma waves (Giraud and Poeppel, 2012; Gross et al., 2013). The speaker is entrained in delta, theta, and alpha waves (Pérez et al., 2017). INS is observed between interlocutors contingent upon the listener's possession of the speaker's language (Spiegelhalder et al., 2014). Speech as an SSR appears as the most intuitive of our formative list. The group, as it attends a speaker, is entrained and synchronized to the speaker and, by proxy of the shared entrainment, to the rest of the aggregate. With communicative turn taking, a staple element of interpersonal communication (Woolley et al., 2010; Nguyen et al., 2020), the SSR demarcation will remain transferable between speakers.

In a singular-brain frame of reference, nasal respiration, occurring at 0.16–0.33 Hz, entrains delta, theta, and beta EEG bands (Zelano et al., 2016). Respiratory cycles are theorized to constitute a global coupling rhythm by which complex neural activity in the brain is organized (Başar, 2008; Corcoran et al., 2018; Klimesch, 2018). On a multi-brain scale, group entrainment can occur to the breathing frequency of an attended individual (Bachrach et al., 2015). In the cited example, a dancer, the subject of group attention, is performing a routine characterized by incredibly slow movement and centered around the dancer's respiratory cycles. A positive correlation was observed between audience attention and interpersonal respiratory synchrony. Coupled respiration may serve as a group entraining rhythm and represents the most feasible option for empirical testing. Coupling participants *via* respiration is unobtrusive and allows experimenters to incorporate a task amidst coupling, opening the analysis to include synchronization as a factor as opposed to an effect.

Behavioral cue exchange is represented by the sender's ostensible cues that indicate communicative intent and the receiver's contingent responsiveness that implies communicative sensitivity (Wass et al., 2020). As group attention shifts, the roles of imitator (receiver) and sender are regularly exchanged, and mutual behavioral negotiation engaged (Dumas et al., 2010). This behavioral dialog generates a state of behavioral synchrony within communicating groups. Ostensive cues in particular increase the behavioral entrainment of the receiver to the sender (Feldman, 2007; Murray et al., 2016; Wass et al., 2020). Participants entrained in behavior cues exhibit inter-brain synchronization in alpha-mu, beta, and gamma bands (Dumas et al., 2010).

Sexual activity, interpersonal, or solitary, occurring at a semi-stable rhythm, offers an avenue for entrainment in producing orgasm, hypothesized to be a trance state enabled by the entrainment (Safron, 2016). Interpersonal sexual activity should predictably exhibit INS during a portion in which both (or more) partners are simultaneously being stimulated by a shared rhythm (i.e., penetration or other kinds of stimulation). Surprisingly, no study has looked to INS between active sexual partners during performance (to our knowledge at the time of this writing). Although this modality is empirically less dense than our other entraining avenues, it represents a promising line for future research.

Exogenous entraining stimuli of a non-social variety present a point of contention with regard to true versus false synchronization. The brain is liable to be entrained *via* photic (Adrian and Matthews, 1934) and auditory (Chatrian et al.,

1960) means, collectively termed audiovisual entrainment (AVE). Music, present in nearly half (44%) of experience-sampled events (Sloboda and O'neill, 2001), is a reliable entraining stimulus of cortical oscillations (Doelling and Poeppel, 2015). On an interpersonal scale, music comprises a coupling signal that is a fundamental component of social coordination and cultural practices (Clayton et al., 2020). INS within synchronized groups conducting coordinated actions is strengthened by the administration of steady exogenous auditory rhythms (Ikeda et al., 2017). The Clayton piece would argue that music, an external driver, is a viable coupling signal for group practices and would reflect a true interpersonal synchronization. It may be argued that the necessary mutual adjustment is present between musicians in producing the stimuli as well as between musicians and audience in situations wherein the audience is considered an active participant in the performance. The Ikeda piece takes a lighter stance on their findings in that the exogenous stimuli during group walking (activity that exhibits INS) was an adjunct that strengthened prior synchronization. One method of artificial synchronization, shared transcranial brain stimulation (TBS), bypasses the sensory pathways entirely to directly entrain neural oscillations. Mice, prepared with optogenetics, displayed greater affinity when TBS signals were synchronized than when each was stimulated at different frequencies (Yang et al., 2021). This novel method of neural coupling muddies the distinction between true and false synchronization, and any attempt here to define it would rely purely on intuition. Artificial oscillators possess the potential to constitute a group coupling signal or, at the very least, a facilitator of synchronization by social means.

This list is by no means exhaustive. There exists a large conceptual space for the addition of countless other group entraining stimuli, as they are discovered and elucidated. Speech, respiration, behavioral cues, and sexual stimulation are the most readily available modalities of social origin at the time of our writing. This line of research is one deserving of additional attention and development. The following section will review qualitative and quantitative markers that distinguish a truly synchronized, merged group apart from one exhibiting spurious synchrony.

PHASE TRANSITION

GRT micro-to-macro combination is marked by a phase transition in the informational speeds between micro-conscious entities as a result of shared resonance (Hunt and Schooler, 2019). This is a term borrowed from physics referring to a process in which a critical threshold is exceeded, and the state of information flow is modified. The phase transition that occurs within the conscious mammalian brain, according to GRT, is the shift from electrochemical information (synaptic) to electromagnetic field exchanges (ephaptic), the latter of which is significantly faster. This point of criticality supports the vast flow of information during conscious, as opposed to unconscious, states (Toker et al., 2022). As informational speed and bandwidth increase, the depth and scope of the phenomenal consciousness increase. Within this section, "phase transition" will revert to an analog representation of its meaning to refer to a (as yet unknown) critical point that, when exceeded, is then followed by a collection of cognitive, social, and behavioral changes in synchronized groups as a result of optimized information flow. Returning to the Huygens' clock illustration, the transition from a desynchronized to a synchronized state, within which collective oscillations emerge, occurs when the system exceeds coupling strength K (Kuramoto, 1975).

Although the GRT framework suggests the presence of a larger macro-consciousness that encompasses a sufficiently synchronized group, this is a difficult position within the current state of cognitive neuroscience. A point of contention among field theorists includes whether decreasing field strength across space limits the ability of EM fields to unify consciousness (see Libet, 1994, Jones, 2013, and McFadden, 2013 for dissenting opinions). This section, however, will examine evidence that likely represents a phase transition in-group information processing and may indicate some kind of larger group consciousness, albeit fleeting. Our purview is purely in building a representative model of what micro-to-macro combination of superseding scale would look like according to GRT axioms and conjectures.

In synchronizing with local group members, the brain's internal representations of the self and the other become blurred, optimizing predictive capabilities and efficiently increasing cooperative capacity (Koban et al., 2019). This is a result of temporally aligning the oscillatory windows of group members, a phenomenon akin to the saccadic entrainment of theta and alpha EEG bands during active sensing (Leszczynski and Schroeder, 2019; Leszczynski et al., 2021). The temporal alignment of oscillators generates a coupled system within which the rhythmic flow of visual information is received in-phase of visual cortical oscillations. Perceptual thresholds are lowered, and acute visual sense is facilitated. A similarly effective coupled system emerges within a synchronized group that exhibits an identical alignment of oscillatory windows.

We have compiled a list of cognitive effects that appear representative of the occurrence of phase transition across individuals. Group synchrony is, for example, associated with:

1. Increased performance in cooperative tasks (Szymanski et al., 2017; Nguyen et al., 2020). It is a robust finding that INS-established groups experience greater cooperative task performance as compared to non-synchronized groups. The cited Szymanski study compared individual performance against non-synchronized groups against synchronized groups on identical tasks. Synchronized groups exhibited significant increases in task capability.
2. Self-other merging (Valencia and Froese, 2020). This is one of several signs that there is some manner of altered state of consciousness induced during group synchronization (perhaps a bit on the nose). It falls within Ludwig's ASC framework under characteristic E: "body image change" (Ludwig, 1966). Hyperscanning fMRI studies indicate a shared synchronization in the right anterior insula, a structure responsible for interoception (Koike et al., 2019; Yoshioka et al., 2021). Tied to this is the hypothesized increased

capacity for empathy regarding group members (Hove, 2008), an intuitive result of experienced self-other merging.

3. Increased feelings of group affiliation (Hove and Risen, 2009; Hoehl et al., 2021). There is a positive relationship between group affiliation and INS. Group affiliation increases the likelihood of INS establishment. Inversely, INS generates stronger feelings of inclusion in the group. Synchronous groups, experiencing cues to their affiliation, exhibit behavior that is measurably more prosocial (Hu et al., 2017; Cirelli, 2018), an effect convergent of both factors. Additionally, INS may influence intergroup relations: individuals are more strongly synchronized to politically like-minded peers during polarizing political debate than to political opponents. The strength of synchrony between committed partisans is associated with producing similar polarized attitudes regarding the debate (van Baar et al., 2021).
4. Increased capacity for interpersonal communication (Miles et al., 2009; Hoehl et al., 2021). The coupling of neural activity between communicators aligns predictions with outputs. Wilson suggests that coupled groups in coordination experience an ease of information flow stemming from their synchronization that saves computational power (Wilson, 2001). Friston and Frith (2015), in tandem with Wilson, propose that, to avoid an infinite regression of modeling your partner that is modeling you, an n + 1 "shared model/prediction" emerges to unify the active inference mechanisms of interacting agents.

The coupling of neural activity across a group enables an optimized synchronization of cognitive-behavioral inputs and outputs across the aggregate (Koban et al., 2019; Valencia and Froese, 2020). Just as theta and alpha entrainment by saccadic rhythms decreases perceptual thresholds for acute visual sense, INS increases sensitivity to the conspecific nodes of the emerging group brain. The improvement of cooperative ability and altered experience of the individual demonstrates a phenomenon of integration.

In our discussion of resonance at the inter-individual scale, effects such as those listed are hypothesized to signal a critical point by which the collection of individuals becomes an integrated, functional unit. The exact moment the critical point is traversed is yet unknown. The INS effects only suggest the line was likely crossed at some moment preceding its social and cognitive influences. Thus, INS separates a synchronized aggregate from a mere aggregation of individuals.

INTERPERSONAL RESONANT COMBINATION

Twenty years of brain-to-brain synchrony literature has informed us of the peculiarities that emerge amidst intensive social interaction. The collection of effects is accompanied by the growing notion that it is not an epiphenomenal occurrence. Arising in early developmental stages, it facilitates social learning between child and caregiver. The phenomenon is rearticulated to other social interactions to function as a neural bind between communicators, cooperators, and companions. As we approach this advancing frontier, it is time we begin considering the implications of brain-to-brain synchronization.

The mechanism of combination that unifies the central and peripheral nervous systems is reflected in the similar resonance that occurs between distinct brains of cooperative group members. It is a recent hypothesis that INS may be the means by which micro-to-macro combination of interpersonal scale occurs (Valencia and Froese, 2020). Valencia and Froese's recent review of similar interpersonal EEG synchrony, in light of Clark's "extended mind framework" (Clark and Chalmers, 1998), hypothesized the origins of an extended consciousness rooted in the interpersonal synchronization of the fastest EEG frequency bands. Aligning the quantitative neural oscillations associated with qualitative experiences, when paired with various effects of social closeness and cooperation, makes such conclusions of possible combination or consciousness extension relevant.

We echo this hypothesis under the auspices of GRT's axioms and conjectures. In line with previous research, we support the notion that INS is established *via* shared neural oscillations, entrained through behavioral rhythms that arise during social interaction and selected for by group attention. Utilizing GRT's SSR conjecture, we suggest that the slowest shared entraining signal be designated as the boundary of the macro-cognitive system that encompasses the synchronized group.

At the extreme end of our speculation, we hypothesize the macro-cognitive system that has succeeded in a phase transition in group information exchange constitutes a macro-conscious entity to which constituent group members are part and parcel. Within the GRT framework, merged group members are not extinguished as merged micro-conscious entities but continue to persevere as individual and contributing agents. This, however, does not imply mutual horizontal access to the phenomenal contents of synchronized group members (i.e., shared consciousness). Instead, our description is that of a combined consciousness in which interpersonal synchronization of the individual oscillatory correlates of consciousness may link, horizontally, conspecific nodes that combine, vertically, into a supervening n + 1 system. The supervening system exhibits a greater (the contents of all merged agents) and deeper (increased horizontal communicative capacity) processing of information, the process and products of which are distinct from its merged agents. The combined system will span multiple spatiotemporal scales. Ultraslow behavioral rhythms entrain EEG bands and likewise affect other disparate neural rhythms that functionally interact with the entrained frequency. Akin to the brain–body spatiotemporal hierarchy referenced in section "Intra-Body Resonance to Inter-individual Synchrony", the group consciousness is constrained by the phase state of the recurrent interactions that uphold it (Loh and Froese, 2021).

The notion that groups are entities distinct from the constituent individuals was referenced in the introduction as a common motif in popular knowledge and an increasingly operationalized factor in recent psychological studies. This text details the neuroelectrical backbone upon which such a notion may exist. The following will detail several empirical concepts we would speculate to be products of a supervening cognitive system.

Intergroup Emotion Theory describes an emotional system originating within the social group that governs intergroup relations and perceptions (Mackie et al., 2008). In-group INS is associated with out-group hostility (Yang et al., 2020) and the strength of neural synchrony between like-minded partisans influences their perceptions of a prior conflict with political opponents (van Baar et al., 2021). Collective intelligence factor, a measure of group capability apart from individual performance, is correlated with social sensitivity and communicative turn taking (Woolley et al., 2010). These are components involved in the generation of INS: active, attending individuals and reciprocal adjustment of behavior. The previous section discusses improved group performance in cooperative tasks as a robust finding in hyperscanning studies.

In considering what constitutes the phenomenal experience of the macro-system, we may respond by regarding the influences discussed in the previous section as components of the group experience. As a nested yet unextinguished agent, the individual will experience an alteration in their state of consciousness: self-other merging and increased feelings of affiliation toward synchronized group members. The macro-system, possessing the contents of merged agents and optimized communication between its nested nodes, exhibits an information processing that increases performance capability and a cognitive influence in separating in-group (merged) and out-group (non-merged). To unlock the deeper contents, the "to be" so to speak, of merged/merging agents and the system they nest within, which we theorize is a conscious entity in and of itself, we suggest the mapping of altering states of consciousness as individuals combine through INS. Variation in the integrating brains and individual subjective experience will likely provide clues to the hypothesized macro-consciousness they are nested within, however temporary such nesting may be. The following section will propose three feasible experiments for such testing.

ASC MAPPING

We approach macro-consciousness through the contributing agents and aim to use data collected from the parts to make conclusions of the whole. As such, our proposed paradigms target shared experience and anomalous cognition associated with a supervening cognitive system. By sharing entrainment through oscillators discussed in section "Inter-individual SSRs", INS will be imposed as a factor and ASC inducement, to varying degrees of severity, will be measured as the dependent variable. A mixed participant pool of stranger and true couple dyads is recommended in the following configurations for all three proposed studies: synched-stranger dyads, non-synched-stranger dyads, synched-empathetic dyads, and non-synched-empathetic dyads.

SHARED EXPERIENCE OF TIME AND SELF-OTHER MERGING

The first of our proposed experiments targets shared subjective experience of time and self-other merging. It is hypothesized that there will be a positive association between homogeneity in temporal experience and self-other merging with the INS factor. That is to say the strength of INS (closer to zero-lag synchrony) will correlate with increased homogeneity of temporal experience and increased perception of self-other merging. The self-other merging is an effect regularly associated with INS (Valencia and Froese, 2020). The qualitative experience of time is theorized to rely on the quantitative frequency of neural oscillations. This is supported by Samaha's results suggesting the frequency of alpha oscillations underlie the temporal granularity of visual perception (Samaha and Postle, 2015).

Dyads will share entrainment *via* oscillators listed in section "Inter-individual SSRs", although we suggest respiration coupling be implemented as the least demanding of the selection. As participants synchronize and are recorded through hyperscanning EEG, a self-other merging scale is administered intermittently, a method similar to mind wandering studies' use of thought probes (Smallwood and Schooler, 2006). Following the synchronization task (coupled respiration), a scale measuring subjective experience of time is administered to which questions are answered relating to the time frame of coupling.

Possible measures are included here: the Inclusion of Other in the Self Scale (IOS) for self-other merging (Aron et al., 1992) and the Time Experience Scale (TES) for temporal experience (Sanders, 1986). The TES factor of interest is "Slow Tempo," the subjective speed of time in a specific situation. If our hypotheses hold true, there will be a positive correlation between IOS results and INS, homogeneity of TES results and INS, and IOS results and homogeneity of TES results. Such results would demonstrate some manner of merged experience between synchronized group members.

HYPERSCANNING RELIGIOUS RITUALS

INS is, in our suggested framework, contingent upon two factors: empathetic relationships and mutual attention. Religious group rituals performed by devout religious followers fulfill both requirements, but surprisingly no hyperscanning study has been published to fill this niche. The benefits of a hyperscanning study involving devout religious followers engaging in ritual are 2-fold: (1) this will be the first hyperscanning study in this domain and (2) a correlation may be established between the experience of God (or related deity) and strength of INS.

We hypothesize the presence of INS within such a group. Difficulty will arise in the equipment's interference with the ritual. The headgear may be intrusive to our preferred natural setting. Portable EEG, used in Dikker's classroom study (Dikker et al., 2017), may alleviate these issues (Debener et al., 2012).

Contingent on the first hypothesis' successful results, we hypothesize the experience of God, equated to the religious experience itself (Alston, 2014), will be associated with INS establishment. Scales for God experiences are rare and often not validated. We suggest an inventory of select items from validated mystical experience scales such as Taves' Inventory of Non-Ordinary Experiences (Taves et al., 2019). The selected inventory should contain items measuring emotional, sensory, and non-ordinary experiences intuitively and empirically associated with God. Empirically supported items include emotional measures for positive affect, peace, joy, and unconditional love (Beauregard and Paquette, 2008). Intuitive items include feelings of a non-ordinary presence, absorption, and connectedness to others.

The experience of God is selected as one such manifestation/interpretation of a group macro-conscious entity and a hypothetical ASC of combination. The implications of significant effects for the described study establish a preliminary link between INS and an experience of a supervening entity. The philosophical implications for such doctrines as Whitehead's panentheism (Griffin, 2007, 2008) would require a separate article entirely.

INTERPERSONAL SYNCHRONY IN PHYSIOLOGICAL RHYTHMS

The shared resonance relationships between the peripheral organs and central nervous system covered in section "Intra-Body Resonance to Inter-individual Synchrony", the predecessor model to interpersonal resonant combination, constitute the oscillatory links of an embodied mind (Young et al., 2022). The body constrains, distributes, and regulates cognitive processes (Foglia and Wilson, 2013) allowing for a theoretical extension of consciousness to an organism-wide phenomenon. The previous two experimental routes suggest various measurements of cerebral activity and their association with merging experience. Here, we recommend the third avenue through the hyperscan recording of physiological synchrony across empathetic dyads engaged in joint action.

Interpersonal synchrony research has taken a recent turn in this direction. Current work utilizes physiological variables in addition to behavioral and neural (Mayo and Gordon, 2020, see also Helm et al., 2018). Variables include, for example: heart rate, heart rate variability, respiratory sinus arrhythmia, cardiological impedance, body tremor, blood pressure, and electrodermal activity. The spontaneous synchronization of these endogenous rhythms, within an embodied framework, represents an extension to our INS model of resonant combination.

Müller and Lindenberger (2011), in coupling respiration among participants, likewise registered synchronization in heart rate variability. Relative phase synchronization in heart beats is exhibited between co-sleepers in a bi-directional fashion (Yoon et al., 2019). The inclusion of cognitive measures in such paradigms produces an intra- and inter-individual relationship between physiological variables and their associated cognitive activity. Murata found individuals' subjective excitement in a cooperative game increased not only with their own heart rate, but also with their partner's (Murata et al., 2021). Observing bystanders' reports of perceived excitement increased with players' heart rate synchrony. Kang and Wheatley's group pupillometry demonstrated a synchronization of pupil dilation in expressive speakers and empathetic listeners (Kang and Wheatley, 2017). Pupillary synchrony was strongest at emotional peaks and less engaging moments observed a diminished coupling.

An entire class of experiments can be designed for the extended study of resonant combination through the shared resonance of non-neural endogenous rhythms concomitant with measures of cognitive activity. An alternative path can be the addition of hyperscanning physiological measures to pre-existing paradigms starting with the previous two studies proposed. It may be hypothesized that, in line with Murata and Kang's separate findings, synchrony in the physiological markers, similar to INS, will be associated with some manner of merging experience. In time, a comprehensive framework encompassing neural, behavioral, physiological, and other shared resonances can be developed detailing the multimodal process of resonant combination.

CONCLUSION

The present paper offers a reanalysis of the literature and proposes, through our model of interpersonal resonant combination, an explanation of INS-driven micro-to-macro consciousness merging toward a new and higher-level phenomenal consciousness. Entraining behavioral rhythms, selected for by mutual attention, appear to underlie the coupling of rhythmic neural oscillations between discrete brains. Syllabic rate of speech, respiratory cycles, interpersonal sexual activity, and behavioral cue exchange have been explored as possible common denominator rhythms that demarcate the boundaries of the coupled, cognitive system. Phase transitions, the critical point marking combination, are hypothesized to be represented in increased cooperative ability and altered states of consciousness that are associated with INS establishment. It is our hypothesis that the current literature supports a capacity for interpersonal resonant combination.

Empathetically related groups engaged in joint action provide the greatest potential for such a phenomenon. However, autism spectrum disorder (ASD), characterized by atypical social interaction and communication, has been linked to a decreased capacity to synchronize neural activity with communicative partners (Quiñones-Camacho et al., 2021). The coupling deficit is extended to include interpersonal motor, conversational, and physiological synchrony (McNaughton and Redcay, 2020). These recent findings yield a new dimension to the resonant combination model. Although it can be concluded with ease that empathetically related groups sharing attention possess the greatest potential for resonant combination, the conclusion may require a future addendum to further state: "empathetically related groups *of neurotypical individuals* engaged in joint action possess the greatest potential for resonant combination." Subsequent research will decide the matter of its inclusion.

ASC mapping of individuals pre-, peri-, and post-combination provides an approach appropriate for the current state of cognitive neuroscience. To this end, we suggest three avenues of empirical exploration for exploring combined consciousness. Results are hypothesized to represent a convergence of experience between synchronized individuals.

In sum, our proposed model constitutes the first step in a million-mile journey toward generating a concrete account of micro-to-macro combination beyond discrete brains. There is a general shift, beginning with the oscillatory correlates approach (Young, 2022, in press), toward a greater consideration of supervening cognitive systems and our capability for interpersonal merging. Containing two decades of INS literature we have described what is known, identified what is missing, and speculated on what is yet to be discovered. It is with great confidence and dense empirical evidence that we theorize the innate potential for a consciousness transcending the complex subjective experience we now enjoy.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

AY designed the model. AY, IR, and SS conducted the literature reviews and wrote the paper. All authors contributed to the article and approved the submitted version.

REFERENCES

Adrian, E. D., and Matthews, B. H. (1934). The Berger rhythm: potential changes from the occipital lobes in man. *Brain* 57, 355–385. doi: 10.1093/brain/57.4.355

Alston, W. P. (2014). *Perceiving God*. United States: Cornell University Press.

Anastassiou, C. A., Perin, R., Markram, H., and Koch, C. (2011). Ephaptic coupling of cortical neurons. *Nat. Neurosci.* 14, 217–223. doi: 10.1038/nn.2727

Aron, A., Aron, E. N., and Smollan, D. (1992). Inclusion of other in the self scale and the structure of interpersonal closeness. *J. Pers. Soc. Psychol.* 63, 596–612. doi: 10.1037/0022-3514.63.4.596

Bachrach, A., Fontbonne, Y., Joufflineau, C., and Ulloa, J. L. (2015). Audience entrainment during live contemporary dance performance: physiological and cognitive measures. *Front. Hum. Neurosci.* 9:179. doi: 10.3389/fnhum.2015.00179

Başar, E. (2008). Oscillations in "brain–body–mind"—A holistic view including the autonomous system. *Brain Res.* 1235, 2–11. doi: 10.1016/j.brainres.2008.06.102

Beauregard, M., and Paquette, V. (2008). EEG activity in Carmelite nuns during a mystical experience. *Neurosci. Lett.* 444, 1–4. doi: 10.1016/j.neulet.2008.08.028

Buzsáki, G., Anastassiou, C. A., and Koch, C. (2012). The origin of extracellular fields and currents—EEG, ECoG, LFP and spikes. *Nature Rev. Neurosci.* 13, 407–420. doi: 10.1038/nrn3241

Canolty, R. T., and Knight, R. T. (2010). The functional role of cross-frequency coupling. *Trends Cogn. Sci.* 14, 506–515. doi: 10.1016/j.tics.2010.09.001

Chatrian, G. E., Petersen, M. C., and Lazarte, J. A. (1960). Responses to clicks from the human brain: some depth electrographic observations. *Electroencephalogr. Clin. Neurophysiol.* 12, 479–489. doi: 10.1016/0013-4694(60)90024-9

Chiang, C. C., Shivacharan, R. S., Wei, X., Gonzalez-Reyes, L. E., and Durand, D. M. (2019). Slow periodic activity in the longitudinal hippocampal slice can self-propagate non-synaptically by a mechanism consistent with ephaptic coupling. *J. Physiol.* 597, 249–269. doi: 10.1113/JP276904

Cirelli, L. K. (2018). How interpersonal synchrony facilitates early prosocial behavior. *Curr. Opin. Psychol.* 20, 35–39. doi: 10.1016/j.copsyc.2017.08.009

Clark, A., and Chalmers, D. (1998). The extended mind. *Analysis* 58, 7–19. doi: 10.1093/analys/58.1.7

Clayton, M., Jakubowski, K., Eerola, T., Keller, P. E., Camurri, A., Volpe, G., et al. (2020). Interpersonal entrainment in music performance: theory, method, and model. *Music Percept. Interdiscip. J.* 38, 136–194. doi: 10.1525/mp.2020.38.2.136

Corcoran, A. W., Pezzulo, G., and Hohwy, J. (2018). Commentary: respiration-entrained brain rhythms are global but often overlooked. *Front. Syst. Neurosci.* 12:25. doi: 10.3389/fnsys.2018.00025

Czeszumski, A., Eustergerling, S., Lang, A., Menrath, D., Gerstenberger, M., Schuberth, S., et al. (2020). Hyperscanning: a valid method to study neural inter-brain underpinnings of social interaction. *Front. Hum. Neurosci.* 14:39. doi: 10.3389/fnhum.2020.00039

Debener, S., Minow, F., Emkes, R., Gandras, K., and De Vos, M. (2012). How about taking a low-cost, small, and wireless EEG for a walk? *Psychophysiology* 49, 1617–1621. doi: 10.1111/j.1469-8986.2012.01471.x

Dehaene, S. (2014). *Consciousness and the Brain: Deciphering How the Brain Codes Our Thoughts*. New York: Penguin.

Dikker, S., Wan, L., Davidesco, I., Kaggen, L., Oostrik, M., McClintock, J., et al. (2017). Brain-to-brain synchrony tracks real-world dynamic group interactions in the classroom. *Curr. Biol.* 27, 1375–1380. doi: 10.1016/j.cub.2017.04.002

Djalovski, A., Dumas, G., Kinreich, S., and Feldman, R. (2021). Human attachments shape interbrain synchrony toward efficient performance of social goals. *NeuroImage* 226:117600. doi: 10.1016/j.neuroimage.2020.117600

Doelling, K. B., and Poeppel, D. (2015). Cortical entrainment to music and its modulation by expertise. *Proc. Natl. Acad. Sci.* 112, E6233–E6242. doi: 10.1073/pnas.1508431112

Dumas, G., Nadel, J., Soussignan, R., Martinerie, J., and Garnero, L. (2010). Inter-brain synchronization during social interaction. *PLoS One* 5:e12166. doi: 10.1371/journal.pone.0012166

Feldman, R. (2007). Parent–infant synchrony and the construction of shared timing; physiological precursors, developmental outcomes, and risk conditions. *J. Child Psychol. Psychiatry* 48, 329–354. doi: 10.1111/j.1469-7610.2006.01701.x

Fields, R. D. (2020). *Electric Brain: How the New Science of Brainwaves Reads Minds, Tells Us How We Learn, and Helps Us Change for the Better*. Dallas: BenBella Books Inc.

Foglia, L., and Wilson, R. A. (2013). Embodied cognition. *Wiley Interdiscip. Rev. Cogn. Sci.* 4, 319–325. doi: 10.1002/wcs.1226

Friston, K., and Frith, C. (2015). A duet for one. *Conscious. Cogn.* 36, 390–405. doi: 10.1016/j.concog.2014.12.003

Fujii, S., and Wan, C. Y. (2014). The role of rhythm in speech and language rehabilitation: the SEP hypothesis. *Front. Hum. Neurosci.* 8:777. doi: 10.3389/fnhum.2014.00777

Giraud, A. L., and Poeppel, D. (2012). Cortical oscillations and speech processing: emerging computational principles and operations. *Nat. Neurosci.* 15, 511–517. doi: 10.1038/nn.3063

Griffin, D. R. (2007). *Whitehead's Radically Different Postmodern Philosophy an Argument for Its Contemporary Relevance*. New York: State University of New York Press.

Griffin, D. R. (2008). *Unsnarling the World-Knot: Consciousness, Freedom, and the Mind-Body Problem*. Eugene, OR: Wipf and Stock Publishers.

Gross, J., Hoogenboom, N., Thut, G., Schyns, P., Panzeri, S., Belin, P., et al. (2013). Speech rhythms and multiplexed oscillatory sensory coding in the human brain. *PLoS Biol.* 11:e1001752. doi: 10.1371/journal.pbio.1001752

Hales, C. G. (2017). "The origins of the brain's endogenous electromagnetic field and its relationship to provision of consciousness," in *Biophysics of Consciousness: A Foundational Approach*. eds. R. R. Poznanski, J. A. Tuszynski and T. E. Feinberg (United states: World Scientific), 295–354.

Hasson, U., Ghazanfar, A. A., Galantucci, B., Garrod, S., and Keysers, C. (2012). Brain-to-brain coupling: a mechanism for creating and sharing a social world. *Trends Cogn. Sci.* 16, 114–121. doi: 10.1016/j.tics.2011.12.007

Helm, J. L., Miller, J. G., Kahle, S., Troxel, N. R., and Hastings, P. D. (2018). On measuring and modeling physiological synchrony in dyads. *Multivar. Behav. Res.* 53, 521–543. doi: 10.1080/00273171.2018.1459292

Hoehl, S., Fairhurst, M., and Schirmer, A. (2021). Interactional synchrony: signals, mechanisms and benefits. *Soc. Cogn. Affect. Neurosci.* 16, 5–18. doi: 10.1093/scan/nsaa024

Hove, M. J. (2008). Shared circuits, shared time, and interpersonal synchrony. *Behav. Brain Sci.* 31, 29–30. doi: 10.1017/S0140525X07003202

Hove, M. J., and Risen, J. L. (2009). It's all in the timing: interpersonal synchrony increases affiliation. *Soc. Cogn.* 27, 949–960. doi: 10.1521/soco.2009.27.6.949

Hu, Y., Hu, Y., Li, X., Pan, Y., and Cheng, X. (2017). Brain-to-brain synchronization across two persons predicts mutual prosociality. *Soc. Cogn. Affect. Neurosci.* 12, 1835–1844. doi: 10.1093/scan/nsx118

Huizinga, J. D. (2017). Commentary: phase-amplitude coupling at the organism level: The amplitude of spontaneous alpha rhythm fluctuations varies with the phase of the infra-slow gastric basal rhythm. *Front. Neurosci.* 11:102. doi: 10.3389/fnins.2017.00102

Hunt, T. (2014). *Eco, Ego, Eros: Essays in Philosophy, Spirituality and Science.* Aramis Press.

Hunt, T. (2020). Calculating the boundaries of consciousness in general resonance theory. *J. Conscious. Stud.* 27, 55–80.

Hunt, T., Ericson, M., and School, J. W. (2021). Where's my Consciousness-Ometer? How to test for the presence and complexity of consciousness. *Perspect. Psychol. Sci.* doi: 10.1177/17456916211029942 [Epub ahead of print].

Hunt, T., and Schooler, J. W. (2019). The easy part of the hard problem: a resonance theory of consciousness. *Front. Hum. Neurosci.* 13:378. doi: 10.3389/fnhum.2019.00378

Ikeda, S., Nozawa, T., Yokoyama, R., Miyazaki, A., Sasaki, Y., Sakaki, K., et al. (2017). Steady beat sound facilitates both coordinated group walking and inter-subject neural synchrony. *Front. Hum. Neurosci.* 11:147. doi: 10.3389/fnhum.2017.00147

Jena, A., Montoya, C. A., Mullaney, J. A., Dilger, R. N., Young, W., McNabb, W. C., et al. (2020). Gut-brain axis in the early postnatal years of life: a developmental perspective. *Front. Integr. Neurosci.* 14:44. doi: 10.3389/fnint.2020.00044

Jones, M. (2013). Electromagnetic-field theories of mind. *J. Conscious. Stud.* 20, 124–149.

Jones, M. W. (2016). Neuroelectrical approaches to binding problems. *J. Mind Behav.* 37, 99–118.

Kang, O., and Wheatley, T. (2017). Pupil dilation patterns spontaneously synchronize across individuals during shared attention. *J. Exp. Psychol. Gen.* 146, 569–576. doi: 10.1037/xge0000271

Kinreich, S., Djalovski, A., Kraus, L., Louzoun, Y., and Feldman, R. (2017). Brain-to-brain synchrony during naturalistic social interactions. *Sci. Rep.* 7, 1–12. doi: 10.1038/s41598-017-17339-5

Klimesch, W. (2018). The frequency architecture of brain and brain body oscillations: an analysis. *Eur. J. Neurosci.* 48, 2431–2453. doi: 10.1111/ejn.14192

Koban, L., Ramamoorthy, A., and Konvalinka, I. (2019). Why do we fall into sync with others? Interpersonal synchronization and the brain's optimization principle. *Soc. Neurosci.* 14, 1–9. doi: 10.1080/17470919.2017.1400463

Koike, T., Sumiya, M., Nakagawa, E., Okazaki, S., and Sadato, N. (2019). What makes eye contact special? Neural substrates of on-line mutual eye-gaze: a hyperscanning fMRI study. *Eneuro* 6, ENEURO.0284–ENEU18.2019. doi: 10.1523/ENEURO.0284-18.2019

Kotler, S., and Wheal, J. (2018). Stealing fire: how Silicon Valley, the navy seals, and maverick scientists are revolutionizing the way we live and work. Dey St.

Kuramoto, Y. (1975). "Self-entrainment of a population of coupled non-linear oscillators." in *International Symposium on Mathematical Problems in Theoretical Physics*; January 23–29, 1975; Berlin, Heidelberg: Springer, 420–422.

Lachat, F., and George, N. (2012). Oscillatory brain correlates of live joint attention: a dual-EEG study. *Front. Hum. Neurosci.* 6:156. doi: 10.3389/fnhum.2012.00156

Lakatos, P., Gross, J., and Thut, G. (2019). A new unifying account of the roles of neuronal entrainment. *Curr. Biol.* 29, R890–R905. doi: 10.1016/j.cub.2019.07.075

Leong, V., Byrne, E., Clackson, K., Georgieva, S., Lam, S., and Wass, S. (2017). Speaker gaze increases information coupling between infant and adult brains. *Proc. Natl. Acad. Sci.* 114, 13290–13295. doi: 10.1073/pnas.1702493114

Leszczynski, M., Chaieb, L., Staudigl, T., Enkirch, S. J., Fell, J., and Schroeder, C. E. (2021). Neural activity in the human anterior thalamus during natural vision. *Sci. Rep.* 11, 1–13. doi: 10.1038/s41598-021-96588-x

Leszczynski, M., and Schroeder, C. E. (2019). The role of neuronal oscillations in visual active sensing. *Front. Integr. Neurosci.* 13:32. doi: 10.3389/fnint.2019.00032

Libet, B. (1994). A testable field theory of mind-brain interaction. *J. Conscious. Stud.* 1, 119–126.

Liu, D., Liu, S., Liu, X., Zhang, C., Li, A., Jin, C., et al. (2018). Interactive brain activity: review and progress on EEG-based hyperscanning in social interactions. *Front. Psychol.* 9:1862. doi: 10.3389/fpsyg.2018.01862

Loh, C. L., and Froese, T. (2021). "An oscillator model for interbrain synchrony: slow interactional rhythms entrain fast neural activity." in *2021 IEEE Conference on Computational Intelligence in Bioinformatics and Computational Biology* (CIBCB). IEEE; October 13-15, 2021, 1–8.

Ludwig, A. M. (1966). Altered states of consciousness. *Arch. Gen. Psychiatry* 15, 225–234. doi: 10.1001/archpsyc.1966.01730150001001

Mackie, D. M., Smith, E. R., and Ray, D. G. (2008). Intergroup emotions and intergroup relations. *Soc. Personal. Psychol. Compass* 2, 1866–1880. doi: 10.1111/j.1751-9004.2008.00130.x

Mayo, O., and Gordon, I. (2020). In and out of synchrony—behavioral and physiological dynamics of dyadic interpersonal coordination. *Psychophysiology* 57:e13574. doi: 10.1111/psyp.13574

McCraty, R., Atkinson, M., Tomasino, D., and Bradley, R. T. (2009). The coherent heart heart-brain interactions, psychophysiological coherence, and the emergence of system-wide order. *Integral Review* 5, 10–115.

McFadden, J. (2013). The CEMI field theory closing the loop. *J. Conscious. Stud.* 20, 153–168.

McNaughton, K. A., and Redcay, E. (2020). Interpersonal synchrony in autism. *Curr. Psychiatry Rep.* 22, 1–11. doi: 10.1007/s11920-020-1135-8

Miles, L. K., Nind, L. K., and Macrae, C. N. (2009). The rhythm of rapport: interpersonal synchrony and social perception. *J. Exp. Soc. Psychol.* 45, 585–589. doi: 10.1016/j.jesp.2009.02.002

Montague, P. R., Berns, G. S., Cohen, J. D., McClure, S. M., Pagnoni, G., Dhamala, M., et al. (2002). Hyperscanning: simultaneous fMRI during linked social interactions. *NeuroImage* 16, 1159–1164. doi: 10.1006/nimg.2002.1150

Müller, V., and Lindenberger, U. (2011). Cardiac and respiratory patterns synchronize between persons during choir singing. *PLoS One* 6:e24893. doi: 10.1371/journal.pone.0024893

Mundy, P., and Newell, L. (2007). Attention, joint attention, and social cognition. *Curr. Dir. Psychol. Sci.* 16, 269–274. doi: 10.1111/j.1467-8721.2007.00518.x

Murata, A., Nomura, K., Watanabe, J., and Kumano, S. (2021). Interpersonal physiological synchrony is associated with first person and third person subjective assessments of excitement during cooperative joint tasks. *Sci. Rep.* 11, 1–11. doi: 10.1038/s41598-021-91831-x

Murray, L., De Pascalis, L., Bozicevic, L., Hawkins, L., Sclafani, V., and Ferrari, P. F. (2016). The functional architecture of mother-infant communication, and the development of infant social expressiveness in the first two months. *Sci. Rep.* 6, 1–9. doi: 10.1038/srep39019

Nguyen, T., Schleihauf, H., Kayhan, E., Matthes, D., Vrtička, P., and Hoehl, S. (2020). The effects of interaction quality on neural synchrony during mother-child problem solving. *cortex* 124, 235–249. doi: 10.1016/j.cortex.2019.11.020

O'Gieblyn, M. (2020). Is the Internet Conscious? If it Were, how Would we Know? Wired. Available at: https://www.wired.com/story/is-the-internet-conscious-if-it-were-how-would-we-know/ (Accessed June 3, 2021).

Oliveira, H. M., and Melo, L. V. (2015). Huygens synchronization of two clocks. *Sci. Rep.* 5, 1–12. doi: 10.1038/srep11548

O'Sullivan, J. (2010). Collective Consciousness in Science Fiction. *Foundation* 39:80.

Pérez, A., Carreiras, M., and Duñabeitia, J. A. (2017). Brain-to-brain entrainment: EEG interbrain synchronization while speaking and listening. *Sci. Rep.* 7, 4190–4112. doi: 10.1038/s41598-017-04464-4

Quiñones-Camacho, L. E., Fishburn, F. A., Belardi, K., Williams, D. L., Huppert, T. J., and Perlman, S. B. (2021). Dysfunction in interpersonal neural synchronization as a mechanism for social impairment in autism spectrum disorder. *Autism Res.* 14, 1585–1596. doi: 10.1002/aur.2513

Rebollo, I., Devauchelle, A. D., Béranger, B., and Tallon-Baudry, C. (2018). Stomach-brain synchrony reveals a novel, delayed-connectivity resting-state network in humans. *elife* 7:e33321. doi: 10.7554/eLife.33321

Richter, C. G., Babo-Rebelo, M., Schwartz, D., and Tallon-Baudry, C. (2017). Phase-amplitude coupling at the organism level: The amplitude of spontaneous alpha rhythm fluctuations varies with the phase of the infra-slow gastric basal rhythm. *NeuroImage* 146, 951–958. doi: 10.1016/j.neuroimage.2016.08.043

Safron, A. (2016). What is orgasm? A model of sexual trance and climax via rhythmic entrainment. *Socioaffect. Neurosci. Psychol.* 6:31763. doi: 10.3402/snp.v6.31763

Samaha, J., and Postle, B. R. (2015). The speed of alpha-band oscillations predicts the temporal resolution of visual perception. *Curr. Biol.* 25, 2985–2990. doi: 10.1016/j.cub.2015.10.007

Sanders, S. A. (1986). Development of a tool to measure subjective time experience. *Nurs. Res.* 35, 178–182. doi: 10.1097/00006199-198605000-00016

Scholkmann, F., Holper, L., Wolf, U., and Wolf, M. (2013). A new methodical approach in neuroscience: assessing inter-personal brain coupling using functional near-infrared imaging (fNIRI) hyperscanning. *Front. Hum. Neurosci.* 7:813. doi: 10.3389/fnhum.2013.00813

Schooler, J. W., Baumgart, S., and Franklin, M. (2018). Entertaining without endorsing: The case for the scientific investigation of anomalous cognition. *Psychol. Conscious. Theory Res. Pract.* 5, 63–77. doi: 10.1037/cns0000151

Sloboda, J. A., and O'neill, S. A. (2001). Emotions in everyday listening to music. *Music Emot. Theory Res.* 8, 415–429.

Smallwood, J., and Schooler, J. W. (2006). The restless mind. *Psychol. Bull.* 132, 946–958. doi: 10.1037/0033-2909.132.6.946

Smith, E. R., Seger, C. R., and Mackie, D. M. (2007). Can emotions be truly group level? Evidence regarding four conceptual criteria. *J. Pers. Soc. Psychol.* 93, 431–446. doi: 10.1037/0022-3514.93.3.431

Spiegelhalder, K., Ohlendorf, S., Regen, W., Feige, B., van Elst, L. T., Weiller, C., et al. (2014). Interindividual synchronization of brain activity during live verbal communication. *Behav. Brain Res.* 258, 75–79. doi: 10.1016/j.bbr.2013.10.015

Szymanski, C., Pesquita, A., Brennan, A. A., Perdikis, D., Enns, J. T., Brick, T. R., et al. (2017). Teams on the same wavelength perform better: inter-brain phase synchronization constitutes a neural substrate for social facilitation. *NeuroImage* 152, 425–436. doi: 10.1016/j.neuroimage.2017.03.013

Taves, A., Wolf, M. G., Ihm, E. D., Barlev, M., Kinsella, M., and Vyas, M. (2019). What counts as religious experience? The Inventory of Nonordinary Experiences as a Tool for Analysis across Cultures. *PsyArXive*. 1–24. doi: 10.31234/osf.io/ux28d [Epub ahead of print].

Toker, D., Pappas, I., Lendner, J. D., Frohlich, J., Mateos, D. M., Muthukumaraswamy, S., et al. (2022). Consciousness is supported by near-critical slow cortical electrodynamics. *Proc. Natl. Acad. Sci.* 119. doi: 10.1073/pnas.2024455119

Valencia, A. L., and Froese, T. (2020). What binds us? Inter-brain neural synchronization and its implications for theories of human consciousness. *Neuroscience of consciousness* 2020:niaa010. doi: 10.1093/nc/niaa010

van Baar, J. M., Halpern, D. J., and FeldmanHall, O. (2021). Intolerance of uncertainty modulates brain-to-brain synchrony during politically polarized perception. *Proc. Natl. Acad. Sci.* 118:e2022491118. doi: 10.1073/pnas.2022491118

Wass, S. V., Whitehorn, M., Haresign, I. M., Phillips, E., and Leong, V. (2020). Interpersonal neural entrainment during early social interaction. *Trends Cogn. Sci.* 24, 329–342. doi: 10.1016/j.tics.2020.01.006

Whitehouse, B., and Heller, D. P. (2008). Heart rate in trauma: patterns found in somatic experiencing and trauma resolution. *Biofeedback* 36, 24–29.

Wilson, M. (2001). Perceiving imitatible stimuli: consequences of isomorphism between input and output. *Psychol. Bull.* 127, 543–553. doi: 10.1037/0033-2909.127.4.543

Woolley, A. W., Chabris, C. F., Pentland, A., Hashmi, N., and Malone, T. W. (2010). Evidence for a collective intelligence factor in the performance of human groups. *Science* 330, 686–688. doi: 10.1126/science.1193147

Yang, Y., Wu, M., Vázquez-Guardado, A., Wegener, A. J., Grajales-Reyes, J. G., Deng, Y., et al. (2021). Wireless multilateral devices for optogenetic studies of individual and social behaviors. *Nat. Neurosci.* 24, 1035–1045. doi: 10.1038/s41593-021-00849-x

Yang, J., Zhang, H., Ni, J., De Dreu, C. K., and Ma, Y. (2020). Within-group synchronization in the prefrontal cortex associates with intergroup conflict. *Nat. Neurosci.* 23, 754–760. doi: 10.1038/s41593-020-0630-x

Yoon, H., Choi, S. H., Kim, S. K., Kwon, H. B., Oh, S. M., Choi, J. W., et al. (2019). Human heart rhythms synchronize while co-sleeping. *Front. Physiol.* 10:190. doi: 10.3389/fphys.2019.00190

Yoshioka, A., Tanabe, H. C., Sumiya, M., Nakagawa, E., Okazaki, S., Koike, T., et al. (2021). Neural substrates of shared visual experiences: a hyperscanning fMRI study. *Soc. Cogn. Affect. Neurosci.* 16, 1264–1275. doi: 10.1093/scan/nsab082

Young, A. (2022). Altered states of consciousness induced by exogenous audio signals: toward a better understanding of the oscillatory correlates of consciousness. *J. Sound Cult.* (in press).

Young, A., Hunt, T., and Ericson, M. (2022). The slowest shared resonance: A review of electromagnetic field oscillations Between central and peripheral nervous systems. *Front. Hum. Neurosci.* 15:796455. doi: 10.3389/fnhum.2021.796455

Zelano, C., Jiang, H., Zhou, G., Arora, N., Schuele, S., Rosenow, J., et al. (2016). Nasal respiration entrains human limbic oscillations and modulates cognitive function. *J. Neurosci.* 36, 12448–12467. doi: 10.1523/JNEUROSCI.2586-16.2016

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Electromagnetism's Bridge Across the Explanatory Gap: How a Neuroscience/Physics Collaboration Delivers Explanation Into All Theories of Consciousness

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A productive, informative three decades of correlates of phenomenal consciousness (P-Consciousness) have delivered valuable knowledge while simultaneously locating us in a unique and unprecedented explanatory cul-de-sac. Observational correlates are demonstrated to be intrinsically very unlikely to explain or lead to a fundamental principle underlying the strongly emergent 1st-person-perspective (1PP) invisibly stowed away inside them. That lack is now solidly evidenced in practice. To escape our explanatory impasse, this article focuses on fundamental physics (the standard model of particle physics), which brings to light a foundational argument for how the brain is an essentially electromagnetic (EM) field object from the atomic level up. That is, our multitude of correlates of P-Consciousness are actually descriptions of specific EM field behaviors that are posed (hypothesized) as "the right" correlate by a particular theory of consciousness. Because of this, our 30 years of empirical progress can be reinterpreted as, in effect, the delivery of a large body of evidence that the standard model's EM quadrant can deliver a 1PP. That is, all theories of consciousness are, in the end, merely recipes that select a particular subset of the totality of EM field expression that is brain tissue. With a universal convergence on EM, the science of P-Consciousness becomes a collaborative effort between neuroscience and physics. The collaboration acts in pursuit of a unified explanation applicable to all theories of consciousness while remaining mindful that the process still contains no real explanation as to why or how EM fields deliver a 1PP. The apparent continued lack of explanation is, however, different: this time, the way forward is opened through its direct connection to fundamental physics. This is the first result (Part I). Part II posits, in general terms, a structural (epistemic) add-on/upgrade to the standard model that has the potential to deliver the missing route to an explanation of how subjectivity is delivered through EM fields. The revised standard model, under the neuroscience/physics collaboration, intimately integrates with the existing "correlates of-" paradigm, which acts as its source of empirical evidence. No existing theory of consciousness is lost or invalidated.

Keywords: theory of consciousness, electromagnetic field theory, neuroscience, standard model of particle physics, electromagnetic field theory of consciousness

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INTRODUCTION

2020 marked the 30th birthday of the modern form of the empirical science of consciousness introduced by Crick and Koch's influential 1990 "*Toward a neurobiological theory of consciousness*" (Crick and Koch, 1990). The science of consciousness, or the science of phenomenal consciousness, as David Chalmers described it (Chalmers, 1996), is the scientific account of the 1st-person perspective (1PP), a perspective that delivers subjective experience (subjectivity) or "what it is like to be us" (Nagel, 1974). Throughout this article, we also interchangeably employ the term P-Consciousness (Block, 1995) to refer to the 1PP.

That moment in 1990 has a threefold significance. First, it marked a transition of the science of P-Consciousness into the physical sciences. Prior to this time, it could be career trouble for neuroscientists to directly attend to P-Consciousness (Koch, 2019). Mainstream neuroscientists confined themselves to the neurobiological account of nervous system function, its disorders, and their treatment. Post-1990, however, the swelling ranks of neuroscientists funded in the science of P-Consciousness have made remarkable progress.

Second, neuroscientists embraced a categorically distinct, novel explanandum unprecedented in any physical science: the 1PP of the nature under consideration. No other physical science tackles this. It tends to be under-acknowledged that on behalf of all physical sciences, and alone, neuroscientists have entered the realm of the novel explanandum that is the 1PP. The reason for this solitude is that neuroscience's central target, the human brain, is the only natural context with an empirically proven, accessible instance of a 1PP. Its existence has led to the science of consciousness: we know that somehow, some of the details found in "being" the activity of this vast neural/glial complex is highly correlated with the details of P-Consciousness. Neuroscience alone has this evidence base within its explanatory ambit.

Consider that no geologist is currently required to or is able to account for what it is like to be a rock, from the perspective of being a rock made of atoms from the same table of elements used in a brain. Neuroscience that successfully explains the origins of P-Consciousness in brains will consequently and incidentally facilitate, ultimately, an equally proved scientific basis for what it is like to be a rock. This is not any kind of claim that rocks are conscious. This is about being able to say something scientific about the consciousness of a rock. A claim "*It is not like anything to be a natural rock,*" originating in a future mature science of consciousness, will be a formal scientific position, not merely an intuition. In this future, all scientists will require enough training in the science of P-Consciousness to accurately conceive of how it impacts their purview.

The third feature of the 1990 moment was Crick and Koch's prototyping of a way to normalize the science so that the peculiarities of the novel explanandum could yield to the familiar and trusted empirical methods of neuroscience. This normalization explicitly used the term "correlates" in an empirical method (Crick and Koch, 1990). Their proposition became the "Neural Correlates of Consciousness" (NCC) empirical paradigm, which triggered an extensive literature examining NCC and the idea of "correlates" as an empirical evidence approach that is still ongoing and productive (Salthe, 1985; Crick, 1994; Chalmers, 2000; Metzinger, 2000; Rees et al., 2002; Farber, 2005; Mormann and Koch, 2007; Rees and Frith, 2007; Velmans and Schneider(eds), 2007; Lau, 2008; Molyneux, 2010; Aru et al., 2012; de Graaf et al., 2012; Neisser, 2012; Dehaene, 2014; Axelrod et al., 2015; Tsuchiya et al., 2015; Koch et al., 2016; Mashour and Hudetz, 2018).

A technically accurate generic depiction of the science of consciousness is "*an ongoing attempt to locate and describe the ABC-correlates of consciousness.*" Crick and Koch set the first ABC to "neuronal." All scientific theories of consciousness can be cast in the "ABC-correlates" format. A non-exhaustive list is ABC = "*behavioral*" e.g. (Tononi and Koch, 2015), "*global workspace*," "*integrated information*," "*computation*," "*thalamocortical loop*" e.g. (LaBerge and Kasevich, 2007; Winters, 2021), "*oscillatory/resonance*," "*mathematical*," "*quantum mechanical*" *-correlates of consciousness*. Note that this idea can be extended to ABC = "*philosophical*" correlates such as "*functionalism*," "*physicalism*," and many others. In each case, to suggest an "ABC Theory of Consciousness" is to describe the operation of a brain from an ABC-correlates perspective. The idea is that researchers with enough reproducible empirical evidence of "ABC-correlates of P-Consciousness" can claim to have accounted for P-Consciousness in a familiar, well-traveled manner.

However, decades of experimental work have revealed that even if a particular ABC becomes strongly evidenced, the 1PP will still not be explained. We find ourselves frustrated and forced to admit that ABC-correlates all suffer the same fate as explanation: they do not explain why the particulars of an ABC necessitate a 1PP. We are simultaneously all aware of why this happens: "*However, correlations by themselves cannot supply explanations, they can only constrain them*" (Seth, 2009). In every ABC case, the 1PP somehow just "happens" *via* a mechanism or principle that is not delivered by knowledge of the ABC-correlates. Instead of an explanation, we find ourselves in possession of a collection of collaborating ABC "parts," whose individual connection to a mechanism of a 1PP is lacking, that somehow manages to create a "whole" that delivers it. Later, this explanatory failure will be formally classified as "strong" or "radical" emergence, in contrast with the normal kind of "weak emergence" that is regarded as a successful explanation in science elsewhere.

This quandary is another way of portraying the "hard problem" of consciousness as described by Chalmers (1996), in which he recognizes that P-Consciousness is not explained merely by describing matter (ABC). Why should matter behaving "ABC-ly" be mysteriously tagged with a first-person perspective? Why do we expect the simple enumeration of ABC-correlates to deliver an explanation?

We can more deftly touch the origins of our frustration by an analogy using Newton's 2nd Law, $F = mA$, when notionally used to capture "what it is like to be mass m." Stimulated by force F, if the responding acceleration term mA could "talk" to deliver the "*mA-correlate*" of an extra explanandum, the P-Consciousness of mass m, then the science is structured identically to the ABC-correlates paradigm. Nothing in the statement $F = mA$

explains *why* $F = mA$. In exactly the same way, nothing in the mA term explains why mass m has P-Consciousness. The formula $F = mA$ could be described as the "force correlate of acceleration." It was constructed because F and m behavior are directly evidenced (even if *via* solid inference) in the normal manner of scientific observation (originating as the contents of the consciousness of the scientific observer). In the "*mA-correlate*" of the P-Consciousness of mass *m,* we cannot evidence both sides of the relationship in the familiar way. The process actually delivers the correlate of a P-Consciousness *report.* In what amounts to a highly curated form of hearsay evidence, reports can be explicit ("report") and implicit ("no report") (Tsuchiya et al., 2015). Because of the indirectness and non-uniqueness of the evidence, we cannot conclusively argue to have encountered the "correct" ABC-correlate. To make that crucial argument a cogent argument is impossible because it presupposes accurate knowledge of the 1PP that the ABC is somehow expected to deliver. That makes the expectation of uncovering a real explanation (the underlying 1PP mechanism/principle) from ABC-correlates optimistic at best. This is the now 30-year-old, familiar struggle that all ABC-correlates scientists face daily at the coalface of empirical work and critical argument in respect of the origins of P-Consciousness (Pitts et al., 2014; Storm et al., 2017).

The search for the elusive "smoking gun" ABC-correlate has certainly been worth the effort. It has revealed most of what we now know about P-Consciousness. It has been a very successful program of work. However, the "explanatory cul-de-sac" is a deeply unsatisfactory state for our knowledge of consciousness. It continues to locate practitioners out of reach of an empirically proved full explanation, leaving us all in the grip of strong emergence. This is the paradoxical presentation of the current operational structure of the science. After 30 years, these observations deliver us the license and an obligation to explore the possibility of a way to transcend the strong-emergence cul-de-sac. This article is a result of that exploration.

In what follows, we do not deliver the "correct" ABC theory of consciousness or a set of modifications to an existing ABC. One of the existing ABC, or perhaps a combination thereof, is likely to be "right." This article is agnostic in that regard. Our interest is in how it is to be conclusively *proved.* It is the inconclusive evidence basis, in the face of the unique explanandum that is the 1PP, that we address here. That is, on behalf of all ABC, this article targets the reason for the explanatory cul-de-sac and what to do about it. In what we have called an "electromagnetic turn" in the science of consciousness, we demonstrate that it is in the science of consciousness acquiring its mature operational structure that leads all ABC out of the explanatory cul-de-sac. In the process, all (top–down) ABC get their long-sought connection to explanation and proof in (bottom–up) fundamental physics. The result is delivered in two parts.

In Part I, we first explore the brain from a fundamental physics perspective (the standard model of particle physics). It reveals the brain to be an intrinsically unitary electromagnetic (EM) field object, seamlessly impressed throughout and beyond the space occupied by the brain's cellular componentry, from the atomic level up. We include a review of the anatomical membrane-scale origins of endogenous EM field expression by brain tissue (see **Supplementary Material A**). This is followed by an analysis of six classes of ABC-correlates theories of consciousness, confirming how each class locates itself in the strong emergence cul-de-sac. The brain's specialized complexity in EM field expression distinguishes it from other organs (such as the liver and the heart) that are also EM field entities from the atomic level up. The consequence is that there is only one natural, fundamental physics correlate of P-Consciousness: EM fields as "electromagnetic correlates of consciousness" (EMCC). ABC-correlates neuroscience has, in effect, implicitly proved that (bottom–up) EM is the ultimate origin of the 1PP for all (top–down) ABC-correlates. This has the consequence of moving EM field expression by brains to center-stage in the science of consciousness, thereby positioning neuroscience in the heart of fundamental physics. This is the first result.

In Part II, inspired by the Part I analysis of six classes of ABC-correlates, we deliver the second, speculative result. It reframes the science of P-Consciousness into a neuroscience/physics collaboration charged with accounting for how it is that standard model EM fields have, within them, the potential for a 1PP, and what EM is doing when it delivers it in a brain. Part II is a preliminary/introductory discussion outlining how, in the EM basis of all ABC, neuroscience and physics communities may collaborate to discover how EM fields acquire the potential for subjectivity that neuroscience has proved must exist within them. In that final EM account, all ABC-correlate theories of consciousness gain, from fundamental physics, a common link to an explanation. Physics benefits in acquiring, from neuroscience, a route to an explanation of the scientific observer. Together, the two science communities have the potential to build a viable bridge over the explanatory gap (Levine, 1983; Van Gulick, 2018) that offers hope for a solution to the "hard problem". The practicalities of the implementation and empirical proof of the proposal are described in general terms as the beginning of an ongoing discourse that can guide us into the future.

PART I: ABC-CORRELATES OF CONSCIOUSNESS ARE ELECTROMAGNETIC CORRELATES

We now detail how the following claim is a natural consequence of the standard model of particle physics:

Claim C1 = All "*ABC correlates of consciousness*" are actually "*electromagnetic correlates of consciousness*" (EMCC) in ABC guise.

Claim C1 is not a theory of consciousness. C1 merely recognizes that whatever the ABC, it is ultimately implemented by some subset of the EM field behavior comprising a brain. To proceed with precision, let us specialize the context of claim C1 to humans. As already advised in the introduction, human 1PP is the only proven, accessible instance of it known to science. The human 1PP has led us to the need for and development of a science of consciousness. The human 1PP thus becomes the primary explanandum of the science. Extending the explanation to include the 1PP of non-human fauna, flora, and artificial/machine consciousness can be left to a separate discussion because it changes nothing in relation to the validity of C1, which is based on simply taking a fundamental physics perspective of the human brain. Note that the fundamental EM basis of the 1PP has previously been examined from specific perspectives (Barrett, 2014; McFadden, 2020). *Via* C1, this article extends the work to a full evaluation including its generalized implications.

The Standard Model of Particle Physics

The Standard Model of Particle Physics (SMPP) best (but not yet perfectly) describes the physical basis of everything found within the space comprising our universe, along with the properties of space itself (Cottingham and Greenwood, 2007; Rich, 2010). The SMPP has four quadrants (see **Figure 1**) covering four fundamental forces: EM, strong-nuclear, weak nuclear, and gravitation/inertia. This presents us with a fundamental ontology of forces based on the fields that manifest them. This list is exhaustive. There are no others known to exist. Claim C1 confines us specifically to the highlighted **Figure 1** EM field quadrant of the standard model [for physicists it is known as the U(1) symmetry group].

The SMPP delivers a stark shift in neuroscience's comprehension of the true nature of the atomic basis of our biosphere. The reason for the C1 confinement to EM fields as originating the 1PP is a very simple one: In the context of the atomic basis of everything relevant to life in our biosphere, there is literally nothing else to hold accountable for the 1PP because there is nothing else there to choose from: *It is all EM field*. Choosing from a list of one item is a very simple and attractive choice. It is the job of the rest of Part I to demonstrate how the SMPP proves C1, and how this has been the case ever since the standard model was assembled half a century ago. What has changed, paradoxically, is that the SMPP news will finally reach neuroscience in the context of a 30-year-old empirical, physical science of P-Consciousness.

The SMPP picture of "matter" made of atoms involves atomic nuclei and electrons as the collaborating particles that comprise the material (atomic) basis of our biosphere. These are vanishingly small, punctate containers of all the deep driving originators and constraints leading to the atomic basis of the biosphere. Synergy between atomic nuclei and electrons is fundamentally defined by their electromagnetic properties, the most dominant of which is their electric charge and magnetic moment (spin) source content. Everything else about the particles (such as their associated mass), in our context of interest, is secondary.

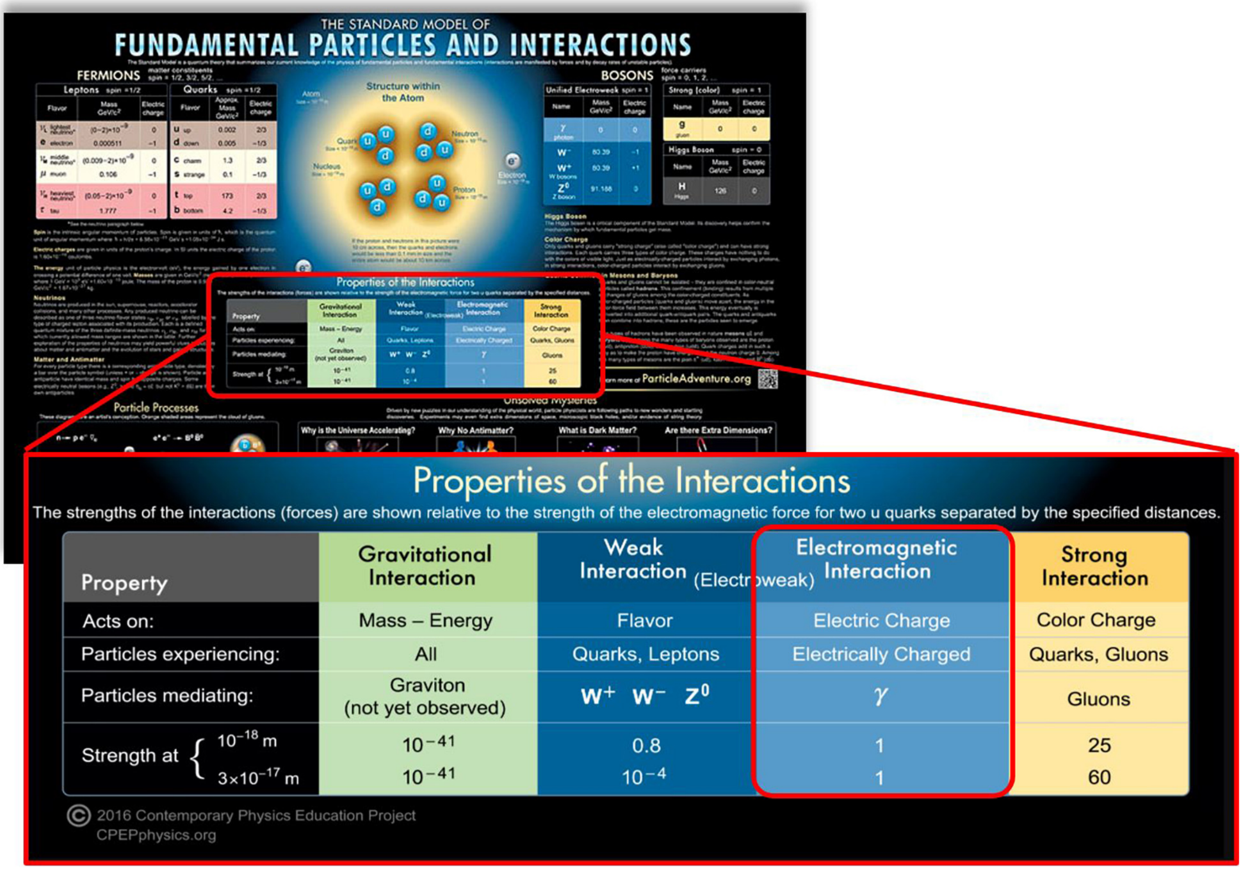
Consider a rough and conservative estimate of the spatial occupancy by the interior of electrons and nuclei, as a proportion of the space attributed to being occupied by a complete, typical atom from the table of the elements. If we divide the spatial occupancy of a single atom into 15,000 parts, the amount of space occupied by electrons and nuclei is a fraction of 1 part (Kitchener and Hales, 2022). Contained within that part are all the charge and spin sources expressing EM fields that intimately interrelate in the manner that stabilizes an atom that, in ionized form, can then impress EM fields on space at distances far greater than the size of the atom. In this way, the position and motion of charge and spin, existing in space at the vanishingly small level of the interior of atomic particles, literally create the EM field that exists in the space outside atoms, manifesting the forces that have us regarding it as "material" or a "substance" behaving "physically." EM fields are the ultimate origin of the forces that create atoms and hold them together to make molecules and higher-level structures (this organizational hierarchy is detailed below).

More generally, at and above the level of the atomic particles, the **Figure 1** SMPP tells us that the familiar atomic basis of the material of our biosphere is entirely comprised of only three things: First is space itself. The second originates in the SMPP EM field quadrant, which tells us we have large EM fields originating from the charge/spin source content within the interior of atomic particles. The third originates in the SMPP gravitation quadrant, which tells us we have a gravitational field originating in the mass intimately entangled with the EM (charge/spin) sources *inside the same atomic particles*. **Figure 1** also tells us that the gravitational field can be regarded as functionally inert at the level of the biosphere contents (things like humans and our brains). This is because the gravitational force is at least 16 orders of magnitude weaker than the EM field force. While the mass delivers inertia into the Newtonian transport dynamics motivated by the EM field forces that charges/spins mutually experience and impose on each other (the Lorentz force – see **Supplementary Material A**), this is distinct from the gravitational field forces produced by the mass component of the atomic particles. For all intents and purposes here, the space occupied by a brain is therefore effectively entirely permeated by nothing but EM fields.

This cursory appreciation of basic SMPP facts is, in fact, loaded with a fundamental challenge. As scientists, we must face the rather confronting fact that our own standard model is telling us that, for all practical purposes in the science of P-Consciousness, we *are* electromagnetic field objects in our entirety. As is a car, a computer, lunch, a pile of dirt, a tree, your dog, steam, and the air we breathe. When we use the words "physical" or "material" in the natural context of the brain's delivery of a 1PP, these words refer to the supra-atomic scale EM fields impressed on space by atoms. In a quest to understand the 1PP that arises from "being" made of atoms, to the extreme levels enumerated above, there is nothing else left to hold accountable for the origins of the 1PP but EM fields because there is, effectively, nothing else there to be found but EM fields.

Fully engaging and substantiating this change in perspective involves details that it is the job of the rest of Part I to assemble. We do not intend to deliver anything but the mundane, long-proved empirical reality delivered by the SMPP. There are no new facts here. We simply engage more fully in what physics tells us of the brain and how it relates to a potential scientific account of the origins of P-Consciousness.

For completeness in an understanding of how EM may ultimately be understood to originate the 1PP *via* C1, we now consider the remaining three quadrants of the standard model: the strong-nuclear, weak nuclear, and gravitation/inertia quadrants. The strong and weak nuclear forces are exquisitely



THE STANDARD MODEL OF
FUNDAMENTAL PARTICLES AND INTERACTIONS

Properties of the Interactions

The strengths of the interactions (forces) are shown relative to the strength of the electromagnetic force for two u quarks separated by the specified distances.

Property		Gravitational Interaction	Weak Interaction (Electroweak)	Electromagnetic Interaction	Strong Interaction
Acts on:		Mass – Energy	Flavor	Electric Charge	Color Charge
Particles experiencing:		All	Quarks, Leptons	Electrically Charged	Quarks, Gluons
Particles mediating:		Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons
Strength at	10^{-18} m	10^{-41}	0.8	1	25
	3×10^{-17} m	10^{-41}	10^{-4}	1	60

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FIGURE 1 | A popular representation of the standard model of particle physics in which we find the four fundamental forces, within which is the electromagnetic force. For further information, a useful starting point can be found in Aitchison and Hey (1984), Halzen et al. (1985), Cottingham and Greenwood (2007), and Griffiths (2020). Credit: the model can be purchased in many forms from the non-profit "Contemporary Education Physics Project" (https://www.CPEPphysics.org).

localized within the nucleus of atoms, holding the nucleus together. Together, these three quadrants create and maintain the structure and dynamics of the atomic basis of all the members of the table of the elements, thereby creating and stabilizing the EM field quadrant as expressed by atoms. In effect, they form an intra-atomic constraining envelope for EM fields to work at the scale of life and consciousness.

That said, C1 does not entail any presupposition that the intimate entanglement of all four quadrants, at the subatomic and deeper levels, has no role in some aspect of the production of P-Consciousness. Put simply, the core fundamental claim of C1 is that the EM field quadrant has *primacy* in the establishment of P-Consciousness for human brains, including its array of qualitative kinds and their degrees. C1 is upheld even when all four quadrants of the standard model may ultimately be proved to be severally necessary and only then jointly sufficient to produce P-Consciousness. Note that the three subsidiary quadrants are physically contained within, and expressed by, the atomic layer of the natural matter hierarchy to be discussed in the next section. Therefore, any account of the EM quadrant involving atoms (and therefore their components) implicitly entails the presence of the other three quadrants. To that extent, in reality, C1 invokes a necessity for all four quadrants, while claiming that it is ultimately the electromagnetic quadrant that physically results in P-Consciousness being associated with brains. A practical note: EM field theories of consciousness that partition electromagnetism across a supra-/infra- atomic/molecular level boundary exist and are consistent with C1 e.g., (Poznanski et al., 2019; Keppler, 2021).

C1 as a Consequence of a Natural Containment Hierarchy

Switching to a transdisciplinary view, as a fundamental shift in perspective, is key to understanding the EM origins of P-Consciousness. Consider **Figure 2A** line A, which depicts all existing ABC theories listed in roughly science-disciplinary order. The physical sciences shown in **Figure 2A** below line B have discovered the nested containment hierarchy of our biosphere shown in **Figure 2B**. It depicts the hierarchy seen on a generic descriptive trajectory leading deep into the excitable cell tissue *of a scientist*. Take a moment to compare it with a very specific descriptive trajectory into the brain (say, into a particular mitochondrial DNA codon), or a descriptive

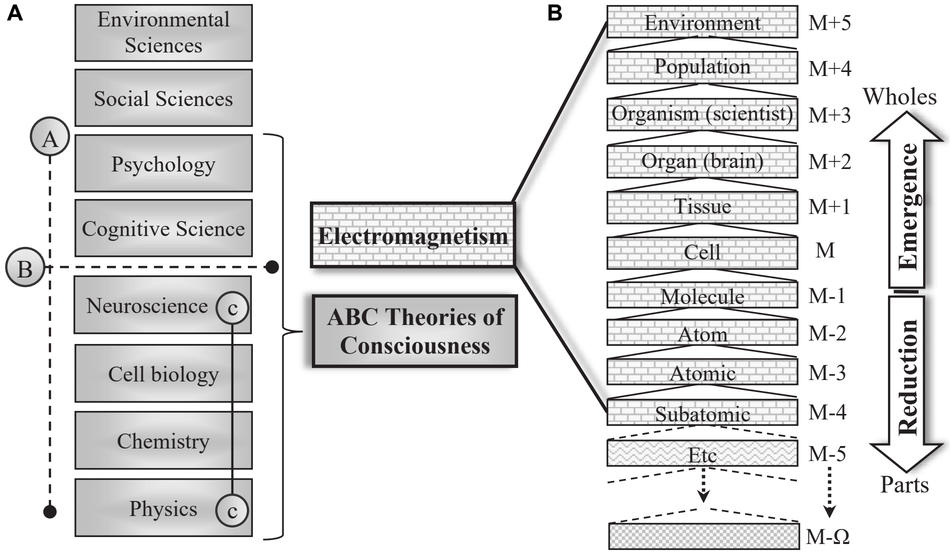

FIGURE 2 | (A) The organizational hierarchy of sciences in the lineage relevant to the study of the brain, consciousness, cognition, intelligence, and behavior. Line A shows the hierarchy of the sciences tackling consciousness. Line B depicts the upper boundary of the physical sciences. Line C shows the connection between neuroscience and the standard model of particle physics that is central to Parts I and II. **(B)** The natural hierarchy identified by scientists beneath line B. Each layer of description is constructed from within the hierarchy by scientists within layer [M + 3]. The specific case shown leads deep into the ultra-structure of the notional brain of the particular observing/describing scientist. Each layer is a collection of weakly emergent "wholes" comprised of members of all the layers below. Based on Hales (2014, Figure 10.1). See also Feinberg (2011, Figure 7) and Bongard and Levin (2021, Figure 1) and hierarchy theory in general (Koestler, 1967, 1978; Grobstein, 1973; Pattee, 1973; Simon, 1973; Allen and Starr, 1982; Salthe, 1985; Ahl and Allen, 1996).

trajectory taken through a rock, a kidney, a computer, a tree, or a star.

The **Figure 2B** descriptive trajectory has been deliberately chosen to highlight the position of all scientists within the hierarchy at the organism layer [M+3]. This can be viewed as a specialized sample from the population of humans included in **Figure 2B** layer [M+4] that are contained within our biosphere, the environment layer [M+5]. The symbol M serves merely as a reference point to ensure consistency and accuracy.

The overall height of the hierarchy is artificially limited to suit our context. It does not include higher levels of containment, such as a planetary system. The accretion of **Figure 2B** hierarchy layers arises in synergies between aggregated members at a particular layer (spatiotemporal scale). Within a given layer, "horizontal" aggregates of members (parts) of deeper layers form qualitatively new composites (wholes). For example, atoms form molecules and they jointly aggregate to form cellular organelles. These jointly form whole cells, and so forth. It is explaining these qualitatively novel, persistent organizational structures that attracts the attention of **Figure 2A** scientists.

The **Figure 2** nested containment hierarchy perspective appropriately grounds our activities as scientists in our pursuit of a scientific understanding of the natural biosphere hierarchy, from within that biosphere hierarchy, by use of properties acquired by being literally made of what the biosphere hierarchy is made of.

Describing the observed apparent structure at some point in the hierarchy has traditionally located us in our chosen science discipline. The labeling of a layer's appearance by scientifically behaving humans is a mere human abstraction of the layer's characteristics (such as thermodynamic, informational, cognitive, and so forth), including influences from or properties of the lower layers. If you deleted (in the sense of "de-organized") any layer below M, for example, the entire hierarchy disappears from that layer upwards. For example, deleting all atomic particles deletes atoms, molecules, cells, and so forth, all the way to the containing environment. In these cases, none of the deletions eliminate the lower levels, including sub-atomic particles, space, and so forth. This fact reveals the existence of a powerful *vertically* acting system of constraints that is not within the ambit of any individual scientific discipline. This system of constraints operates through the entire hierarchy, from top to bottom e.g. (Feinberg, 2011, Figure 7).

Next, from a position within the environment layer [M+5], we take in the inward, transdisciplinary perspective "down" the hierarchy. The **Figure 2B** hierarchical whole/part decomposition takes a descriptive vector indefinitely deep into our nominated scientist's brain tissue layer [M+2] at finer and finer spatiotemporal scales. Note that to "be" a scientist's brain at layer [M+2], by definition, includes everything in all deeper layers. If there are a thousand layers of nested structural containment hierarchy beneath [M+2] then we human scientists are "being" all of them. Note that the hierarchy is depicted as ending at some unspecified deep layer signified as [M-**Ω**], the possibility and nature of which is beyond the scope of this article. It does not impact C1.

In representing the natural hierarchy in this way, the phrase "fundamental physics" acquires the practical meaning needed to support C1 and interpret its implications. The SMPP is a set of empirically proven formal descriptions, beginning around layer [M-5], that covers a vast range of exotic entities, most of which are not relevant to the science of our primary explanandum, human P-Consciousness, because they are uninvolved in human anatomy or physiology from the atomic level up.

The EM field basis of our chosen vector through the hierarchy is indicated by the "electromagnetism" layers with the brick background in **Figure 2B**. It arises at the organizational level [M−4] (protons, neutrons and electrons). Accreting (vector-superposing) layers of electromagnetic fields, starting at the deepest levels of quantum electrodynamics, form the fundamental basis of everything above the subatomic layer [M−4], culminating in the creation of our biosphere [M+5], the containing environment of our notional scientist in a natural setting. The hierarchy (as previously described) is, in effect, entirely EM field from the atomic level [M−3] (electrons and nuclei) up.

Consider now the specific context of interest here. Those of us studying the science of P-Consciousness are located with all other scientists as particular "organisms" within layer [M+3]. The scientific outcome is, in effect, a scientific account of the scientific observer. Applied to the context of the acquisition of objective scientific evidence (originating as "contents of a scientist's P-Consciousness"), an explanation of the observer has the consequence of explaining how scientists can "scientifically observe" the biosphere from our layer [M+3] position within the hierarchy. The **Figure 2** transdisciplinary view thereby reveals the science of consciousness as part of a science of how we can do any science at all. In the ABC-correlates context, this literally makes us scientific observers trying to explain P-Consciousness (an ability to scientifically observe) through the use of scientific observation (P-Consciousness). **Figure 2** thereby demonstrates the logical flaw of "question-begging" at the heart of the recognized difficulties with the process of explanation within the ABC-correlates of consciousness paradigm: We are using observation (of ABC-correlates of a consciousness report delivered *via* the 1PP of a presupposed human scientist observer) to account for how we scientists can observe anything at all. The result is that, because of the way a presupposed 1PP is used to source all scientific evidence, science is essentially rendered voiceless in respect of an explanation of the 1PP.

When it comes to the science of P-Consciousness, we must all face the vertical hierarchy of **Figure 2B** and our position within its layers. It is the complete hierarchy that delivers P-Consciousness, not any abstractions of it (such as the ABC of the introduction) created by a practitioner making a horizontal slice, thereby abstracting-away the fundamental EM basis of P-Consciousness that arises in the entirety of the hierarchy. To prevail over this unique and unprecedented explanandum in science, we must all shift our perspective from a horizontal discipline-centric reductive view to a vertical transdisciplinary holistic view. In doing so, we all encounter fundamental physics — in this case, the fundamental physics of EM in the standard model.

Hierarchically organized EM fields are still just EM fields. However, their intimately nested hierarchical structure raises the possibility that, depending on how layers are organized, fundamental properties of consciousness such as "unity" (Cleeremans and Frith, 2003; Bayne, 2010) or "symbol-grounding" or "binding" or "combination" (Harnad, 1990; Treisman, 1996; Revonsuo and Newman, 1999; Roskies, 1999; Singer, 2001; Chalmers, 2016), inherited at layer [M−4], can potentially be conserved, inherited and incorporated in higher organizational layers. For more detail on these nuanced aspects of consciousness and EM's natural suitability in accounting for them see Kitchener and Hales (2022). In relation to EM's natural solution to the combination problem, for example, the "inheritance" is literally manifest in the layered accretion (vector field superposition) of EM fields, where qualitatively novel emergent 1PP wholes can be traced back to vectorially superadded EM field parts. Insofar as any brain property may be inherited in the deep layers and then assembled with more complexity as the layers accrete as a coherent unity, the **Figure 2B** vertical direction is the ultimate origin of anything that can be claimed to be "emergent" in the hierarchy. That accreted/collective inheritance may then act with an emergent influence and have functional implications. The concept of emergence is formalized below.

It is in **Figure 2B** cranial central nervous system organ layer [M+2] that we can conceive of brains as an exotic solid entirely comprised of EM field phenomena expressed as a deeply nested containment hierarchy. It is, therefore, only a transdisciplinary perspective that can fully account for P-Consciousness as a collective property of layer [M+1] tissue, regarded as an EM field object. Layer [M+1] is where the EM field system impressed on space by brain tissue acquires its fully detailed form, including all properties inherited by the constraints, drives, and properties of the deeper layers. The EM field system is impressed on space with a spatial organizational resolution of 7–8 orders of magnitude, from the nm scale of the cell membrane to cm at the tissue scale.

When sampled within scientific disciplines, we find that scientists tend not to answer the question "*What are humans/human brains made of*?" either consistently or with technical specificity. In day-to-day science, this inconsistency simply does not matter much. However, we have now seen how fundamental physics has answered the question: Humans are made of the EM fields expressed by atoms based on the subatomic-level electric charge and magnetic spin sources that originate them. In principle, that answer should suffice, regardless of one's disciplinary standpoint. Differently organized EM fields are still EM fields, just as two very different kinds of wall can be made of the same bricks, and when each wall is finished, the bricks are still just bricks. The EM field of different sources intimately sum, through vector superposition, into a single, unified EM field whole in a way that bricks do not, but the result has the same interpretation. The origins of P-Consciousness must ultimately rest on our fundamental composition/whatever it is we are made of. At the heart of the answer is the fundamental EM field basis of cranial nervous tissue. Somehow, "being" these exquisitely detailed EM fields, manifest by an atomic substrate, delivers P-Consciousness, however mysterious the connection may be.

C1 in Measurement and Control

We now examine the scientific evidence collected in empirical work published in the science of consciousness at the various levels in the **Figure 2B** hierarchy. In the context of a brain, within the hierarchy shown, we can enumerate the types of measured data and their method of acquisition. First, consider raw counts. If we are studying diffusion processes, we are, in effect, looking at spatiotemporal counts (thermal concentration dynamics) of what are ultimately electromagnetic objects randomly flying through space and colliding with each other.

Consider the ubiquitous measurements known as Local Field Potentials (LFP) (see Einevoll et al., 2013), the Electrocorticogram (ECoG), the Electroencephalogram (EEG), and the Magnetoencephalogram (MEG) (Buzsaki et al., 2012; Obien et al., 2015). These are all measurements of spatially averaged, time-sampled/temporally averaged electric and magnetic field properties at a nominated spatiotemporal scale. Each of these kinds of measurement bears witness to the EM nature of the measured object. MRI/fMRI, scanning and transmission electron microscopes, atomic force microscopy and all forms of probes, actuators and stimulators are also an EM interaction with the studied material.

Insofar as brains are able to perform sensory measurement, the same concept applies. All of the sensory modes are, in the end, EM field phenomena, even those that are thought of as purely chemical or mechanical. When we touch something with our finger or another appendage (or, more generally, when atoms of any kind collide), at the atomic level, EM fields interact with EM fields. That is what "touching" is. The process of sound waves impacting sensory hairs in the cochlea is also ultimately an EM field interaction. Sound transmission occurs through the propagation of phonons (disturbances in the EM field system at the atom level of **Figure 2** layer [M–2]). We tend to think of sound as a "mechanical" property. In reality, the "mechanical" descriptor is merely a label we apply to what is actually an EM phenomenon. Phonons are bosonic (Ashcroft and Mermin, 1976, pp. 780–783; Feynman, 1976, p. 159), originating naturally within the EM quadrant of the standard model of particle physics through their atomic-level propagation mechanism.

When it comes to the artificial control of the operation of brain signaling, all the various forms of it involve the exogenous application of EM fields. Consider transcranial magnetic and electric stimulation (TMS/TES) or intracranial electrical stimulation (Raccah et al., 2021). These are clearly and entirely the topical application of EM fields to influence the brain's endogenous EM field system either for exploratory or clinical purposes. In the same context, brain tissue surface and penetrating electrodes also function by delivering EM field system influences and, similarly, acquire their effectiveness *because* of the EM field basis of the brain's endogenous signaling systems. Another more recent arrival in this area is transcranial ultrasonic stimulation (TUS). This, too, is an EM phenomenon for the reasons stated in the previous paragraph. Introducing chemicals into the brain is also the introduction of EM field phenomena. Surgery is also an EM field disruption using the EM field of surgical instruments.

In this way, all sensory/motor action within a brain, and all scientific measurement and control applied in the science of P-Consciousness, implicitly involve EM field properties in the chosen context. This empirical reality undergirds C1 and the EM field basis of P-Consciousness, with these diverse phenomena ultimately becoming the measured electromagnetic correlates of consciousness (EMCC) cited in C1. Essentially every measurement ever made in support of any ABC theory of consciousness is also an EMCC acting in support of an EM field theory. C1 thereby serves to reinforce the fact of the EM basis of all brain phenomena as something the science has been implicitly involved in all along.

The Hierarchy and Weak/Strong Emergence

For the purposes of completing our examination of C1 and connecting it with the processes of explanation in the science of P-Consciousness, here we calibrate our understanding of emergence and how it operates in the natural hierarchy of **Figure 2B**. The brain is a thermodynamically open, far-from-equilibrium, non-linear, non-stationary, self-assembling, self-organizing complex dynamical system with power-law dynamics (e.g., Kitzbichler et al., 2009; Fingelkurts et al., 2013; Zare and Grigolini, 2013; Cocchi et al., 2017; Tagliazucchi, 2017) based on the **Figure 2B** nested physical containment hierarchy of fundamental EM field activity impressed on space by excitable cells forming brain tissue organized in the manner detailed in **Supplementary Material A**.

Two technical categories apply to complexity expressed by hierarchical systems. The first category, "weak-emergence," signifies a collective behavior that is not obviously related to any individual part/component, yet is a "whole" that is, in-principle, predictable and explained by a sufficiently detailed exploration of groupings of well-understood, explained, and predictable parts. The containment hierarchy in **Figure 2B** is a nested hierarchy of natural "weakly-emergent" objects described by scientists in **Figure 2A**.

The second category occurs when a property of complexity in nature defies such prediction and cannot be found in a description of collective behavior. It is a failure of explanation called "strong/radical emergence" (sometimes "magical emergence"; e.g., see Rosen, 2012, p172). It occurs when a property is so completely unexpected and unpredicted that its presence seems magical and signifies that something is missing in our knowledge of the natural world (Baas, 1994; Bedau, 1997; Van Gulick, 2001; Corning, 2002; De Wolf and Holvoet, 2005; Chalmers, 2006; Clayton and Davies, 2006; Kim, 2006; Stepney et al., 2006; Hendry et al., 2019; O'Connor, 2020).

We now note that the transition from strong to weak emergence is a fundamental feature of the process that science experienced when deconstructing the natural biosphere into the layered descriptions shown in **Figure 2B**. In **Figure 2B** this process has been labeled as "reduction." Before the science was completed, every progression in scientific understanding started as a mystery: a question unanswered. Molecules were mysteriously related to atoms. Atoms were mysteriously emergent from what turned out to be their subatomic constituents. Higher up, we find the mystery of the strongly emergent flight of bumblebees, which turned out to be a weakly-emergent property of turbulence. The story of science is a multiplicity of singular moments of transition, in the vertical direction, from initially strongly emergent wholes that were eventually reduced to weakly emergent properties of sufficiently well-understood parts. In each case, it was scientific practitioners operating at a particular descriptive level in **Figure 2A** that curated the transition from strong to weak emergence in the day-to-day operation of science. It is the job of this section to clearly articulate, *via* C1, how the location of ABC-correlates of a 1PP does not transform the 1PP from strong to weak emergence.

The Ultra-Scale Origins of Excitable Cell Tissue-Level Electromagnetic Fields

To complete the picture of the EM field nature of brain tissue under C1, a comprehensive overview of the expression of the EM field basis of the familiar, dominant endogenous EM field system involved in brain tissue intercellular signaling has been included in **Supplementary Material A**. It describes how **Figure 2B** layer [M] excitable cell behavior (in our **Figure 2B** notional scientist's brain) expresses (literally is) a pair of unitary fields: an electric field **E** and a magnetic field **B**, each expressed with seven to eight orders of magnitude of structural resolution (from layer [M−2] atomic-dimensions up). These two fields, in static and dynamic forms, pervade all the space occupied by the brain, spilling out into the space around the organ layer [M+2]. The familiar endogenous EM field system of the brain originates in the nanometer-scale (sub-cellular) action of the membrane of neurons and glia. To comprehend C1, simply recognize that to place an atom in space is to place an EM field system in space. When an atom or molecule has an imbalance of charge it becomes an ionic net source of electric field system in space. In the formal sense of Maxwell's equations of electromagnetism, charges positioned in space become a source of electric charge density expressing electric field. Moving charges become a source of current density that introduces a dynamic magnetic field. Together these two systems of sources produce the dominant static and dynamic **E** field and a purely dynamic **B** field that inherit the **Figure 2B** tissue ultra-structure in their layout in space.

Further elaboration of the details of the EM field source system is included in **Supplementary Material A**. Everything needed to articulate the case for EM field as the ultimate origin of P-Consciousness exists in well-known cell biophysics interpreted from a fundamental physics perspective. Under C1, when ABC-correlate researchers at any **Figure 2A** level mentally step into the **Figure 2B** hierarchy, turn, and look down into the deep vertical structure, this is what ABC-correlates ultimately look like: a finely expressed collection of EM field activity impressed on space with an atomic-level resolution by excitable cells in the manner of **Supplementary Figure A.1**. It is posited here that "being" this EM field behavior delivers the 1PP, albeit for reasons not understood. As outlined in the section on the SMPP, this is a result of the tissue literally "being" an EM field system and the fact that there is nothing else to hold accountable for a 1PP. Until this possibility is empirically refuted, it is a reasonable basis for directing research into the 1PP.

The C1 convergence on EM fields and the **Supplementary Material A** depiction of the origins of EM in brain tissue reveal an anomaly in neuroscience practice. Neuroscience completely lacks the inorganic (*in silico*) replication of the (**Supplementary Material A**) kind of EM fields expressed by cell membrane. The creation of chip materials able to express EM fields structurally identical to those produced by neurons can be used to construct artificial neurons that replicate neuron signal processing through allowing the actual, natural EM fields to naturally interact in the manner they do in the brain, thereby replicating the same kind of signaling and signal processing (computation). This kind of *in silico* empirical approach is simply missing from the science. No instances of *in silico*-equivalent EM field replication can be found. Artificial neurons created this way could help in understanding EM field expression by excitable cell tissue. It would also facilitate a novel way to test hypotheses *in silico*. Neuroscience and physics, together, could embark on such a development. It would help us reveal the neural dynamics and signal processing that are unknowingly not captured by the familiar models that abstract-away EM fields and that currently dominate computational neuroscience. Note that the computational exploration of the EM fields (*via* Maxwell's equations) impressed on space by the novel chip would constitute the design phase of the chip. The design would be sent to a foundry to be built. What comes back from the foundry would express the EM fields themselves. The empirical method would be, to neuroscience, what the Wright Brothers' construction of flying craft did for artificial flight. Thirty years ago, we did not have chip foundries capable of brain-scale (∼5 nm feature size) EM field expression. Now it is routine. With a convergence on EM fields in the science of consciousness, it seems reasonable and apt to begin to explore the potential use of this technique.

C1 and Some ABC-Correlate Classes in the Modern Science of Consciousness

Loosely guided by the categories of theories found in the Stanford Encyclopedia of Philosophy entry "Consciousness" (Van Gulick, 2018, Section 9) and the Scholarpedia entry "Models of Consciousness" (Seth, 2007), the following six sections examine, under the C1 spotlight, six classes of ABC-correlate theories of consciousness roughly representing how they tend to be found grouped in the science literature.

As far as can be ascertained, and while the classes can be argued to overlap, the list is exhaustive. All ABC not explicitly mentioned seem to fit within one of them. "Active Inference" (Friston et al., 2017), for example, fits into the cognitive/computational class. The "Temporally Integrated Causality Landscape" (Winters, 2020) (TICL), for example, fits into the neurobiological class. And so forth. As an exercise for the reader, a recent major review included eight ABC (Northoff and Lamme, 2020) that might be used as an example. The "correct"

ABC-correlate is assumed to be somewhere in the six nominated classes. Exactly which ABC is "right" is moot to the analysis.

Finally, for completeness, we examine, again under the C1 spotlight, ABC = philosophical categorizations as recognized in the introduction. In practice these indirectly and variously map into the six nominated classes and are amenable to our treatment as ABC-correlates under C1.

ABC = Neural/Neurobiological Theories of Consciousness

In the first ABC of the modern era, Crick and Koch suggested that "*coherent semi-synchronous oscillations, probably in the 40–70 Hz range*" (gamma synchrony) in primary visual cortex were possibly responsible for aspects of visual experience (Crick and Koch, 1990). Primary visual cortex was later accepted as disproved as a contributor to visual experience generation (Weiskrantz, 1996; Lamme and Roelfsema, 2000; He and MacLeod, 2001; Jiang et al., 2007), but as stated above, this fact is not germane to this analysis. Also included in this ABC category would be the influential "Darwinian neuronal group selection" work of Gerald Edelman and colleagues (Edelman, 1987, 1989, 1992; Edelman and Tononi, 2000).

There are many other interesting contributions in this neurobiological class, too many to list here. Fundamentally, they all distill down to the same approach. Each is an attempt to hold specific neural organization, and its activity, as the originating correlate of some aspect of P-Consciousness. In the process of describing the neurobiological basis, the physics substrate – the EM basis of the tissue – is abstracted away. The C1 perspective tells us, however, that no matter how elaborate the description, or which aspects of the brain are described, or at what descriptive level (cell, cell ensemble, brain region), all are actually implemented as EM phenomena of the **Supplementary Material A** kind. Posed in this way, their contribution is an implicit enrollment in a form of strong emergence. They lack any principled reason why a 1st-person perspective necessarily inheres in the described tissue behavior and not somewhere else. Such neurobiological accounts of P-Consciousness will, however, get their ultimate connection to P-Consciousness through the EM field system's delivery of P-Consciousness. This is what C1 tells us about this class of ABC: that the origin of an explanation of a 1PP for the entire class entails the single task of explaining how EM fields deliver the 1PP.

ABC = Cognitive/Computational Theories of Consciousness

Cognitive/computational accounts of consciousness involve abstractions (again, the abstracting-away of the EM basis) of brain function that are neuroscience-inspired to an extent determined by the researchers. Cognitive accounts tend to be associated with empirical investigation of function with a focus on a wide range of domains including memory, attention, sensory modalities, motor/actuation systems, language, and so forth. These are applied to a descriptive account of development, learning, intelligence, planning, mood, prioritizing, goal setting, habit establishment, novelty handling, amongst many others. These processes tend to be expressed in information processing terms (McGovern and Baars, 2007).

In approaching P-Consciousness, influential ABC in this class are the "Global Workspace Theory" (GWT) by Baars (1988, 1997) and "Global Neuronal Workspace Theory" (GNW) primarily developed by Dehaene and Changeux (2011); Dehaene (2014), and Mashour et al. (2020). In GWT and GNW, integrated and unified activity of brain regions (such as multiple sensory modalities) is said to "be conscious." Dehaene and colleagues' "signatures of consciousness" include high-frequency neural firing synchronization across distant brain regions. Under C1 we can now see that however a "global workspace" might be imagined, the brain implements it as a single unified (global) dynamic EM field system impressed on space. The term "global workspace" is a human abstraction of something comprised of EM fields.

The cognitive approach's contact with P-Consciousness can be understood in a more general sense in appreciation of the ABC "computation" (generally thought of as "information processing"). When the signal processing or information processing of the brain (such as a "global workspace") is regarded as computation, it reveals an unusual relationship between nature and models of nature that only exists in brains. Once a particular aspect of the brain's signal processing is recognized as significant and mentally excised from the tissue for scientific description, the information transformations going on in the abstract model are identical to the information transformations apparently going on in the brain. This relationship between a model and nature is unique to neuroscience. Contrast this with, for example, the "information processing" that is going on in a kidney that results in purified blood. In fire (combustion), it results in heat. These phenomena are not abstract models of something. In the brain, this identity between a model of nature and the modeled nature would indicate that everything the brain does is done by the model. This uniqueness has been pivotal in the impact that computing has had in understanding the brain.

In practice, researchers implement these abstract models on general-purpose (stored-program) computers [digital/von Neumann (Aspray, 1990) or analog/neuromorphic (Schuman et al., 2017)] where there is no fixed relationship between the EM physics of the brain and the EM physics of the general-purpose (GP–) computer. This fact must be remembered when trying to construe any contact between the 1PP resulting from "being" a GP-computer and the 1PP resulting from "being" a brain. If it is held that the GP-computer has a 1PP, then the practitioners have disposed of the specific EM organization of the brain, replaced it with the EM organization of a GP-computer, and enrolled themselves in the same kind of strong emergence discussed above. The implicit claim is that "computation" causes the emergence of the 1PP associated with the original tissue being modeled, but in a way that is not evident in the model. If this approach is not acceptable, then one could abstract out the associated functional role of consciousness into the model. Then the new model might have the 1PP of the modeled nature. Again, the relationship with the origins of the 1PP is strong emergence. No necessary relationship between a 1PP and the

EM physics of the GP-computer/model combination is provided by this approach.

The key to understanding this approach's critical weakness is in the above step "*mentally excised from the tissue.*" At that excision moment, the particular EM field organization of the brain is lost, and that specific loss involves everything that the excised model failed to capture. The way to see this loss more clearly is to ask: "*What is the thing analogous to blood filtration and heat in the above examples that may be lost in the 'mental excising'?*" What goes missing? How would we know it was missing and justify it? If the original EM included delivery of all the information processing content associated with delivery of a component of a 1PP, then that information is gone and its functional role in the natural process goes with it. That is the loss associated with the novel explanandum that is the 1PP. It is lost in an apparently benign act of mental excision that until now was all there is in neuroscience practice. This is what the ABC = cognitive/computational correlates of P-Consciousness look like under the C1 spotlight: the very thing abstracted away (EM fields organized in the manner of a brain), is the thing delivering (however mysteriously) the 1PP. The practitioners involved cannot claim that nothing is lost in the "abstracting-away" of the EM basis of the tissue. To scientifically examine what is lost is to experimentally retain the natural EM physics for comparison/contrast with the "abstracted-away" version. Successful measurement of the properties predicted by a model does not prove that there are no other important tissue properties at work, where tissue and model may part company in important, interesting ways.

ABC = Higher-Order Theories of Consciousness

These ABC are often referred to as metacognition and could possibly be included above in the cognitive/computational class (Rosenthal and Weisberg, 2008; Carruthers, 2018; Van Gulick, 2018; Brown et al., 2019). Where P-Consciousness is an explanandum, these ABC theories focus on an account of the origins of P-Consciousness being exhausted (in terms of necessity and sufficiency) by considerations such as:

(i) The existence of a "self."
(ii) Agency that "knows that it knows."
(iii) Representation.
(iv) "Narrative assemblies" of (i)…(iii).

This class of ABC simply holds that these attributes of cognition are the specific properties necessary and sufficient for P-Consciousness to arise. Just as in Information Integration Theory (IIT) (see below), there is substrate-independence in the sense that P-Consciousness emerges in anything (say X) that can be scientifically decomposed into classes (i)-(iv). Substrate independence is challenged by C1. This is because these high-level characteristics, in the end, are also physically delivered by the brain's EM field-based signaling system that physically implements any/all of (i)-(iv). As already stated here, the human brain, clearly an instance of (i)-(iv) based on EM fields, is the only known originator of P-Consciousness. Once again, in these higher-order approaches, the EM field basis of the actual implementation of (i)…(iv) is abstracted away. This is the sense in which C1 involves itself in this class of theory. They, too, become EM field theories and again engage, in connection to a 1st-person perspective, the explanatory failure that is strong emergence.

ABC = "Fundamental" Theories of Consciousness

Some ABC claim to be fundamental in some way, but not in the sense of the standard model of particle physics. This class of ABC-theory of consciousness variously involves new posited characteristics of the underlying structure of the fabric of reality, the usual province of physics, not neuroscience. An early pioneer is Benjamin Libet's putative "conscious mental field" or "cerebral mental field" (CMF) that "*would not be in any category of known physical fields, such as electromagnetic, gravitational, etc.*" (Libet, 1994, 2006). In pursuit of an explanation of P-Consciousness, Libet, in effect, is implicitly calling for a revision to the standard model of particle physics.

As the science has unfolded, a single, dominant and promising theory of this kind has emerged. It is the "Information Integration Theory (IIT) of Consciousness" by Tononi (2004, 2008), Balduzzi and Tononi (2008); Oizumi et al. (2014), and Tononi et al. (2016). IIT claims that it is the integration of information measured statistically, in terms of mutual information content, that form the necessary and sufficient conditions originating P-Consciousness. IIT proposes that the information content of the system as a whole — over and above the information content of its parts — originates P-Consciousness. In IIT, an undefined microscopic proto-conscious information "mote" is assumed. When this unspecified proto-element is aggregated in the IIT manner, a subject made of the aggregate is claimed to have P-Consciousness of a kind and degree prescribed by the details of the IIT formalisms.

IIT also holds that the physical substrate is irrelevant. From a C1 perspective, this position is rather hard to understand, because C1 tells us there is only one substrate that we know delivers P-Consciousness: EM fields organized in the form of a brain made of atoms. In the formulation of IIT the fundamental EM basis of the brain, the only place known to originate P-Consciousness, is apparently abstracted away. If IIT is claiming it is independent of **Supplementary Material A** brain EM (atoms), then exactly what other substrate is IIT referring to, and how does it relate to the "information mote" described above? Additionally, nowhere in IIT is there any justified/proved connection, except axiomatically by premise, to why "being" integrated information delivers P-Consciousness and what the fundamental proto-information element might be. A recent variant of IIT suggests that "causal power" is identical to P-Consciousness (Koch, 2019). The primary origin of causation in the brain is that which inheres in its fundamental EM field basis: the Lorentz force (**Supplementary Material A**). The Lorentz force (EM in general) lacks all specification of "what it is like to be the Lorentz force." There has, more recently, been some success using EM field measurements to quantify and explore the integrated information content (measured level of P-Consciousness) of the vast and real fundamental EM field system of the brain impressed on space as per **Supplementary Material A** (Koch, 2019; Seth and Bayne, 2022). How can IIT use EM as empirical evidence (thereby proving EM delivers the 1PP) while, in effect, denying that it is EM that is actually delivering the 1PP? Exactly how does the IIT "information mote" fit into the SMPP in a way that makes sense of this?

For the purposes of this analysis, this kind of "fundamental" ABC also fails as an explanation. Once again, we are left with strong-emergence. IIT, however, fails in a revealing way. IIT implicitly denies C1 (the fact that EM fields deliver the 1PP), replacing it with organizations of an "information mote" that is axiomatically (by fiat) charged with the responsibility for the 1PP. It is in reconciling IIT's relationship with the (also fundamental) EM field class, that reveals unity in the structure of the science that is the subject of detailed discussion in Part II. Note that presaging this unification are the first explicit encounters between IIT and fundamental physics (specifically EM) (Barrett, 2014; McFadden, 2020).

ABC = Quantum-Mechanical Theories of Consciousness

The following two broad categories of QM phenomena form the basis of a potential account of P-Consciousness (Atmanspacher, 2020). First, the "atom" level in the **Figure 2B** structural hierarchy is stabilized by the interacting (coherent) EM fields expressed by nuclei and electrons being quantized according to QM constraints. Quantized EM field systems produced by the charge content in atoms and molecules are still just EM fields. Down deep in the **Figure 2B** hierarchy, EM fields themselves are a quantum phenomenon [virtual photon exchange (Jackson, 1999)]. Quantum phenomena are built into the processes of forming molecules from atoms and vice versa. Chemical reactions of all kinds (including enzyme, second-messenger, ligand docking, and ion channel conformation dynamics) are non-equilibrium quantum EM events. "Chemical potentials" are simply electrical potentials within EM field phenomena expressed by atoms and molecules. Heat (thermal radiation) and ultraweak biophotons are also EM field phenomena, again products of QM processes intrinsic to the atomic basis of brains.

Therefore, QM is already built into the substrate (at the **Figure 2B** [M–3] atomic level) of any EM field treatment of the common matter of our biosphere, prior to any considerations of brain material. It is, therefore, logically entailed that whatever EM fields contribute to an account of P-Consciousness in brains automatically incorporates any QM-constrained affinities operating horizontally, and inherited structural constraints/properties operating vertically within the deep hierarchical structure of **Figure 2B**.

Second, there is a significant history of attempts at a quantum account of P-Consciousness through attribution to exotic quantum effects within brain structure and activity. "Fröhlich Condensates" and quantum coherences in neuron microtubules are prominent examples of this kind of approach (Fröhlich, 1968, 1970, 1975, 1986; Marcer and Hameroff, 1998; Hameroff and Penrose, 2014). The historical critique leveled at exotic QM accounts of consciousness is that the brain's high temperature thermodynamics prevents the persistent spatiotemporal coherence (spatial size, intensity, and duration) needed to enable functional relevance (Tegmark, 2000). This critique has not survived. Recent work by various scholars posits strong examples of "warm and wet" quantum coherence in biology, and its involvement in brain tissue can now be taken seriously (Lambert et al., 2013; McFadden and Al-Khalili, 2018). If specialized quantum coherence does happen in the brain (such as the subcellular-level/microtubule exotic QM proposed by Hameroff and Penrose, 2014), it would insert a localized horizontal organizational layer in the EM hierarchy of **Figure 2B** at the tissue (M+1) level.

Broadly speaking, in either of these two categories of QM, wave functions constrain EM fields. QM-constrained EM fields are, however, still EM fields. Note that a proven absence of QM-constrained coherence in EM fields at the functional level in excitable cell tissue does not exclude the possibility that classically constrained coherence in EM fields operates at the same functional level. Macroscopic coherence through intermittent EM field resonances could therefore originate P-Consciousness merely through the quantum mechanics that already pervades the **Figure 2B** hierarchy. Either way, it is again supra-atomic EM fields that proximately deliver P-Consciousness and its dynamics.

Under the C1 spotlight, we can now see that *quantum mechanics is actually part of an EM field theory of P-Consciousness*, but the atomic-level EM basis of QM propositions tends to be lost in the process of explication of the QM details.

Note that an ABC theory of P-Consciousness that extends its attribution of P-Consciousness origins to properties of the subatomic layers (including the other three quadrants of the standard model) does not invalidate the EM basis of P-Consciousness. It is the EM fields that carry forward the subatomic level activity/properties to the higher levels in the **Figure 2B** nested containment hierarchy. This is a consequence of the natural containment hierarchy's reframing of P-Consciousness as a product of the (EM) unity of the entire hierarchy.

ABC = Electromagnetic Field Theories of Consciousness

Electromagnetic field theories of P-Consciousness have their own long history but tend to present sparsely and rest in relative obscurity. For example, a recent major review focused on eight ABC while not mentioning EM fields as a basis for consciousness, even though it is represented within the eight (Northoff and Lamme, 2020). Another recent major review covered four classes and thirteen individual ABC also completely lacked attention to EM fields as a basis for consciousness (Doerig et al., 2020). As this article goes to press a new review article has been published listing 22 theories of consciousness, including the EM field theory of consciousness. This evidences a small improvement in the visibility of the EM account of consciousness (Seth and Bayne, 2022). The abstracting-away of the EM basis of the brain (physics-shyness within neuroscience) is a common factor that is the most likely explanation of the observed relative obscurity. Modern-era pioneers of EM field theories start with Sue Pockett in the 1990s (Pockett, 2000). This was followed early in the century by McFadden (2002a; 2002b; 2006; 2007; 2013; 2020). Later, we have a contribution by (Fingelkurts et al., 2013). For reviews, including the early history and its pioneers, see Jones (2013, 2017) and Pockett (2013).

A recent example is the General Resonance Theory (GRT) of consciousness (Hunt and Schooler, 2019), which offers a general theory that encompasses mammalian/vertebrate consciousness and any other species of consciousness, whether that consciousness is based on EM fields or any other kind of field. GRT focuses on the Oscillatory Correlates of Consciousness (OCC), where the particular "oscillations" most relevant to P-Consciousness are those arising from the brain's endogenous EM field system as described in **Supplementary Material A**.

The abovementioned EM account offered by JohnJoe McFadden is the wave-mechanical approach in his "Conscious Electromagnetic Information" (CEMI) field theory (McFadden, 2002a,b, 2006, 2007, 2013, 2020). "*I therefore examine the proposition that the brain's EM field is consciousness and that information held in distributed neurons is integrated into a single conscious EM field: the CEMI field*" (McFadden, 2002a). In essence, it is the information content of the wave-mechanical behavior within the spatial structure of the brain's endogenous EM field that is claimed to deliver P-Consciousness.

The abovementioned (Fingelkurts et al., 2013) is a result of earlier developments that ultimately became "Operational Architectonics" (OA). It specifically describes P-Consciousness as arising in the complexity of a system of nested EM fields of the kind described in the section on containment hierarchy and in **Supplementary Material A**.

Paradoxically, C1 tells us that the EM class of theory also fails to explain the 1PP and leaves us with an explanatory gap. EM fields do not come pre-packaged (within the existing standard model) with an explicit, principled scientific account of "what it is like to be EM fields". Because of this, EM fields formally fail to explain P-Consciousness. Therefore, at first blush, the various EM accounts also relate to P-Consciousness in the strongly emergent manner of any other ABC. However, EM fields are fundamental, and for this reason, they inherit a way forward in fundamental physics tackled later in Part II.

ABC and Philosophy in the Explanation of P-Consciousness

At this moment in its relatively nascent development as a physical science, philosophical analysis can still sometimes form a part of a scientific approach to explaining P-Consciousness. There is one significant form of this in play at the moment: panpsychism (Skrbina, 2007; Chalmers, 2016; Goff et al., 2018). It offers an interim way to deal with the refractory lack of ultimate explanation of P-Consciousness in any ABC-correlate. Panpsychism operates as an approach of the "fundamental" class, where a novel field or particle or similar elemental component/property of a 1PP (akin to charge or spin) is considered built into the underlying fabric of the universe in some way. In effect, the unspecified property panpsychism invokes is something extra, invisibly inherited and accreting along the **Figure 2B** vertical EM field hierarchy.

Like fundamental ABC, this approach implicitly invokes a connection to a missing or incomplete part of the standard model of particle physics. It can be used in combination with an ABC to notionally complete its contact with a full explanation of P-Consciousness, thereby avoiding strong emergence. Used like this, panpsychism acts as a placeholder that does the job of recognizing that explanation is missing without requiring immediate attention to the lack of a scientific law of nature (*within* the standard model) that defines what the superadded fundamental element is and how it functions. This is how GRT and IIT connect to their conception of P-Consciousness, thereby explaining it *via* the normal weak emergence within a *future* standard model (although neither speak of it in standard model terms). In this way, panpsychism operates as an explanation-in-waiting for a later upgrade to the standard model that scientifically solves the hard problem. Such a potential future upgrade is outlined below in Part II.

The above analysis of panpsychism is likely to be typical of the many philosophical treatments of subjectivity. That is, under C1, the philosophical ABC also fail/succeed as a form of correlate, although in nuanced ways (as exemplified for panpsychism) that are best left to philosophers to properly calibrate. Note that EM field theories of consciousness have no obvious philosophical category umbrella that we can cite with any authority, and if we were able to do so, it would not alter any of the outcomes of this article. Like all ABC, the philosophical ABC will also get their ultimate contact with explanation through the physics/neuroscience collaboration focused on EM fields.

ABC Classes and C1: Conclusion

A few salient features of the analysis are:

- Both the ABC = QM class and the ABC = EM class are fundamental in the sense of the existing standard model of particle physics.
- The fundamental class IIT is fundamental in the sense that it addresses the fabric of reality, but outside the existing standard model.
- The ABC = QM class is revealed as an EM field theory and should be considered inside the EM class.

Overall, the analysis depicts how each class connects to the explanatory failure mode of "strong emergence" in a slightly different way that the C1/EM field approach has the potential to redress. *However, the EM field class of ABC fails in the same way*. That is, P-Consciousness arises for reasons that are not delivered by merely nominating "EM fields behaving ABC-ly." The EM field basis of the 1PP, proved under C1, does not transform any ABC into explanation of the 1PP. C1 merely locates where the solution is to be found. In effect, we are left with two fundamental classes, IIT and EM, both failing to deliver real explanation in the manner described. However, because they are "fundamental," they have a potential route to explanation afforded by their fundamental physics status. That potential is to be explored in Part II.

Concluding the Case for C1

The hierarchical view tells us that the familiar complex endogenous EM field system of the brain is not a side effect produced by excitable cells made of something else. The entire thing *is* electromagnetic fields, from the atomic level up (impressed on space with atomic level resolution). What we normally encounter in excitable cell tissue is merely the final, net observable expression (in an EM field signal-to-noise sense) of a natural system entirely comprised of nested (**Figure 2B**) EM phenomena organized in **Supplementary Material A** form.

A neuron is a collection of EM fields "behaving neuron-ly" to an observer made of EM fields. Terms like "chemical," "chemical reaction," "chemical pathway," "electricity," "electro-chemical," "chemical potential," "action potential," "electrical/chemical synapse," "Nernst potential" and many other recognizable terms used to distinguish cellular processes and properties, are not pointing to anything other than an EM field system behaving in a certain way. "Electrical current" is a transit of an EM field system through space. That transiting EM field system (magnetic and electric) is impressed on space by the transiting charge source. The EM basis of the tissue applies deep down into the substructure of atoms, where quantum mechanics is merely a set of (wave-equation-based) quantizing constraints on EM field expression. This is the kind of readjustment that is necessitated when drawing a connection between EM fields and P-Consciousness. Which of the many candidates is the "ABC" activity that originates the 1PP? Whatever it is, the ABC's ultimate contact with explanation of a 1PP inheres in the EM basis of all ABC because an ABC is actually a descriptor delineating particular aspects of an EM field system. It does not matter if the ABC involves descriptions of information content, information processing, signal processing, energy transformations, networking, anatomical details, causality, entropy, function, or anything else. The descriptive scale (subcellular/atomic, cell, cell ensemble or cell population) of an ABC does not matter. No matter how elaborate or technically abstract the ABC, it is physically implemented as an EM field system of the kind exemplified in **Supplementary Material A**.

As a result, and however mysterious it is to us, a hierarchy of the fundamental physics of electromagnetism based on atoms somehow defines the context of the human brain's origination of both its outward (3rd-person-perspective or 3PP) observable behavior and its 1st-person perspective (1PP). Under C1 we can now see that to explain P-Consciousness involves more than merely specifying an ABC. It also involves an additional account of how "being" electromagnetism delivers a 1PP. This is because EM field is literally what we are made of. With our current understanding of weak/strong emergence, it is our ultimate task here to curate the circumstances under which the 1PP may ultimately become a weakly emergent (predictable) property of a future, deeper understanding of EM field activity.

Even without an explanation of how EM fields originate the 1PP, an EM field account of P-Consciousness is intrinsically advantaged and has much to commend it. This occurs merely because of the well-understood properties of EM fields and their fundamental physics status. Under the C1 dialogue we have seen that it is (for reasons not provided yet) EM fields, configured in ABC form, that actually deliver the computation/signal processing/information flow behind cognition while simultaneously delivering P-Consciousness, but only when the EM fields are configured in the special ABC way (whatever that turns out to be). This easily explains how unconscious brain signaling processes can arise that are also entirely made of EM. In unconscious brain process, the normal signaling (also made of EM) continues to act in the familiar adaptive manner but lacks a contribution to the 1PP because it does not incorporate the extra specific EM structure/dynamics of the necessary ABC kind. It has also been shown how EM has intrinsic natural solutions to the unity, binding, grounding and combination problems while providing for P-Consciousness to involve itself in the causality inherent in the fundamental physics of the brain (see **Supplementary Material A** and the Lorentz force as well as Kitchener and Hales, 2022). An EM perspective also naturally handles time. Contents of consciousness can enter and exit P-Consciousness (addition and removal of a particular vectorial contribution to the EM field system) with a variable spatial/temporal granularity and at the rate of the field system dynamics, with the observed levels of continuity/discontinuity, and with the subtle experiential "flavor" of the passage of time (Kent and Wittmann, 2021). Under C1 we have also seen that from a measurement and control perspective, neuroscience has tacitly been enrolled in an EM account of P-Consciousness all along. All the evidence collected in the science of any ABC is also acting in direct support of an EM field theory. These are the advantages all ABC inherit through C1 and the relocation of the science of P-Consciousness into the fundamental physics of the existing standard model.

Part I Final Result: Summary

This section compiles the first of two overall results from this article that form the basis of our "electromagnetic turn" in the science of consciousness:

1. Through C1, we now understand how 30 years of ABC-correlates science has delivered an enormous body of evidence that the standard model's EM quadrant delivers the 1PP (by means not specified). All correlates of consciousness are actually electromagnetic correlates.
2. The science undergoes a shift in emphasis involving a convergence (for everyone involved) on EM fields as the ultimate origin of the 1PP. EM fields are moved to center-stage in the science of consciousness.
3. The science is formally connected with fundamental physics. This is because (i) EM fields are a quadrant in the standard model and (ii) EM fields, through the nested hierarchy shown in **Figure 2B**, literally connect fundamental physics directly to a neuroscience context, spanning the entire interdisciplinary gap. The future therefore necessarily involves a close collaboration between physics and neuroscience. This connection is highlighted by the **Figure 2A** line C. It is a transdisciplinary connection consistent with the unification of the brain in the nested EM field hierarchy shown in **Figure 2B**. The responsibility for science's account of P-Consciousness is to be shared.
4. One of, or a combination of, the many existing ABC will be right (the "right correlate"). Nothing in what has been delivered here denies that. What is denied by C1 in the above analysis (in the unique, unprecedented context of the 1PP as an explanandum), is that delivery of the "right" ABC-correlate also delivers explanation. This is the explanatory (strong emergence) cul-de-sac identified in the introduction: in the absence of prior knowledge of

the underlying mechanism of a 1PP, the low likelihood of empirically proving that the "right" ABC has been found.

5. The use of the empirical results arising in the use of the above, *in silico* generation of the brain's EM signaling physics, is also flagged as a potential activity for the new neuroscience/physics collaboration.

These five changes provide a solid basis for the science to progress into its fourth decade and beyond. However, we must also recognize that the changes to the conduct of the science are posed while being fully cognizant that none of them deliver the reasons why/how EM fields have, within them, the potential for a 1PP and what specialized form EM fields necessarily take when delivering it. Having used the standard model to arrive at this point, we must also encounter the paradoxical fact that there is nothing in the standard model's EM quadrant that specifies "what it is like to be EM fields." We can take some solace in the knowledge that we have focused the ultimate source of the problem (lack of explanation) to one location in fundamental physics. Dealing with the lack of explanation is the subject of the next section.

PART II: A SPECULATED ROUTE TO EXPLANATION FOR THE SCIENCE OF P-CONSCIOUSNESS

The Part I result stands on its own as a way forward. We could have stopped there. It involved a reframing of perspective that shifted the explanation of the origins of the 1PP to a single place in fundamental physics: Electromagnetism. That is, the "where to look" part of explaining P-Consciousness is solved. What is not solved is how EM can be re-examined/reframed in a way that somehow reveals "what it is like to be" EM fields. This is the moment when the real challenge is laid bare: the uniqueness of the explanandum. How do we introduce, into science, a way of dealing with the 1PP? We can proceed with one key new bit of knowledge: that a way of introducing a novel explanandum exists in the 1PP of electromagnetic fields. Neuroscience has proved EM fields can create a 1PP. It is now up to us to explore how an explanation of the 1PP of EM fields can be approached. In what follows, the most important factor is *that there appears to be at least one way ahead*. It is not fully articulated and is posed as a tentative exploration. It is in this possibility that we hope that we can escape the "strong emergence cul-de-sac." The challenge is in the realization that the shift in thinking is a shift in how we organize *ourselves* as scientists. It is a "discovery" about the operation of science itself. It should not be surprising that a new kind of scientific explanandum necessitates some kind of reframing or expansion of our options for scientific behavior. The 30 years of the modern form of the neuroscience of consciousness give us the latitude to explore this possibility so that a discussion can be taken up, forming a nucleus of activity for the neuroscience/physics collaboration to come.

We start by reaffirming what was found in Part I: the proved EM field basis of the 1PP does not transform any ABC into explanation of the 1PP. C1 merely locates where the solution is to be found. Here in Part II, we move forward by recognizing that explanation involves a separate fundamental physics account, of an as yet unknown kind, of how EM fields deliver a 1PP, thereby adding explanation (underlying or bottom–up mechanism) to the science of P-Consciousness, potentially transforming the strong emergence to weak emergence, normalizing the science of subjectivity in the sense of the section on weak/strong emergence. The following discussion does not "solve the hard problem." It merely locates a suggested departure point of a trajectory that offers the best hope of it. It delivers, in fundamental physics terms, the origin of a potential account of the 1PP that clearly somehow inheres in EM fields. In doing so, and because of C1, all ABC-correlates theories benefit equally, and the "right" ABC correlate can, in the end, be empirically confirmed conclusively. The remarkable aspect of what follows is that it naturally merges IIT (Integrated Information Theory) into the EM class, locating them both in fundamental physics, *but in a revised standard model* that procedurally offers a route to finding the missing explanation of *why/how* EM field, configured in the form of the "right" ABC, delivers the 1PP.

The starting point is the consequence of C1 found in Part I summary result 1: that the 30 years of work on ABC-correlates has, in effect, delivered a vast body of evidence that the **Figure 1** SMPP's EM quadrant can and does deliver a 1PP to human brains. This creates a direct encounter with a deep anomaly: the current form of the SMPP lacks any account of the 1PP (subjectivity) of any member of its four quadrants in any context. "*What is it like to be an EM field?*" has no answer. Likewise, the possibly irrelevant but nevertheless possible question "*What is it like to be a neutrino?*" has no answer. Yet neuroscience tells us that the SMPP's EM quadrant delivers a 1PP. This anomaly is demonstrating the incompleteness of the SMPP as an explanatory instrument. This is the doorway to a way ahead, just as anomalous scientific evidence has been so many times in science (Kuhn and Hacking, 2012). Clearly the SMPP is missing whatever kind of scientific account of nature is needed to explain the 1PP proven to be delivered by one of its quadrants.

Remember that our natural nested containment hierarchy approach has already revealed the generalized "1PP-voicelessness" that currently pervades the whole of science. The 1PP-voicelessness results from the presupposition of the 1PP in the form of the scientific observer that accessed and provided all the evidence that validates laws of nature of the kind currently produced by science. Scientific behavior's generalized critical dependence on the 1PP for its evidence source, in effect, means that scientific behavior, as it is currently configured, can scientifically describe, and in some sense explain, everything in the universe except the 1PP (the scientific observer) it presupposes. If scientific behavior is regarded as a completed or somehow fixed behavior (no justification for this has been found in the literature, it is simply presupposed), then this situation could be regarded as "game over" for a scientific account of the 1PP. But now we have new evidence – the SMPP anomaly – that we can examine with a view to potentially overcoming this limitation. The approach explored here is that scientific behavior itself is incomplete and is in need of revision in some sense.

Before we tackle the SMPP anomaly, we need to better understand the "critical dependence" of scientific behavior on the 1PP. It is something that tends to be invisible in science. Understanding it properly is part of the key to understanding how, for example, the SMPP can be expanded to accommodate the explanation of the 1PP currently lacking in it. As already noted in Part I, in seeking the goal of the science of consciousness, the science of the 1PP is implicitly and ultimately being used to explain the nature of the acquisition of any/all "objective" scientific evidence, by *any* scientific observer. In the current 3rd-person-perspective (3PP or "objectively evidenced") mode of the operation of science, at the end of the evidence trail in every finished act of scientific measurement, we scientists *demand* that the contents of the consciousness of a scientific observer (say, S), during an encounter with the measurements themselves or their representational proxy, becomes a formal part of the evidence inference trail that empirically proves every 3PP law of nature (such as F = mA or the existing SMPP, for example). This final step of passing measurements through the 1PP of scientific observer S is or completes an act of "scientific observation" by S. Without the involvement of that final stage of evidence acquisition, involving the natural causality that somehow originates the 1PP within the brain of the observing scientist S, applied to the chain of evidence, scientist S cannot claim to have "objective evidence" in support of any 3PP hypothesis. Counterevidence, also delivered *via* the 1PP of the scientific observer S, is similarly demanded to refute or modify 3PP laws of nature. We scientists insist that such "contents of consciousness" be experienced, documented and *repeatable* by other scientists (the contents of the 1PP of different and various S) on pain of having our scientific claims rejected in critical argument through lack of scientific evidence. Put another way, if it weren't for the 1PP (subjectivity) of the scientific observer S, there would be no "objectivity." Put yet another way, the apparently objectively evidenced 3PP laws of nature are actually predicting how nature shall appear in the 1PP of a presupposed scientific observer. Moreover, without the 1PP of scientist S, creating 3PP laws of nature would be a meaningless concept because there would be no (scientific) observer to experience, as contents of the 1PP, the predicted observable consequences of a studied/hypothesized natural regularity.

This critical dependency of 3PP laws of nature on the observer's 1PP is, at a surface level, at odds with our sense of the "observer independence" that objectivity is supposed to bring to the process of creating 3PP laws of nature. What we call disciplined "objectivity" clearly and successfully works to render 3PP laws of nature independent of the 1PP of any *specific* human scientific observer S. However, the achieved "specific-human-scientific-observer-independence" cannot be used to claim the 3PP laws are independent of (invariant to) the specific physics of the generation of the human 1PP itself. This is not the first time this has been noted (Rosen, 1993)[1]. In being required to coerce nature's regularities into a form suited to engagement with the 1PP of a scientist, the 1PP itself, however benignly, is imprinted on the observed nature. The 1PP is, in this way, implicitly built into all 3PP laws of nature.

Now consider what happens when the familiar "objective" 3PP evidence process, with its demonstrated critical dependency on the 1PP, is applied to construct a science of the 1PP itself: the science of P-Consciousness. In that context the science of P-Consciousness, with its unprecedented and unique explanandum, the 1PP, operates at a scientific evidence "boundary condition" – the explanation of the scientific observer that no other science inhabits and in which it is not the contents of the 1PP that are being explained, but the very existence and nature of the 1PP itself.

This is the constellation of unique circumstances that surround the critical dependency that our system of establishing 3PP laws of nature has on the 1PP of its presupposed and consequently unexplainable scientific observer. With this understanding of the critical dependency in hand, we now return to the anomaly identified earlier when the 1PP-voicelessness of the SMPP confronts powerful evidence from neuroscience that the SMPP's EM quadrant does indeed deliver the 1PP.

The strong anomaly, visible only across the **Figure 2A** extent of line C in the context of C1 within the science of P-Consciousness, spanning the physical sciences into the fundamental physics of the EM quadrant of the SMPP, gives physicists, under the guidance/empirical support of neuroscience, license to explore whatever kind of novel abstract description of nature has the potential to reveal the origins of the subjectivity that is empirically proved (by neuroscience) to inhere in EM fields. Let us first designate as (i) the familiar 3PP class of scientific "laws of the appearance of nature" (such as those that form the existing SMPP). Our physics/neuroscience collaboration, inspired by the anomaly, can now set about creating a novel kind of abstract description of nature, say type (ii), that somehow *does* explain the 1PP. Clearly these new (ii) laws of nature *cannot presuppose the scientific observer* in the manner of the existing (i) 3PP laws. Instead, the (ii) descriptions must somehow assist in *predicting* the scientific observer and in the process explain the origins of the 1PP that creates the possibility of (i) 3PP laws of nature. This basic idea is the main contribution of Part II. Notice that this change presents as a change in ourselves as scientists. The options for scientific behavior have been expanded to allow a new, categorically distinct, kind of abstract scientific description of nature. Laws of nature of an as yet unspecified kind (ii).

What is it that the new set (ii) of abstractions of nature are describing? The manner of the failure of the existing SMPP to predict the 1PP gives us the main clue. The failure presents as proof of a stark difference between (i) what the universe *appears* to be made of, and what the universe is *actually* made of. The SMPP anomaly tells us these two things cannot be the same. This is highly suggestive that the new (ii) descriptions must somehow depict laws of the underlying structural fabric of the universe in a way that is very different to (i) but yet is consistent with and ultimately somehow predictive of how it appears in (i). The difference between (i) and (ii) descriptions, and their simultaneous mutual consistency in describing the same natural world in two different ways [(i) appearance and (ii) underlying

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[1] Observer independence is not always achieved. Quantum mechanics has shown us this is not always possible, as the Rosen article details.

structure], offers a route to understanding the mechanism that creates the 1PP of the scientific observer presupposed by (i).

We can use the SMPP as a vehicle to bring this bifurcation of the abstract products of scientific behavior into a more practical light. The current SMPP is a product of the current confinement to (i) 3PP laws of nature. Our proposition is that the standard model's scope of scientific deliverables, and the scientific behavior that produces them, is to be expanded to include (ii). We now know that EM field, as depicted by the particular (i) 3PP "laws of appearances" in the SMPP's EM quadrant, is merely a (i) appearance of something behaving EM-field-ly to a scientific observer apparently, but not actually, made of EM fields. Instead, the scientific observer is made of something else. What is this building block of the underlying fabric of reality described by (ii)? At this point we must be mindful that the full elucidation of the (ii) new kind of descriptions of nature is well outside the scope of this article. This is a job for a physics-neuroscience collaboration. What we can do here is make a few general observations about descriptions (i) and (ii) before we sign off.

To help tease out the difference between (i) "appearance" descriptions (what the universe, say, U, appears to be made of, such as "space," "atoms" or "EM fields") and (ii) "underlying structure" descriptions (what the universe U is actually made of), let us assume that (ii) involves abstractions describing a universe made of a large collection of a single kind of primitive structural element, say X. This "X" could be perhaps regarded as an "event" or "information mote" or "energy quantum" or all these simultaneously. Its true identity is not our job to specify here. We do this to emphasize the point that under the proposed upgraded standard model's science framework, the scientific observer inhabiting the **Figure 2B** hierarchy at layer [M+3], is *actually made of X*. Indeed, the entire **Figure 2B** hierarchy is actually made of X. What the hierarchy *appears* to be made of, to a scientific observer made of X and located within the hierarchy, is EM fields emerging from the depths of the nested containment hierarchy depicted in **Figure 2B**. That is, the **Figure 2B** hierarchy is merely how the hierarchy appears to an observer embedded in, and part of, a hierarchy actually made of X. It is the web of causal relations between instances of X that literally creates the hierarchy. It is in the underlying structure of a web of causal relations between X in the context of their literal creation of what we see as EM fields operating in a brain context, that we can find the origins of the 1PP. The upgrade to the operational structure for science, driven by a need to explain the origins of the 1PP, is instead leading us to the origins of causality in nature that have been mysterious for centuries (Hume and Steinberg, 1993). The two problems can now be seen as correlated in a manner to be explored in the new (ii) "laws of underlying structure" necessitated by the science of P-Consciousness.

Next we can summarize the final state of the upgraded framework for science, perhaps best understood as a description of the "natural world of human scientific behavior" in the following three contexts:

(i) Abstract "Laws of Appearances" constructed by a scientific observer S inside our universe U. The descriptions are based on scientific evidence that arrives in S as the contents of the consciousness (1PP) of S. This produces the familiar 3PP ("objectively evidenced") models of nature that predict how U appears (regularities evident in what U appears to be made of) to a presupposed scientific observer S. For example, S is the presupposed scientific observer that acquired all the evidence that proved the existing SMPP. The existing SMPP is a system of analytic (mathematical) laws of kind (i).

(ii) Abstract "Laws of the underlying structure of a U made of X." These abstractions are also constructed and explored by scientist S. The process results in a categorically distinct class of analytically or computationally/algorithmically explored abstract formalisms that depict the underlying fabric of reality as a collection of networked structural primitives X. The structural primitives have nothing directly to do with space or atoms or EM fields or any other (i) 3PP "laws" and are of a kind exemplified below. Hidden within the explored systems of networked abstractions of X we will find (with the correct abstract X and appropriate computational or analytic metrics and their probes) emergent properties of U we recognize as space, atoms, EM fields and (ultimately) the scientific observer S inside U, also actually made of X, that is mandated to "see" U operating in the manner of the (i) laws of nature. Within (ii) we have an account of the origins of the 1PP that explains the scientific observer that simultaneously provides equal empirical proof of both the (i) and (ii) abstract scientific accounts of U by S.

(iii) The actual universe U, made of what we have abstracted as X in (ii), that has a real scientific observer S in it who has a real 1PP in which "contents of the 1PP" originate all the scientific evidence supporting both the (i) "laws of appearances" and the (ii) "laws of underlying structure." Note that the *in silico* chip discussed in Part I is *empirical* science exploring (iii) to validate (i) and (ii) in the same way that, say, cellular organoids or flying aircraft are exploring (iii). Abstract descriptions (i) and (ii) are the "real" *theoretical* science products (delivered into the journal system within U) of a human scientific observer S. Do not confuse (i) and (ii) abstract descriptions of U, and/or their exploration with general-purpose computers (also made of X), with the (iii) actual U.

The solution to the hard problem, we suggest, has been hard because it must be discovered (not invented) in a completely different realm of descriptions of nature of kind (ii). In effect, the very meaning of what it is that a scientist does to explain nature has itself had to change.

What scientific evidence do we have that it is possible or practical to describe the natural world U in (ii) form? When we look for it, we easily find that we have already been doing it (X descriptions) for decades, *but in physics and outside the science of consciousness*. They are familiar to all of us. Some examples: X = "string theory" e.g. (Sen, 1998), "loops" e.g. (Rovelli, 2006), "branes" e.g. (Ne'eman and Eizenberg, 1995), "dynamic hierarchies of structured noise" e.g. (Cahill and Klinger, 1998, 2000; Cahill, 2003, 2005), "cellular automata" e.g. (Mitchell et al., 1994; Hordijk et al., 1996; Wolfram, 2002), and "quantum froth" e.g. (Swarup, 2006).

Additionally, and relatively recently, *within the science of consciousness*, it is possible to reinterpret the "Information Integration Theory (IIT)"-correlate of consciousness as being a contributor of (ii) descriptions of X (*via* its specified

X = "information mote"). The kinds of networked abstract-X descriptions can easily be recognized in IIT, for example see Albantakis and Tononi (2017). That being the case, we already have an example of X and (ii) *within the science of consciousness* – it just hasn't been formally recognized in "standard-model-upgrade" terms that physics can accommodate. It is a connection to EM that provides the mechanism for accommodating IIT into fundamental physics. Working with physics to reformulate IIT in (i)/(ii) terms is probably the best way to launch a revision to the operational framework of science in the form of an upgraded SMPP. It would powerfully validate and enable IIT, allowing it to migrate to its proper place within a revised standard model on the other side of the disciplinary/explanatory gap. It seems an apt way of forging a path ahead. IIT and its variants have already demonstrated unique progress in "detecting consciousness" *using EM field measurements* (Koch, 2019; Seth and Bayne, 2022). It may be that IIT's apparent access to deeper insight is actually a result of it being unknowingly involved in the novel (ii) kind of fundamental physics. The science framework upgrade approach explains why IIT has had so much trouble proving its validity under the current science framework e.g. (Merker et al., 2021). It has had to artificially erect an entrance to (ii) in the form of the many postulates (axioms) upon which its proposals are based. This article offers the potential to replace the postulates with empirically proved fundamental physics (*via* the EM field basis of the 1PP) and thereby deliver a route to the empirical support it needs. If neuroscience proposals like IIT require the addressing of matters relating to the fabric of reality (however they do this), the correct place to do so is in its natural home, across the transdisciplinary divide in fundamental physics, not in neuroscience.

Having created this system of epistemologically dual-aspect [paired, appearance/underlying structure, (i)/(ii), 3PP/1PP] abstract, symbolic scientific descriptions of nature, empirically proved in an account of the 1PP (*via* the EM field basis of the scientific observer), the practical form of a trajectory toward a solution to the hard problem exists as follows: Motivated by the essential knowledge that EM somehow delivers the 1PP, computational and/or analytic mathematical investigation of (ii) self-modifying tangled webs of X are conducted. They explore the various X such as strings, loops, branes, structured noise hierarchies, cellular automata, quantum froth, "*IIT information motes*" and so forth. They are explored to see if they can be configured in a manner that naturally expresses emergent processes that can be interpreted to have the properties we recognize as space, atoms, charge/spin systems and so forth, expressing EM fields of the familiar (i) kind. The moment a (ii) collection of abstracted X can be found to express EM fields as an emergent behavior of the collection, the physicists involved, by directly comparing the (i) and (ii) depictions of the same nature, would then be able to see, within (ii), that part of the underlying structure of (i) that may be responsible for the 1PP. That may then suggest a fundamental principle that would apply if a 1PP was to somehow be a result of the difference between (i) and (ii). That principle, it is proposed, is either the ultimate solution to the hard problem or a route to it. Posed as a possibility within a revised framework for science, the principle is something to be discovered, not invented. We authors do not know what this principle is, but we look forward to somebody discovering it.

The revised dual-aspect standard model/framework for scientific behavior is intrinsically self-evidencing because of its capacity to account for the scientific observer. All the evidence that proved all the (i) familiar laws of nature is also brought to bear in evidencing (ii). The content of the existing (i) standard model is unaffected by the additional set of (ii) descriptions (they are a categorically distinct class). Rather, (i) forms a set of well formulated and time-tested constraints that can be used to find and formulate the correct set (ii) descriptions. Once the set (ii) descriptions are established and can naturally express EM as an emergent property, and EM's role in creating the brain's 1PP is understood, all ABC-correlates proposals have the means to validate/invalidate their claim to have captured the "correct" correlate of the 1PP. Neuroscientists will then know what to look for in the brain to find the delivery-sites of the 1PP, in all its kinds and degrees.

Part II Final Result: Summary

Until the above approach is used, the formal lack of explanation is predicted to continue to thwart the ABC-correlates paradigm indefinitely. Indeed, even if the perfect "smoking gun" ABC-correlate is somehow located and proved, the researchers involved would still be left high and dry wondering why/how the 1PP arises and would end up with a need to seek the kind of ultimate explanation process depicted above. That process will lead to the "discovery" of the full extent of scientific behavior, the lack of which possibly underlies the confounds that have prevented progress for so long. It is hoped that our Part II speculations start a dialogue directed at developing these ideas into solid proposals. IIT would be a recommended place to commence that dialogue because it is already involved in the shift, albeit informally, inadvertently and incompletely. To assist, a final reminder of the two existing consolidations of IIT and EM: (Barrett, 2014; McFadden, 2020). It is hoped that the above analysis has helped to extend these propositions in the service of all theories of consciousness (all ABC). EM is ultimately at the heart of the matter for everyone. Researchers familiar with EM, and that see EM's role as obvious, may find this article helpful in bringing EM into the territory of the bulk of researchers that traditionally have little or no awareness of EM (Kitchener and Hales, 2022), but that are now critically dependent on it as the ultimate source of explanation for their own theories of consciousness.

CONCLUSION

In pursuit of a solution to the decades-long struggle we all inhabit in turning abstract observational correlates into cogent explanation supported by a fundamental principle, this article reframes the science of P-Consciousness through its relocation into the relatively foreign land (to mainstream neuroscientists) of EM fields. It is based on the empirical fact that it is EM fields that ultimately deliver P-Consciousness. This is something that is as empirically certain as it is uncertain exactly how they do it. The correlates of P-Consciousness paradigm must ultimately face the fundamental physics of EM fields if a fully explanatory account of P-Consciousness is to be constructed. The necessary physics-neuroscience collaboration involved in this "electromagnetic turn" pushes EM fields to explanatory center-stage in the science of consciousness, a location that has also been demonstrated to have at least some potential to take us a little closer to a solution to the "hard problem".

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CH contributed the first draft of the manuscript. CH and ME contributed to manuscript revision, read, and approved the submitted version. Both authors contributed to the article and approved the submitted version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fnhum.2022.836046/full#supplementary-material

REFERENCES

Ahl, V., and Allen, T. F. H. (1996). *Hierarchy Theory: A Vision, Vocabulary, and Epistemology*. New York, NY: Columbia University Press.

Aitchison, I., and Hey, A. (1984). *Gauge Theories in Particle Physics*. London: Adam Hilger. doi: 10.1063/1.2916169

Albantakis, L., and Tononi, G. (2017). "Automata and animats: from dynamics to cause-effect structures," in *From Matter to Life: Information and Causality*, eds S. I. Walker, P. C. Davies, and G. F. Ellis (Cambridge: Cambridge University Press).

Allen, T. F. H., and Starr, T. B. (1982). *Hierarchy: Perspectives for Ecological Complexity*. Chicago, IL: University of Chicago Press.

Aru, J., Bachmann, T., Singer, W., and Melloni, L. (2012). Distilling the neural correlates of consciousness. *Neurosci. Biobehav. Rev.* 36, 737–746. doi: 10.1016/j.neubiorev.2011.12.003

Ashcroft, N., and Mermin, N. (1976). *Solid State Physics*. Philadelphia, PA: Saunders College Publishing.

Aspray, W. (1990). *John von Neumann and the Origins of Modern Computing*, Vol. 191. Cambridge, MA: MIT Press.

Atmanspacher, H. (2020). "Quantum approaches to consciousness," in *The Stanford Encyclopedia of Philosophy*, Summer 2020 Edn. ed. E. N. Zalta. Available online at: https://plato.stanford.edu/archives/sum2020/entries/qt-consciousness

Axelrod, V., Bar, M., and Rees, G. (2015). Exploring the unconscious using faces. *Trends Cogn. Sci.* 19, 35–45. doi: 10.1016/j.tics.2014.11.003

Baars, B. J. (1988). *A Cognitive Theory of Consciousness*. Cambridge: Cambridge University Press.

Baars, B. J. (1997). In the theatre of consciousness. Global workspace theory, a rigorous scientific theory of consciousness. *J. Conscious. Stud.* 4, 292–309.

Baas, N. A. (1994). "Emergence, Hierarchies, and Hyperstructures," in *Artificial life III: Proceedings of the Workshop on Artificial Life, held June 1992 in Santa Fe, New Mexico*, ed. C. G. Langton (Reading, MA: Addison-Wesley), 515–537.

Balduzzi, D., and Tononi, G. (2008). Integrated information in discrete dynamical systems: motivation and theoretical framework. *PLoS Comput. Biol.* 4:e1000091. doi: 10.1371/journal.pcbi.1000091

Barrett, A. (2014). An integration of integrated information theory with fundamental physics. *Front. Psychol.* 5:63. doi: 10.3389/fpsyg.2014.00063

Bayne, T. (2010). *The Unity of Consciousness*. Oxford: Oxford University Press. doi: 10.1093/acprof:oso/9780199215386.001.0001

Bedau, M. A. (1997). "Weak Emergence," in *Philosophical Perspectives: Mind, Causation, and World*, ed. J. Tomberlin (Malden, MA: Blackwell), 375–399. doi: 10.1111/0029-4624.31.s11.17

Block, N. (1995). On a confusion about a function of consciousness. *Behav. Brain Sci.* 18, 227–247. doi: 10.1017/S0140525X00038188

Bongard, J., and Levin, M. (2021). Living things are not (20th Century) machines: updating mechanism metaphors in light of the modern science of machine behavior. *Front. Ecol. Evol.* 9:650726. doi: 10.3389/fevo.2021.650726

Brown, R., Lau, H., and LeDoux, J. E. (2019). Understanding the higher-order approach to consciousness. *Trends Cogn. Sci.* 23, 754–768. doi: 10.1016/j.tics.2019.06.009

Buzsaki, G., Anastassiou, C. A., and Koch, C. (2012). The origin of extracellular fields and currents - EEG, ECoG, LFP and spikes. *Nat. Rev. Neurosci.* 13, 407–420. doi: 10.1038/nrn3241

Cahill, R. T. (2003). *'Process Physics: From Information Theory to Quantum Space and Matter'*. Salem, OR: Center for Process Studies.

Cahill, R. T. (2005). *Process Physics: From Information Theory to Quantum Space and Matter*. Hauppauge, NY: Nova Publishers.

Cahill, R. T., and Klinger, C. M. (1998). Self-referential noise and the synthesis of three-dimensional space. *Gen. Relat. Gravit.* 32, 529–540. doi: 10.1023/A:1001984518976

Cahill, R. T., and Klinger, C. M. (2000). "Self-referential noise as a fundamental aspect of reality," in *Proc 2nd Int Conf on Unsolved Problems of Noise and Fluctuations (UPoN'99)*, eds D. Abbott and L. Kish (College Park, MD: American Institute of Physics). doi: 10.1063/1.60018

Carruthers, P. (2018). "Higher-order theories of consciousness," in *The Stanford Encyclopedia of Philosophy*, E. N. Zalta (Redwood City, CA: Stanford University Press).

Chalmers, D. (2016). "The combination problem for panpsychism," in *Panpsychism: Contemporary Perspectives*, eds G. Bruntrup and L. Jaskolla (Oxford: Oxford University Press), 179–214. doi: 10.1093/acprof:oso/9780199359943.003.0008

Chalmers, D. J. (1996). *The Conscious Mind: In Search of a Fundamental Theory*. New York, NY: Oxford University Press.

Chalmers, D. J. (2000). "What is a neural correlate of consciousness?," in *Neural Correlates of Consciousness: Empirical and Conceptual Questions*, ed. T. Metzinger (Cambridge, MA: MIT Press).

Chalmers, D. J. (2006). "Strong and weak emergence," in *The Re-Emergence of Emergence: The Emergentist Hypothesis from Science to Religion*, eds P. Clayton and P. Davies (Oxford: Oxford University Press), 244–254. doi: 10.1093/acprof:oso/9780199544318.003.0011

Clayton, P., and Davies, P. (eds) (2006). *The Re-Emergence of Emergence: The Emergentist Hypothesis from Science to Religion*. Oxford: Oxford University Press.

Cleeremans, A., and Frith, C. (eds) (2003). *The Unity of Consciousness*. Oxford: Oxford University Press.

Cocchi, L., Gollo, L. L., Zalesky, A., and Breakspear, M. (2017). Criticality in the brain: a synthesis of neurobiology, models and cognition. *Prog. Neurobiol.* 158, 132–152. doi: 10.1016/j.pneurobio.2017.07.002

Corning, P. A. (2002). The re-emergence of "emergence": a venerable concept in search of a theory. *Complexity* 7, 18–30. doi: 10.1002/cplx.10043

Cottingham, W. N., and Greenwood, D. A. (2007). *An Introduction to the Standard Model of Particle Physics*. Cambridge: Cambridge university press. doi: 10.1017/CBO9780511791406

Crick, F. (1994). *The Astonishing Hypothesis: The Scientific Search for the Soul*. London: Simon & Schuster.

Crick, F., and Koch, C. (1990). Towards a neurobiological theory of consciousness. *Semin. Neurosci.* 2, 263–275.

de Graaf, T. A., Hsieh, P.-J., and Sack, A. T. (2012). The 'correlates' in neural correlates of consciousness. *Neurosci. Biobehav. Rev.* 36, 191–197. doi: 10.1016/j.neubiorev.2011.05.012

De Wolf, T., and Holvoet, T. (2005). "Emergence versus self-organisation: different concepts but promising when combined," in *Engineering Self-Organising Systems: Methodologies and Applications*, eds S. A. Brueckner, G. D. M. Serugendo, A. Karageorgos, and R. Nagpal (Berlin: Springer), 1–15. doi: 10.1007/11494676_1

Dehaene, S. (2014). Consciousness and the brain: deciphering how the brain codes our thoughts. *J. Undergrad. Neurosci. Educ.* 12, R5–R6.

Dehaene, S., and Changeux, J.-P. (2011). Experimental and theoretical approaches to conscious processing. *Neuron* 70, 200–227. doi: 10.1016/j.neuron.2011.03.018

Doerig, A., Schurger, A., and Herzog, M. H. (2020). Hard criteria for empirical theories of consciousness. *Cogn. Neurosci.* 12, 41–62. doi: 10.1080/17588928.2020.1772214

Edelman, G. M. (1987). *Neural Darwinism: The Theory of Neuronal Group Selection*. New York, NY: Basic Books.

Edelman, G. M. (1989). *The Remembered Present: A Biological Theory of Consciousness*. New York, NY: Basic Books.

Edelman, G. M. (1992). *Bright Air, Brilliant Fire: On the Matter of the Mind*. New York, NY: BasicBooks.

Edelman, G. M., and Tononi, G. (2000). *A Universe of Consciousness: How Matter Becomes Imagination*, 1st Edn. New York, NY: Basic Books.

Einevoll, G. T., Kayser, C., Logothetis, N. K., and Panzeri, S. (2013). Modelling and analysis of local field potentials for studying the function of cortical circuits. *Nat. Rev. Neurosci.* 14, 770–785. doi: 10.1038/nrn3599

Farber, J. (2005). How a neural correlate can function as an explanation of consciousness: evidence from the history of science regarding the likely explanatory value of the NCC approach. *J. Conscious. Stud.* 12, 77–95.

Feinberg, T. E. (2011). The nested neural hierarchy and the self. *Conscious. Cogn.* 20, 4–15. doi: 10.1016/j.concog.2010.09.016

Feynman, R. P. (1976). *Statistical Mechanics: A Set of Lectures, Definitive Edn*. Reading, MA: Benjamin-Cummings.

Fingelkurts, A. A., Fingelkurts, A. A., and Neves, C. F. (2013). Consciousness as a phenomenon in the operational architectonics of brain organization: criticality and self-organization considerations. *Chaos Solitons Fractals* 55, 13–31. doi: 10.1016/j.chaos.2013.02.007

Friston, K., FitzGerald, T., Rigoli, F., Schwartenbeck, P., and Pezzulo, G. (2017). Active inference: a process theory. *Neural Comput.* 29, 1–49. doi: 10.1162/NECO_a_00912

Fröhlich, H. (1968). Long-range coherence and energy storage in biological systems. *Int. J. Quantum Chem.* 2, 641–649. doi: 10.1002/qua.560020505

Fröhlich, H. (1970). Long range coherence and the action of enzymes. *Nature* 228, 1093–1093. doi: 10.1038/2281093a0

Fröhlich, H. (1975). The extraordinary dielectric properties of biological materials and the action of enzymes. *Proc. Natl. Acad. Sci. U.S.A.* 72, 4211–4215. doi: 10.1073/pnas.72.11.4211

Fröhlich, H. (1986). "Coherent excitation in active biological systems," in *Modern Bioelectrochemistry*, eds F. Gutmann and H. Keyzer (New York, NY: Plenum Press), 241–261. doi: 10.1007/978-1-4613-2105-7_8

Goff, P., Seager, W., and Allen-Hermanson, S. (2018). "Panpsychism," in *The Stanford Encyclopedia of Philosophy Summer 2020 Edition*, ed. E. N. Zalta (Stanford, CA: Stanford University).

Griffiths, D. (2020). *Introduction to Elementary Particles*. Hoboken, NJ: John Wiley & Sons.

Grobstein, C. (1973). "Hierarchical order and Neogenesis," in *Hierarchy Theory: The Challenge of Complex Systems*, ed. H. H. Pattee (New York, NY: George Braziller), 30–47.

Hales, C. G. (2014). *The Revolutions of Scientific Structure*. Singapore: World Scientific. doi: 10.1142/9211

Halzen, F., Martin, A. D., and Mitra, N. (1985). Quarks and leptons: an introductory course in modern particle physics. *Am. J. Phys.* 53, 287–287. doi: 10.1119/1.14146

Hameroff, S., and Penrose, R. (2014). Consciousness in the universe: a review of the 'Orch OR'theory. *Phys. Life Rev.* 11, 39–78. doi: 10.1016/j.plrev.2013.08.002

Harnad, S. (1990). The symbol grounding problem. *Physica D* 42, 335–346. doi: 10.1016/0167-2789(90)90087-6

He, S., and MacLeod, D. I. (2001). Orientation-selective adaptation and tilt after-effect from invisible patterns. *Nature* 411, 473–476. doi: 10.1038/35078072

Hendry, R. F., Gibb, S., and Lancaster, T. (2019). "Introduction," in *The Routledge Handbook of Emergence*, eds S. Gibb, R. F. Hendry, and T. Lancaster (London: Routledge), 1–19. doi: 10.4324/9781315675213-1

Hordijk, W., Crutchfield, J., and Mitchell, M. (1996). "Embedded-particle computation in evolved cellular automata," in *PhysComp96*, eds T. Toffoli, M. Biafore, and J. Leao (Cambridge, MA: New England Complex Systems Institute), 153–158.

Hume, D., and Steinberg, E. (1993). *An Enquiry Concerning Human Understanding; [with] A Letter from A Gentleman to His Friend in Edinburgh; [and] An Abstract of a Treatise of Human Nature*, 2nd Edn. Indianapolis, IN: Hackett Pub. Co.

Hunt, T., and Schooler, J. W. (2019). The easy part of the hard problem: a resonance theory of consciousness. *Front. Hum. Neurosci.* 13:378. doi: 10.3389/fnhum.2019.00378

Jackson, J. D. (1999). *Classical Electrodynamics*, 3rd Edn. New York, NY: Wiley. doi: 10.1119/1.19136

Jiang, Y., Zhou, K., and He, S. (2007). Human visual cortex responds to invisible chromatic flicker. *Nat. Neurosci.* 10, 657–662. doi: 10.1038/nn1879

Jones, M. W. (2013). Electromagnetic-field theories of mind. *J. Conscious. Stud.* 20, 124–149.

Jones, M. W. (2017). Mounting evidence that minds are neural EM fields interacting with brains. *J. Conscious. Stud.* 24, 159–183.

Kent, L., and Wittmann, M. (2021). Time consciousness: the missing link in theories of consciousness. *Neurosci. Conscious.* 2021:niab011. doi: 10.1093/nc/niab011

Keppler, J. (2021). Building blocks for the development of a self-consistent electromagnetic field theory of consciousness. *Front. Hum. Neurosci.* 15:723415. doi: 10.3389/fnhum.2021.723415

Kim, J. (2006). Emergence: core ideas and issues. *Synthese* 151, 547–559. doi: 10.1007/s11229-006-9025-0

Kitchener, P. D., and Hales, C. G. (2022). What neuroscientists think, and don't think, about consciousness. *Front. Hum. Neurosci.* 16:767612. doi: 10.3389/fnhum.2022.767612

Kitzbichler, M. G., Smith, M. L., Christensen, S. R. R., and Bullmore, E. (2009). Broadband criticality of human brain network synchronization. *PLoS Comput. Biol.* 5:e1000314. doi: 10.1371/journal.pcbi.1000314

Koch, C. (2019). *The Feeling of Life Itself: Why Consciousness is Widespread but Can't be Computed*. Cambridge, MA: MIT Press. doi: 10.7551/mitpress/11705.001.0001

Koch, C., Massimini, M., Boly, M., and Tononi, G. (2016). Neural correlates of consciousness: progress and problems. *Nat. Rev. Neurosci.* 17, 307–321. doi: 10.1038/nrn.2016.22

Koestler, A. (1967). *The Ghost in the Machine*. London: Hutchinson.

Koestler, A. (1978). *Janus: A Summing Up*, 1st American Edn. New Yor, NY: Random House.

Kuhn, T. S., and Hacking, I. (2012). *The Structure of Scientific Revolutions*, 4th Edn. Chicago, IL: University of Chicago Press. doi: 10.7208/chicago/9780226458144.001.0001

LaBerge, D., and Kasevich, R. (2007). The apical dendrite theory of consciousness. *Neural Netw.* 20, 1004–1020. doi: 10.1016/j.neunet.2007.09.006

Lambert, N., Chen, Y.-N., Cheng, Y.-C., Li, C.-M., Chen, G.-Y., and Nori, F. (2013). Quantum biology. *Nat. Phys.* 9, 10–18. doi: 10.1038/nphys2474

Lamme, V. A., and Roelfsema, P. R. (2000). The distinct modes of vision offered by feedforward and recurrent processing. *Trends Neurosci.* 23, 571–579. doi: 10.1016/S0166-2236(00)01657-X

Lau, H. (2008). "Are we studying consciousness yet?," in *Frontiers of Consciousness: Chichele Lectures*, eds L. Weiskrantz and M. Davies (Oxford: Oxford University Press), 245–258. doi: 10.1093/acprof:oso/9780199233151.003.0008

Levine, J. (1983). Materialism and qualia, the explanatory gap. *Pac. Philos. Q.* 64, 354–361. doi: 10.1111/j.1468-0114.1983.tb00207.x

Libet, B. (1994). A testable field theory of mind-brain interaction. *J. Conscious. Stud.* 1, 119–126.

Libet, B. (2006). Reflections on the interaction of the mind and brain. *Prog. Neurobiol.* 78, 322–326. doi: 10.1016/j.pneurobio.2006.02.003

Marcer, P., and Hameroff, S. (1998). Quantum computation in brain microtubules? The Penrose-Hameroff 'Orch OR' model of consciousness. *Philos. Trans. R. Soc. Lond. Ser. A* 356, 1896–1896. doi: 10.1098/rsta.1998.0254

Mashour, G. A., and Hudetz, A. G. (2018). Neural correlates of unconsciousness in large-scale brain networks. *Trends Neurosci.* 41, 150–160. doi: 10.1016/j.tins.2018.01.003

Mashour, G. A., Roelfsema, P., Changeux, J.-P., and Dehaene, S. (2020). Conscious processing and the global neuronal workspace hypothesis. *Neuron* 105, 776–798. doi: 10.1016/j.neuron.2020.01.026

McFadden, J. (2002a). The conscious electromagnetic information (CEMI) Field Theory. *J. Conscious. Stud.* 9, 45–60.

McFadden, J. (2002b). Synchronous firing and its influence on the brain's electromagnetic field: evidence for an electromagnetic theory of consciousness. *J. Conscious. Stud.* 9, 23–50.

McFadden, J. (2006). "The CEMI field theory: seven clues to the nature of consciousness," in *The Emerging Physics of Consciousness*, ed. J. A. Tuszynski (Berlin: Springer), 387–406. doi: 10.1007/3-540-36723-3_12

McFadden, J. (2007). Conscious electromagnetic field theory. *Neuroquantology* 5, 262–270. doi: 10.14704/nq.2007.5.3.135

McFadden, J. (2013). The CEMI field theory closing the loop. *J. Conscious. Stud.* 20, 153–168.

McFadden, J. (2020). Integrating information in the brain's EM field: the cemi field theory of consciousness. *Neurosci. Conscious.* 2020:niaa016. doi: 10.1093/nc/niaa016

McFadden, J., and Al-Khalili, J. (2018). The origins of quantum biology. *Proc. R. Soc. A* 474:20180674. doi: 10.1098/rspa.2018.0674

McGovern, K., and Baars, B. (2007). "Cognitive theories of consciousness," in *Cambridge Handbook of Consciousness*, eds P. D. Zelazo, M. Moscovitch, and E. Thompson (New York, NY: Cambridge University Press), 177–205. doi: 10.1017/CBO9780511816789.009

Merker, B., Williford, K., and Rudrauf, D. (2021). The integrated information theory of consciousness: a case of mistaken identity. *Behav. Brain Sci.* 45:e41. doi: 10.1017/S0140525X21000881

Metzinger, T. (2000). *Neural Correlates of Consciousness - Empirical and Conceptual Questions*. Cambridge, MA: MIT Press. doi: 10.7551/mitpress/4928.001.0001

Mitchell, M., Crutchfield, J. P., and Hraber, P. T. (1994). Evolving cellular automata to perform computations: mechanisms and impediments. *Physica D* 75, 361–391. doi: 10.1016/0167-2789(94)90293-3

Molyneux, B. (2010). Why the neural correlates of consciousness cannot be found. *J. Conscious. Stud.* 17, 168–188.

Mormann, F., and Koch, C. (2007). Neural correlates of consciousness. *Scholarpedia* 2:1740. doi: 10.4249/scholarpedia.1740

Nagel, T. (1974). What is it like to be a bat? *Philos. Rev.* 83, 435–450. doi: 10.2307/2183914

Ne'eman, Y., and Eizenberg, E. (1995). *Membranes and other Extendons ("p-BRANES"). Classical and Quantum Mechanics of Extended Geometrical Objects*. Singapore: World Scientific Publishing Company. doi: 10.1142/1382

Neisser, J. (2012). Neural correlates of consciousness reconsidered. *Conscious. Cogn.* 21, 681–690. doi: 10.1016/j.concog.2011.03.012

Northoff, G., and Lamme, V. (2020). Neural signs and mechanisms of consciousness: Is there a potential convergence of theories of consciousness in sight? *Neurosci. Biobehav. Rev.* 118, 568–587. doi: 10.1016/j.neubiorev.2020.07.019

Obien, M. E. J., Deligkaris, K., Bullmann, T., Bakkum, D. J., and Frey, U. (2015). Revealing neuronal function through microelectrode array recordings. *Front. Neurosci.* 8:423. doi: 10.3389/fnins.2014.00423

O'Connor, T. (2020). "Emergent Properties," in *The Stanford Encyclopedia of Philosophy*, Fall 2020 Edn. ed. E. N. Zalta. Available online at: https://plato.stanford.edu/archives/fall2020/entries/properties-emergent/

Oizumi, M., Albantakis, L., and Tononi, G. (2014). From the phenomenology to the mechanisms of consciousness: integrated information theory 3.0. *PLoS Comput. Biol.* 10:e1003588. doi: 10.1371/journal.pcbi.1003588

Pattee, H. H. (ed.) (1973). *Hierarchy Theory: The Challenge of complex Systems*. New York, NY: George Braziller.

Pitts, M. A., Metzler, S., and Hillyard, S. A. (2014). Isolating neural correlates of conscious perception from neural correlates of reporting one's perception. *Front. Psychol.* 5:1078. doi: 10.3389/fpsyg.2014.01078

Pockett, S. (2000). *The Nature of Consciousness: A Hypothesis*. Available online at: iUniverse.com

Pockett, S. (2013). Field theories of consciousness. *Scholarpedia* 8:4951. doi: 10.4249/scholarpedia.4951

Poznanski, R. R., Cacha, L. A., Latif, A. Z., Salleh, S. H., Ali, J., Yupapin, P., et al. (2019). Molecular orbitals of delocalized electron clouds in neuronal domains. *Biosystems* 183:103982. doi: 10.1016/j.biosystems.2019.103982

Raccah, O., Block, N., and Fox, K. C. (2021). Does the prefrontal cortex play an essential role in consciousness? Insights from intracranial electrical stimulation of the human brain. *J. Neurosci.* 41, 2076–2087. doi: 10.1523/JNEUROSCI.1141-20.2020

Rees, G., and Frith, C. (2007). "Methodologies for identifying the neural correlates of consciousness," in *The Blackwell Companion to Consciousness*, eds M. Velmans and S. Schneider (Malden, MA: Blackwell Publishing), 553–566. doi: 10.1002/9780470751466.ch44

Rees, G., Kreiman, G., and Koch, C. (2002). Neural correlates of consciousness in humans. *Nat. Rev. Neurosci.* 3, 261–270. doi: 10.1038/nrn783

Revonsuo, A., and Newman, J. (1999). Binding and consciousness. *Conscious. Cogn.* 8, 123–127. doi: 10.1006/ccog.1999.0393

Rich, J. (2010). *Fundamentals of Cosmology*. Berlin: Springer. doi: 10.1007/978-3-642-02800-7

Rosen, R. (1993). Drawing the boundary between subject and object: comments on the mind-brain problem. *Theor. Med.* 14, 89–100. doi: 10.1007/BF00997269

Rosen, R. (2012). Anticipatory systems: philosophical, mathematical, and methodological foundations. *Int. J. Gen. Syst.* 41, 867–871. doi: 10.1080/03081079.2012.726322

Rosenthal, D., and Weisberg, J. (2008). Higher order theoreies of consciousness. *Scholarpedia* 3:4407. doi: 10.4249/scholarpedia.4407

Roskies, A. L. (1999). The binding problem. *Neuron* 24, 7–9. doi: 10.1016/S0896-6273(00)80817-X

Rovelli, C. (2006). Graviton propagator from background-independent quantum gravity. *Phys. Rev. Lett.* 97:151301. doi: 10.1103/PhysRevLett.97.151301

Salthe, S. N. (1985). *Evolving Hierarchical Systems: Their Structure and Representation*. New York, NY: Columbia University Press. doi: 10.7312/salt91068

Schuman, C. D., Potok, T. E., Patton, R. M., Birdwell, J. D., Dean, M. E., Rose, G. S., et al. (2017). A survey of neuromorphic computing and neural networks in hardware. *arXiv* [Preprint]. Available online at: https://arxiv.org/pdf/1705.06963.pdf (accessed May 19, 2017).

Sen, A. (1999). "An introduction to non-perturbative string theory," in *Duality and Supersymmetric Theories*, eds D. I. Olive and P. C. West (Cambridge: Cambridge University Press), 297–413.

Seth, A. (2007). Models of consciousness. *Scholarpedia* 2:1328. doi: 10.4249/scholarpedia.1328

Seth, A. (2009). Explanatory correlates of consciousness: theoretical and computational challenges. *Cogn. Comput.* 1, 50–63. doi: 10.1007/s12559-009-9007-x

Seth, A. (2021). *Being You: A New Science of Consciousness*. New York, NY: Penguin.

Seth, A. K., and Bayne, T. (2022). Theories of consciousness. *Nat. Rev. Neurosci.* 1–14. doi: 10.1038/s41583-022-00587-4

Simon, H. A. (1973). "The organization of complex systems," in *Hierarchy Theory: The Challenge of Complex Systems*, ed. H. H. Pattee (New York, NY: George Braziller), 3–27.

Singer, W. (2001). Consciousness and the binding problem. *Ann. N. Y. Acad. Sci.* 929, 123–146. doi: 10.1111/j.1749-6632.2001.tb05712.x

Skrbina, D. (2007). "Panpsychism," in *Internet Encyclopedia of Philosophy*, eds J. Fieser and B. Dowden (Cambridge MA: MIT Press).

Stepney, S., Polack, F. A., and Turner, H. R. (2006). "Engineering emergence," in *Proceddings of the 11th IEEE International Conference on Engineering of Complex Computer Systems (ICECCS'06)*, Stanford, CA.

Storm, J. F., Boly, M., Casali, A. G., Massimini, M., Olcese, U., Pennartz, C. M., et al. (2017). Consciousness regained: disentangling mechanisms, brain systems, and behavioral responses. *J. Neurosci.* 37, 10882–10893. doi: 10.1523/JNEUROSCI.1838-17.2017

Swarup, A. (2006). Sights set on quantum froth. *New Sci.* 189:18.

Tagliazucchi, E. (2017). The signatures of conscious access and its phenomenology are consistent with large-scale brain communication at criticality. *Conscious. Cogn.* 55, 136–147. doi: 10.1016/j.concog.2017.08.008

Tegmark, M. (2000). Importance of quantum decoherence in brain processes. *Phys. Rev. E* 61, 4194–4206. doi: 10.1103/PhysRevE.61.4194

Tononi, G. (2004). An information integration theory of consciousness. *BMC Neurosci.* 5:42. doi: 10.1186/1471-2202-5-42

Tononi, G. (2008). Consciousness as integrated information: a provisional manifesto. *Biol. Bull.* 215, 216–242. doi: 10.2307/25470707

Tononi, G., Boly, M., Massimini, M., and Koch, C. (2016). Integrated information theory: from consciousness to its physical substrate. *Nat. Rev. Neurosci.* 17, 450–461. doi: 10.1038/nrn.2016.44

Tononi, G., and Koch, C. (2015). Consciousness: Here, there and everywhere? *Philos. Trans. R. Soc. Lond. B Biol. Sci.* 370:20140167. doi: 10.1098/rstb.2014.0167

Treisman, A. (1996). The binding problem. *Curr. Opin. Neurobiol.* 6, 171–178. doi: 10.1016/S0959-4388(96)80070-5

Tsuchiya, N., Wilke, M., Frässle, S., and Lamme, V. A. (2015). No-report paradigms: extracting the true neural correlates of consciousness. *Trends Cogn. Sci.* 19, 757–770. doi: 10.1016/j.tics.2015.10.002

Van Gulick, R. (2001). Reduction, emergence and other recent options on the mind/body problem. A philosophic overview. *J. Conscious. Stud.* 8, 1–34.

Van Gulick, R. (2018). "Consciousness," in *The Stanford Encyclopedia of Philosophy*, Spring 2018 Edn. ed. E. N. Zalta. Available online at: https://plato.stanford.edu/archives/spr2018/entries/consciousness/

Velmans, M., and Schneider, S. (eds) (2007). *The Blackwell Companion to Consciousness*. Malden, MA: Blackwell Publishing. doi: 10.1111/b.9781405120197.2007.x

Weiskrantz, L. (1996). Blindsight revisited. *Curr. Opin. Neurobiol.* 6, 215–220. doi: 10.1016/S0959-4388(96)80075-4

Winters, J. J. (2020). The temporally-integrated causality landscape: a theoretical framework for consciousness and meaning. *Conscious. Cogn.* 83:102976. doi: 10.1016/j.concog.2020.102976

Winters, J. J. (2021). The temporally-integrated causality landscape: reconciling neuroscientific theories with the phenomenology of consciousness. *Front. Hum. Neurosci.* 15:768459. doi: 10.3389/fnhum.2021.768459

Wolfram, S. (2002). *A New Kind of Science*. Champaign, IL: Wolfram Media.

Zare, M., and Grigolini, P. (2013). Criticality and avalanches in neural networks. *Chaos Solitons Fractals* 55, 80–94. doi: 10.1016/j.chaos.2013.05.009

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Qualia and Phenomenal Consciousness Arise From the Information Structure of an Electromagnetic Field in the Brain

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In this paper we address the following problems and provide realistic answers to them: (1) What could be the physical substrate for subjective, phenomenal, consciousness (P-consciousness)? Our answer: the electromagnetic (EM) field generated by the movement and changes of electrical charges in the brain. (2) Is this substrate generated in some particular part of the brains of conscious entities or does it comprise the entirety of the brain/body? Our answer: a part of the thalamus in mammals, and homologous parts of other brains generates the critical EM field. (3) From whence arise the qualia experienced in P-consciousness? Our answer, the relevant EM field is "structured" by emulating in the brain the information in EM fields arising from both external (the environment) and internal (the body) sources. (4) What differentiates the P-conscious EM field from other EM fields, e.g., the flux of photons scattered from object surfaces, the EM field of an electro-magnet, or the EM fields generated in the brain that do not enter P-consciousness, such as those generated in the retina or occipital cortex, or those generated in brain areas that guide behavior through visual information in persons exhibiting "blindsight"? Our answer: living systems express a boundary between themselves and the environment, requiring them to model (coarsely emulate) information from their environment in order to control through actions, to the extent possible, the vast sea of variety in which they are immersed. This model, expressed in an EM field, *is* P-consciousness. The model is the best possible representation of the moment-to-moment niche-relevant (action-relevant: affordance) information an organism can generate (a *Gestalt*). Information that is at a lower level than niche-relevant, such as the unanalyzed retinal vector-field, is not represented in P-consciousness because it is not niche-relevant. Living organisms have sensory and other systems that have evolved to supply such information, albeit in a coarse form.

Keywords: phenomenal consciousness, thalamus, electromagnetic field, information structure, affordances, qualia

INTRODUCTION

The field of consciousness studies is too vast to be reviewed in a short paper. We will, accordingly, only mention a few important aspects of that literature for purposes of orientation to our proposal. First, we are sympathetic to the position of Searle (e.g., Searle, 2000) that phenomenal consciousness (P-consciousness or PC), our focus here, is a property of living, behaving, things. This is also consistent with the position of Gibson (1979/2014) that perception is a property of living, behaving organisms. We wish to avoid panpsychism for a number of reasons, not the least of which is its striking inconsistency with our everyday experience of rocks, BBQs, and even trees and grass (cf. Merker et al., 2021). Second, along with many others (e.g., Crick, 1994; Searle, 2000; Revonsuo, 2006; Fingelkurts et al., 2013), we assume that the fundamental substrate of consciousness involves nervous tissue, in humans the brain and the rest of the central nervous system. When the brain is dead PC is absent. And when the brain is severely injured, particularly the thalamus, PC is severely compromised and in some cases apparently absent as well (e.g., Jennett and Plum, 1972; Jennett et al., 2001; Ward, 2011). Therefore, we search for the physical substrate of PC in the workings of nervous tissue, especially in brains. Third, we agree with the majority of studies of PC in asserting that PC is a unitary, integrated, process that involves all of the senses as well as the emotions, bodily sensations, and semi-modal or amodal thoughts, although embodying different subsets of these elements from moment to moment (e.g., Edelman and Tononi, 2000; Seth and Baars, 2005).

PHYSICAL SUBSTRATE FOR P-CONSCIOUSNESS

What could be the physical substrate for subjective, phenomenal, consciousness? Our answer: the electromagnetic (EM) field generated by the movement and temporal variation of electric charge in the brain. Since neural activity (and that of other aspects of the brain, e.g., slow flow of ionic currents in supporting fluids, activity across electrical synapses, etc.) consists of electrical charge movement (usually ions moving across cell membranes) and/or change in electric fields (as in ephaptic conduction, the coupling of neurons through electric fields), the answer must somehow be related to that activity. Moreover, synchronous neural firing is the normal mode of interaction of coupled neurons, since they are essentially relaxation oscillators whose nature is to be entrained by their inputs (Ward, 2002). Such synchronous (phase-locked, even at non-zero phase lags) firing has many consequences in the brain (e.g., Buzsaki and Draguhn, 2004). One of the most striking is the property that synchronously firing neurons reinforce each other's effects whereas randomly asynchronously firing neurons cancel each other's effects, both on each other and on downstream groups of neurons (cf. Fries, 2005, 2015). One consequence of synchronous firing is synchronous oscillations of electrical currents in the dendritic trees of the participating neurons, and synchronous oscillations of electrical currents in surrounding fluids and across neural membranes. It is important not to place too much emphasis on neural firing alone, even though spike potentials also generate EM fields. Axonal conduction of spike potentials is a neural communicative mechanism but may not be the most important aspect of neural activity related to consciousness. Several researchers have argued that electrical currents flowing in dendritic trees may be more related to consciousness and cognition than is neural firing, namely Mumford (1991, 1992), Pribram (1991), Nunez (2000), LaBerge and Kasevich (2007), and Fingelkurts et al. (2010, 2013). On the other hand, cortical spike potentials do encode information about sensory input, and even motor output, such as speech (e.g., Martin et al., 2018). But then, so do cortical local field potentials, including even imaginary speech (Proix et al., 2022). An important problem for any theory of PC based on EM fields is to describe which aspects of neural activity generate the EM field critical for PC. We will address this problem in several ways in what follows.

One important consequence of the charge flow/current change associated with synchronous (integrated) neural activity is that, according to Maxwell's electromagnetic theory (e.g., Feynman et al., 1964; Hales, 2014), it creates an electromagnetic (EM) field that comprises all of the information expressed by that charge flow. As for electric fields within the brain, they are generated by electric charges according to Gauss's law,

$$\nabla \cdot \overrightarrow{D} = 4\pi\rho,$$

where $\overrightarrow{D}$ is the electric field in matter (displacement field) and ρ is the charge density, and both are time-dependent functions. This implies that if the electric charges are changing with time inside the brain, the generated electric fields are also changing. The charges and currents include not only neural action potentials but also dendritic currents, axonal currents, and myriad other electrical and magnetic effects arising from neural and glial activity.

The sources of magnetic fields are, instead, electric currents, and they are also generated by temporal changes in electric fields:

$$\nabla \times \overrightarrow{H} = \frac{1}{c}\left(4\pi\overrightarrow{J} + \frac{\partial\overrightarrow{D}}{\partial t}\right),$$

where $\overrightarrow{H}$ is the magnetic field, $\overrightarrow{J}$ is the electric current and c is the speed of light. This implies that if currents are changing in time, magnetic fields are also changing in time. Finally, changes in time of electric and magnetic fields generate electromagnetic waves, as expressed in the previous equation and the equation:

$$\nabla \times \vec{E} = -\frac{1}{c}\left(\frac{\partial\vec{B}}{\partial t}\right),$$

where $\vec{E}$ and $\vec{B}$ are the electric and magnetic fields in vacuum, respectively. These equations, when applied to neural tissue, have a special form that is described in detail by Hales (2014). We cannot in this brief article describe in any more detail the physics of how EM fields are generated by neurons. Please see Hales (2014) for a detailed discussion of how neurons generate and sustain EM fields.

Maxwell's equations have another important implication. They relate sources and fields in a deterministic way: once the sources are given, the fields can be uniquely calculated by solving the differential equations. So, if we know how charges are distributed and how they move in space (flows of charge), we know all about the corresponding electromagnetic field. *In other words, all the information contained in source configurations is also contained in the fields.* In this sense, the electromagnetic field "reflects" the sources, which are electric charges and their movement (currents). Or, to put it another way, the sources of the field create the *information structure* of the field.

Furthermore, since Maxwell's equations are linear in the fields (the electric and magnetic fields enter linearly in the equations), their solutions obey the superposition principle. This has an important implication in the context of the current discussion, one that we think has not been sufficiently emphasized in the literature. The electromagnetic field generated by the activity of neurons is more integrated than are the sources themselves. Indeed, the integration of brain activity is mediated through neural synchronization that typically requires a physical interaction at synapses (except for ephaptic connections). But the electromagnetic fields generated in different parts of the brain, *providing they are close enough in space and time*, are automatically integrated, more or less independently of the anatomical connectivity of brain tissues generating them. For example, if two nearby neural sources, in points A and B, produce fields measured in C and D, due to superposition the fields in C and D are very similar, as they are the weighted sums of the fields that the individual sources (A and B) would generate independently. In other words, the fields are integrated, whereas the sources A and B may be integrated or not, depending on the connectivity between those sources. Additionally, the integration is established in very short time, instantaneously in comparison with physiological processes, as perturbations in electromagnetic fields are propagated at the speed of light. Thus, integration of information in an electromagnetic field is free of the temporal constraints of electro-chemical neural interactions, consistent with the phenomenal experience of a continuous flow of conscious experience (cf. James, 1890). Furthermore, phenomenal experience correlates with, and is possibly in causal relation to, information integration in neural circuits (e.g., Fries, 2005, 2015; Tononi et al., 2016). Integration of information between neural assemblies, however, can actually be achieved much faster by integration of their separate EM fields than by traditional synaptic mechanisms. These facts make the EM field a better candidate than the neuronal sources of the field as the physical substrate for consciousness, although of course still dependent on the activity of those neuronal sources for its generation (cf. also Fingelkurts et al., 2010 on this point).

If the synchronous neural activity taking place in the brain is closely associated with conscious awareness (Ward, 2011), then so, too, is the EM field created inevitably by that neural activity. Moreover, only the EM field integrates charge-flow activity into a unified spatio-temporal pattern that encompasses all of the information represented by the various aspects of the relevant neural activity. It is through their field effects that electrical events such as charges flowing across a membrane combine and interact in a smoothly integrated way.

Of course, this integration is time dependent and does not include all the brain, as the strength of an EM field from neural sources (typically, but not only, dipolar in nature) decreases rapidly with distance. At distances larger than a few centimeters, the activity of non-synchronized neuronal networks is indistinguishable from neural noise. An implication of this fact is that only highly synchronized neuronal assemblies contribute to an integrated EM field. In this sense, the EM field that we hypothesize to be a correlate of PC is the result of the activity of highly synchronized neural networks, similarly to other theories of consciousness (e.g., Dehaene, 2014). The most important difference of an EM based theory of PC from other existing theories is in the timing of integration. EM integration is, as we mentioned above, for all practical proposes instantaneous.

The fact that the EM field strength should be sufficient to contribute to PC is not the end of the story. It is the complexity of such fields that is associated with PC. For example, it is well known that during epileptic seizures the EM field is very large, as compared with the EM field in normal brain activity, but epileptic seizures are often accompanied by loss of consciousness, as is the case in generalized epilepsy. It has been shown that the complexity of functional networks of brain activity correlates with consciousness (e.g., Guevara Erra et al., 2016), and this fact should be reflected in the associated EM field. In other words, a necessary condition for an EM field to be relevant to PC is that it be both integrated and complex.

There is at least one problem remaining with our account: both electrical potentials and magnetic fields are volume conducted throughout the brain (Wolters and de Munck, 2007), in spite of the fact that these fields decrease rapidly in strength with distance from their source. The effects of dipolar sources add linearly, as mentioned above, and the mixtures can be detected by surface sensors such as EEG electrodes and MEG SQUIDs. Unmixing of these combined potentials is, in fact, an ongoing problem for noninvasive techniques in cognitive neuroscience (e.g., Wolters and de Munck, 2007; Delorme et al., 2012). Moreover, the various electrical and magnetic fields detected by EEG/MEG, and in particular those sourced to particular brain areas, are highly correlated with perceptual, cognitive, and motor behaviors. An appealing conclusion is that it is these global, integrated, EM fields that comprise PC. And indeed, most, if not all, researchers who propose EM field theories of PC argue that the relevant EM field is brain-wide, consistent with the linear mixing of local EM fields (e.g., Hales, 2014). In this paper, however, we discount brain-wide integration because most local processes are not represented in PC (see Section "Where in the brain? The thalamic dynamic core" for the argument). If our account is to be accepted, then, we must describe some process in the integration of the various EM fields that eliminates or cancels the fields generated by the local processes in favor of the resultant "final field" that represents all of the information our senses, memories, emotions, etc. are generating. There is clearly a tension between brain-wide integration of local coherent EM fields and formation of an integrated EM field in one central brain area of neural inputs from many local areas. In what follows we attempt to address this tension, although at this point we cannot offer a quantitative argument.

Thus, we propose, with several others (Pockett, 2000; John, 2001; McFadden, 2002, 2020; Fingelkurts et al., 2010, 2013; Hales, 2014), that an EM field generated by the brain (or even by some less complicated nervous systems) is directly involved in conscious awareness, indeed it *is* phenomenal consciousness. Proposals that some sort of EM field is conscious awareness have not received much attention previously. As mentioned, one serious problem has been that it is difficult to disentangle the parts of the brain's EM field that reflect conscious awareness from those that reflect unconscious information processing. Some previous proposals implicate the entire EM field of the brain in PC (Pockett, 2000; Hales, 2014), whereas others argue that the EM field relevant to PC is generated in specific parts of the brain (this article; John, 2001) or in respect of a specific kind of brain activity (McFadden, 2002, 2020), and yet others propose a nested hierarchy of EM fields in the brain (Fingelkurts et al., 2010, 2013). We will address this problem directly in Sections "Where in the brain? The thalamic dynamic core" and "The Conscious EM Field."

WHERE IN THE BRAIN? THE THALAMIC DYNAMIC CORE

Is the substrate of PC generated in some particular part of the brains/nervous systems of conscious entities or does it comprise the entirety of the brain/body? Our answer: a part of the thalamus in mammals, and homologous parts of other brains, generates the critical EM field.

Ward (2011) argued that the substrate for PC is located in the thalamus of the brain. The argument rested on four "pillars" of evidence. Here we only adumbrate Ward's (2011) argument – please see that paper for detailed argument and more references. First, and perhaps most important, is the fact that PC is restricted to the *results* of cortical computations; the computations themselves do not enter PC. These results constitute a dynamic (ever-changing) core of integrated neural activity associated with PC (cf. Kinsbourne, 1988; Edelman and Tononi, 2000). Ward (2011) provided numerous examples of this fact, one of the most salient being that the extensive computations required to analyze retinal input into a variety of feature maps and then reconstitute these maps into a visual percept (e.g., Marr, 1980; Treisman, 1988) are never available to PC. As Gibson (1979/2014) described it, visual perception is "direct," meaning that we see our visual environment without any awareness of the many intervening processes taking place. We now know much from a third person perspective about these processes (e.g., Coren et al., 2004) but do not experience any of them. The same applies to perceptions arising from all other sensory systems, including endogenous systems, memory retrieval, speech encoding and decoding, and even to thinking (see Ward, 2011 for discussion). As we will discuss later, these results are presented in PC as a niche-relevant view of the world combined with associated thoughts and emotions, which does not need to contain any of the myriad complicated physiological processes that give rise to them in order to adaptively guide behavior.

Second, the thalamus is deeply involved in the action of all common general anesthetics (e.g., Alkire and Miller, 2005), and is typically dysfunctional in patients with unresponsive wakefulness syndrome (UWS), in which a patient evidences sleep-wakefulness cycles but never responds to any external stimuli while "awake." The case of Karen Ann Quinlan is a striking example of the latter. She persisted in UWS for 11 years after a drug-alcohol interaction caused a cardio-pulmonary arrest. Upon autopsy it was discovered that her cortex was fundamentally intact, but her thalamus had suffered significant damage from hypoxia. Other studies of similar incidents point to involvement of the thalamus in nearly all cases. In particular, the dorso-medial nucleus is especially sensitive to damage, with loss of 30% or more of its neurons always associated with UWS (Maxwell et al., 2004). Finally, tissue atrophy in the thalamus is strongly associated with the signs of awareness upon which clinical diagnoses depend, in contrast to atrophy in the basal ganglia, which is associated with clinical signs of wakefulness (Lutkenhoff et al., 2015). Moreover, nontraumatic brain injury (e.g., anoxia) causes more extensive atrophy in the thalamus, with accompanying UWS, than does traumatic brain injury (Lutkenhoff et al., 2015).

Third, the anatomy and physiology of the thalamic neurons, particularly that of the dorso-medial nucleus, are ideally suited for an integrative role. The excitatory neurons have extensive, branching dendritic trees populated by many different types of synapses. Except for the basic sensory nuclei (lateral geniculate, medial geniculate, etc.), they receive all of their input from the cortex, and about 90% of the traffic over cortico-thalamic loops is from cortex to thalamus, only 10% from thalamus to cortex. It seems that the cortex is downloading the results of its computations to the non-sensory thalamic nuclei (cf. Mumford, 1991). Notably, the dorso-medial nucleus receives inputs from nearly all areas of cortex and sub-cortex and is ideally suited to integrate all of this information into a charge flow that would result in a structured EM field comprising it all. Moreover, the dorso-medial nucleus is implicated in numerous neuropsychological disorders, particularly memory disorders (Ward, 2013).

Fourth, neural synchronization is a fairly well-established cortical neural correlate of PC (e.g., Cosmelli et al., 2004; Doesburg et al., 2009), and the thalamus is also a primary source and controller of synchronization, both in cortex and itself through the matrix neurons found in all higher-order thalamic nuclei (e.g., Barth and MacDonald, 1996; Jones, 2009). Synchronization of oscillations in several, now-canonical, frequency bands (theta, alpha, beta, gamma), generated by populations of neurons, has been associated with modulation of numerous cognitive and behavioral tasks in both humans and other animals (e.g., Varela et al., 2001; Ward, 2003; Buszaki, 2006; Womelsdorf et al., 2007; Palva, 2016). It has also been argued to mediate information transfer throughout the cortex (e.g., Fries, 2005, 2015; Buehlmann and Deco, 2010; Akam and Kullmann, 2014; Quax et al., 2017). Moreover, synchronization-mediated information transfer certainly involves the thalamus, or at least the pulvinar nucleus (e.g., Saalmann et al., 2012; Quax et al., 2017;

Jaramillo et al., 2019). Thus, Ward (2011) argued that a thalamic dynamic core of synchronized neural activity, perhaps principally in the dorso-medial nucleus, constitutes the physical substrate of PC.

Merker (2012) discussed the problem of integrating the various sensory and non-sensory neural codes generated in the brain. According to the idea that the brain minimizes free energy by performing predictive coding based on a hierarchy of Bayesian probabilistic operations (Hinton and Sejnowski, 1983; George and Hawkins, 2009; Friston, 2010; Safron, 2020), the lingua franca of the brain is likely to be those probabilities. But we don't experience probabilities. We experience the environment at a niche-relevant scale. Therefore, there must be someplace in the brain where all of the probabilities collapse into percepts, a kind of "winner-take-all" process regarding the various possible states of the world based on incoming sensory information and previous learning. This has been called the problem of "Bayesian blur" (Lu et al., 2016; Clark, 2018). Merker (2012) proposed that the pulvinar nucleus of the thalamus was likely to be such a place, where a "best estimate buffer" integrated and imaged the results of all of the probabilistic computations performed in the cortex. Merker's work places the ideas of the Gestalt psychologists firmly into a modern framework. Merker (2012) also argued persuasively that only a few million neurons – maybe even 1 million – would suffice to generate the relevant human PC field. The pulvinar nucleus comprises several million neurons, as does the dorso-medial nucleus. Thus, either would suffice to support Merker's best estimate buffer.

Another interesting approach to dealing with the problem of the Bayesian blur was the suggestion of Dehaene (2014) that the "collapse" of the Bayesian probability distributions could be likened to the probabilistic collapse, or reduction, of the deterministically evolving wave function in quantum mechanics (see also Safron, 2022). The wave function, comprised of a superposition of all of the possible state trajectories of a quantum system in phase space, is, in the Copenhagen interpretation, caused to "collapse" into a "real" state by the act of "observation." This is similar to the superposition in the Bayesian brain of all of the possible brain states based on the current external and internal context, the Bayesian blur, and the subsequent collapse of these possibilities into an actuality, corresponding to a "real" percept, a thought, etc. This metaphor is suggestive, and is also similar to the idea of "objective reduction" (OR) of the wave function proposed by Penrose (1989), and elaborated by Penrose (1989) and by Hameroff and Penrose (1996) into a theory of quantum computation in the brain that is the basis for PC. This theory is beyond the scope of the present paper, but we note that the hot (in the quantum sense) environment in the brain is thought to cause quantum wave function reduction far faster than would permit the mechanism suggested by Hameroff and Penrose (e.g., Tegmark, 2000). Nonetheless, it is possible that quantum theory could be applicable to PC in some way. For example, the EM field is quantized, and so a quantum formulation of EM information integration could prove to be enlightening. Perhaps such a formulation would lead to a more explicit description of the computational role of EM fields in PC.

Jerath and Crawford (2014) assembled evidence from contralateral neglect syndrome and other sources that implicated the thalamus in PC of 3D space. They proposed, similarly to Ward (2011), that the thalamus integrates "processed information from corticothalamic feedback loops," and also that the thalamus "reimages" visual and other sensory and non-sensory input in a dynamic virtual 3D space in the "mind."

Rudrauf et al. (2017) proposed a mathematical theory of the spatial field of PC in which projective transformations and active inference (predictive coding) play an important role. In their theory, point of view is informed by projective transformations that integrate memory, expectation, and sensory input. Similar to Jerath and Crawford (2014) they postulated a virtual Cyclopean eye located behind the eyes in the center of the head without taking a position on the location or composition of the neural topology that supports it. Point of view is also implicated in the Gibsonian approach (1979/2014, Section "Qualia") – the niche relevant point of view is that of affordances for action which would be from someplace in the body. Because the eyes in the head can "see" positions and movements of limbs and trunk (feedback from movements) the best visual point of view is from somewhere in the middle of the head.

The thalamic dynamic core and similar proposals just discussed make it possible to separate brain activity that directly gives rise to PC from other, supporting, brain activity that remains unconscious. These proposals separate processing that computes the *contents* of consciousness (cortical) from that which *displays* consciousness itself (thalamic). Thus, we propose that the thalamic dynamic core entails that the critically relevant EM field for conscious experience is the one generated by the synchronous neural activity in the thalamic dynamic core. Interfering with this EM field, e.g., as would a lesion in the intralaminar nuclei (Bogen, 1995a,b), disturbs basic phenomenal experience. Interfering with the EM field generated by the cortex, as does, for example, trans-cranial magnetic stimulation (TMS) or a lesion caused by a localized stroke, tumor, or accident, generally only affects the contents computed by the affected cortical area(s).

There are other, somewhat different, points of view on this question, however. For example, Fingelkurts et al. (2010, 2013) argued that the different parts of the brain each create their own EM fields (characterized by them as EEG fields), and that these participate in a cortex-wide hierarchy of interacting fields. In their view the highest-level phenomenal scene is composed of phenomenal objects that are in turn composed of phenomenal features, each of which arises from activity at its own level of the hierarchy (similar to the doctrine of specific nerve energies – see the discussion in Section "The Conscious EM Field"). So, in a sense, all of the levels participate in creating, or are integrated into, the final phenomenal scene we experience, similarly to other theories of global EM field integration. Although we see much to recommend this view of a phenomenal hierarchy, in our view this approach still doesn't answer the question of why the neural *processes* involved in creating each of these phenomenal levels are not experienced, as they are surely represented in the neural activity giving rise to the various phenomenal aspects. Therefore, we prefer the view adumbrated earlier in this section for why phenomenal experience does not include the neural processes that give rise to it.

Finally, there are several sophisticated theories that locate the critical physical processes generating PC firmly in the neuronal activity of the cerebral cortex. Involvement of the thalamus in these theories is usually in a supporting role of promoting computation in local regions, or influencing inter-regional synchronization (e.g., Dehaene, 2014; Tononi et al., 2016; Safron, 2020). Perhaps the most sophisticated of these is that of Safron (2020), who combines the integrated information theory of Tononi et al. (2016) with the neuronal global workspace theory of Dehaene (2014) in the context of predictive coding based on the free energy principle and an active inference framework (e.g., Friston, 2010). Safron's (2020) approach is much too complex even to adumbrate here. The main argument, however, is that "…integrated information only entails consciousness for systems with perspectival reference frames capable of generating models with spatial, temporal, and causal coherence for self and world." Here "consciousness" is meant to be PC. Access consciousness is provided by the integration with global workspace theory, in which various local processes interact in the service of a given conscious episode. Our approach is sympathetic to Safron's (2020), especially in the reference to predictive coding and the perspectival reference frame. In Safron's approach the contents of PC comprise an egocentrically organized visuospatial field, computed by predictive processing hierarchies, particularly in posterio-medial and inferior-lateral parietal cortices. This visuospatial field, embodied in neural activity, is certainly generating an EM field and this could be the EM field for PC. As we argued earlier, however, cortical processing is more likely to consist of probability distributions over possible states of the world. We would argue that these cortical computations would collapse in a winner-take-all thalamic EM field comprising the brain's best guess as to the state of the world. This then, in our view, would be where the computed visuospatial field would be displayed. Safron argues, however, that EM fields in the thalamus, whereas they could be helpful in establishing synchronization manifolds and interregional communication, would not be sufficient on their own as a physical/computational substrate of consciousness. Thus, we are in disagreement here to the extent that, although we acknowledge the importance of cortical computations in creating the visuospatial field, we argue that this field as computed in the cortex is not the critical EM substrate for PC. Our main disagreement really rests on the fact that Safron's approach does not explain why many, or even most, of the processes involved in computing the integrated information that is said to directly generate PC do not appear in PC. We see Safron's approach as the most sophisticated treatment to date of the complex cortical computations that create the information content of the conscious field.

QUALIA

From whence arise the qualia experienced in P-consciousness? Chalmers (1996) argued that explaining experience (phenomenal consciousness) is the "hard" problem (as opposed to the "easy" ones of explaining cognitive mechanisms), and part of that is the classical philosophical problem of qualia. Why is red red? Why is the experience of sound different from that of light and both different from the smell of roses? How is it that neurons that are virtually identical in structure and function can create such a wide range of different qualia? Why is activity of some neurons in the auditory cortex associated with the experience of the sound of a symphony, whereas activity of the same types of neurons in visual cortex is associated with the visual experience of a painting? How is it that auditory thalamus can support *visual* behavior when retinal projections are directed there neonatally (von Melchner et al., 2000), or that parts of visual cortex in the early blind can support *tactile* processing of Braille (e.g., Sadato et al., 1996), or that parts of the auditory cortex support processing of *visual* stimuli in the early deaf (e.g., Finney et al., 2001)?

In our proposal, *sensory* qualia arise from the fact that the *dynamic EM field created by charge flow in the thalamus comprises the information structure associated with the environmental input to sensory systems.* Again, as described by Maxwell's equations for electromagnetism, any movements of charge or changes in electric or magnetic fields in the physical world generate EM fields unique to, indeed structured by, those changes. In other words, such EM fields embody the information content of the moving charges or changing fields (cf. Wheeler, 1990; Grimes and Grimes, 2004). So, in vision, the flux of scattered and direct photons from any particular visual field that impact the retinae of the eyes, the so-called "isovist" (Benedikt, 1979, **Figure 1**), constitutes a distinct dynamic EM field (albeit only part of the EM field available at that place). In this case, several thalamic

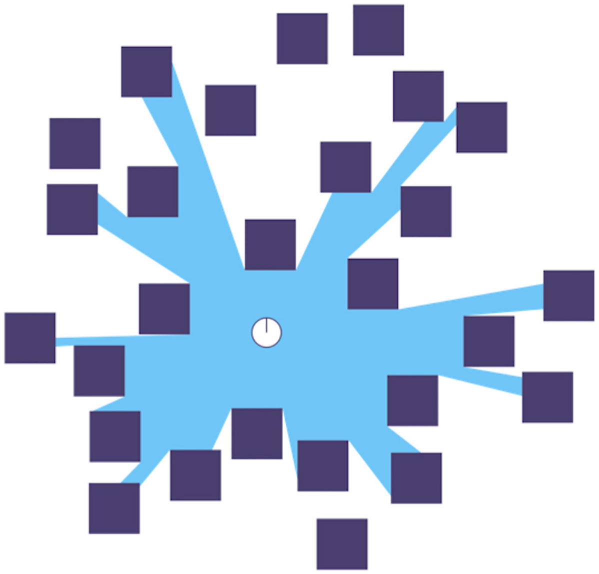

FIGURE 1 | A representation of a 2D isovist in blue relative to the white dot in the center: "A single isovist is the volume of space visible from a given point in space, together with a specification of the location of that point." (Wikipedia). Note how superposition prevents some elements of the scene (some black squares and parts of others) from appearing in the isovist. Diagram from Wikipedia.

nuclei actually emulate that EM field with a thalamic EM field generated by charge flow computed by various visual circuits, mainly cortical, from photons incident on the retinae. Similarly, a structured dynamic EM field is generated in the brain when the sound waves registered by the mechanical actions of the peripheral auditory system stimulate the spiral ganglion and are then processed by the subsequent stages of the auditory system. This EM field comprises the information structure in the sound waves emitted by environmental vibrations characteristic of their sources, including the frequency spectrum and its changes over time. And so on for the other senses, including sensations of movement, pain, pleasure, effort, and thinking (although some of these may be amodal qualia – see later).

More precisely, and consistent with over 200 years of scientific study of sensation and perception (e.g., Gibson, 1979/2014; Coren et al., 2004), the *information structure* of the environment is (approximately) recreated by the brain in the thalamic nuclei (cf. Pribram, 1986; Wheeler, 1990; Chalmers, 1996; John, 2002). The "content of experience" *is* the information structure of the EM field being recreated, or actually emulated in the case of vision, in the thalamic nuclei. Subjectivity arises from the emulating process in a living brain.

What do we mean by "information structure"? Let us focus on vision. When the eyes are open, the spatial distribution of photons from the isovist (**Figure 1**) at any moment comprises a vector field incident on the retina. This is a coarse graining of the photon field scattered from the environment, and also collapsed from three dimensions (3D) to two dimensions (2D). Let us ignore the problem of reconstructing the 3D visual field and focus on the 2D vector field on the retina. We will also ignore time for now. Instead, we assume one small time interval over which the retinal vector-field is integrated/summed. The visual system first analyses and then synthesizes this retinal vector-field, preserving the topology of the retina and thus of the visual field. This analysis also preserves the distribution of wavelengths/frequencies (although only the ratio of long to short wavelengths is used at the highest level) via cone type absorption spectra, and overall density of photons (intensity) at each coarse-grained point. Molecules in rods and cones absorb photons, thus collapsing the integrated fields of those photons and using the energy therein to isomerize pigments and begin biochemical processes that result in generator potentials that stimulate various neurons in the retina, which in turn stimulate neurons further up the visual system and so on. As pointed out by Anne Treisman (e.g., Treisman, 1988) the visual system constructs many retinal-topology-preserving maps containing spatial information about various features, such as color, shape, movement, etc., but then must integrate these maps (in her theory by attending to a spatial location) into a percept as seen from a particular point of view.

The isovist (**Figure 1**) is defined relative to the positions of the eyes in the body – there are two of them for a typical person – one for each eye – the difference of the two isovists, each collapsed to 2D on the retinae and each from a slightly different point of view, contains information that allows inference of the 3D isovist of a centrally placed eye (Cyclopean) from the separate 2D isovists. This must cohere with Rudrauf et al.'s (2017) theory and it does: point of view is a property of the isovist. The information structure of the EM field incident on the retina is comprised of the totality of photons, and their attendant properties, scattered by the elements of the environment within the isovist. We argue that a coarse-grained representation, or *emulation*, of this information structure is recreated by the visual system to produce the image we "see," and that this is done in the thalamus (cf., Jerath and Crawford, 2014), likely in the dorsomedial nucleus (Ward, 2011). This approach is consistent with that of Merker (2012), who argues that this occurs in a "best estimate buffer," although he locates it in the pulvinar nucleus of the thalamus.

In this proposal, the different experiential aspects of *sensory* qualia arise from the fact that the information structures produced in this way are unique to the particular aspect of the environment whose information structure is being emulated, for example, light (including wavelength, intensity, etc.), sound (frequency spectrum, temporal modulation, intensity), molecular vibration of taste and smell molecules, damage to biological structures (pain), and so forth. It all ends up as structured charge flow in the thalamus. Many aspects of higher-level computations, of course, do not have any corresponding environmental informational structure – they are unique to the computations performed in higher human cortex – and such computations will have unique, non-sensory, qualia. Some will be "amodal" (that is, having no sensory modality such as sight, hearing, etc.) and others will "feel" a certain way (perhaps because they would be associated with visual or auditory images), because the EM field created by the results of such computations sent to the relevant thalamic nuclei will "be" unique qualia. Emotional qualia will be blends of "visceral" qualia and "cognitive" qualia (cf. Damasio, 1999). The feeling of acting, of moving limbs and making effort, too, will be blends of various other qualia, both sensory and non-sensory. All of these EM fields must share the special character that differentiates conscious fields from non-conscious ones. This notion is consistent with Edelman and Tononi's (2000) description of a very large-dimensional "qualia space" in which qualia are represented by vectors. In this view, some of the subspaces of this space would be sensory or emotional, and some would be more abstract, having the "feel" of cognition. Some could even be "imaginary," that is, associated with things that aren't real, like the feeling of oneself flying over the ocean without being in an airplane.

THE CONSCIOUS ELECTROMAGNETIC FIELD

What differentiates the P-conscious EM field from other EM fields, e.g., the flux of photons scattered from object surfaces, the EM field of an electromagnet, the EM fields generated in the brain that do not enter P-consciousness, such as those generated in the retina or occipital cortex, or those generated in brain areas that guide behavior through visual information in persons exhibiting "blindsight"? Our answer: living systems express a boundary between themselves and the environment, requiring them to model (coarsely emulate) information from their environment in order to control, through actions, to the extent possible, the vast sea of variety in which they are immersed (cf. Ashby, 1958; Dennett, 1991). This model, expressed in an EM field, *is* P-consciousness. The model is the best possible representation of the moment-to-moment niche-relevant (action-relevant) information an organism can generate, a *Gestalt,* or in Merker's terms a "best-estimate buffer." Information that is at a lower level than niche-relevant, such as the unanalyzed retinal vector-field, is not represented in P-consciousness because it is not niche-relevant. Living organisms have sensory and other systems that have evolved to supply such information, albeit in a coarse form relative to the information actually comprising their environment (e.g., de Vries and Ward, 2016; Feinberg and Mallatt, 2016; Morsella et al., 2016; de Haan et al., 2021).

The group of synchronously active thalamic neurons that constitutes the thalamic dynamic core produces, through its enormously complicated, synchronously oscillating electric charges, an EM field that must have some special characteristic possessed neither by the other, weaker and usually mutually incoherent fields produced by local circuits not joining in the dynamic core, nor by the myriad cortical circuits, also firing synchronously with the thalamic dynamic core, that are computing the contents being represented there. As mentioned earlier, it is difficult to discern what this special character could be. One possibility is that the field would need to be of a certain "strength," although this would deny awareness to smaller animals, a position that is somewhat implausible given the evident similarities in brain structure among, e.g., mammals, and the complicated behavior of some non-mammals such as birds. Another possibility is that the conscious field would have some particular informational character, again, as mentioned earlier, perhaps related to the complexity and differentiation/integration properties emphasized by Sporns et al. (2000) and Tononi et al. (2016). Finally, an EM field arising from the synchronized behavior of millions of neurons would be unitary and reinforcing, whereas those arising from the isolated (although locally synchronous) activity of nuclei not integrated into the dynamic core would tend to cancel out, or at best inform the "fringe" of consciousness identified by James (1890).

Therefore, a question arises: why postulate an EM field rather than just complicated neural activity as the essential physical substrate of PC as has been done by many other researchers? Is dense neural activity alone not sufficient? If it were, then we must ask what aspect(s) of this neural activity creates and differentiate(s) the various qualia, especially sensory qualia?

Some Greek philosophers, such as Democritus (460—370 B.C.E.; cf. Russell, 1945), thought the answer was "eidola," copies shed by perceptual objects that were carried up little pipes to a homunculus in the head that experienced them. In a way this answer was prescient of the view of Gibson (1979/2014), in that some aspect of the environment itself was thought to be entering the perceiver. Descartes (1664) proposed a mechanistic view in which "motions" in the world were translated by the senses into "motions" in the body machine that were related to the motions in the world. These motions were then experienced in the mind via the pineal gland. An even more sophisticated viewpoint, one that prevailed far into the modern era, was the "doctrine of specific nerve energies," in which different sensory nerves conducted to consciousness their own state, not, at least not directly, the state of the external world (Müller, 1835). Here, each type of sensory nerve had its own "specific nerve energy" that equated to the sensation it produced in the observer. Thus, activity in visual nerves would be "seen," activity in auditory nerves would be "heard," activity in gustatory nerves would be "tasted," and so forth. The fact that visual nerves are connected to light sensors, etc., was the connection to the external world. This latter appears to be the view of some researchers still, e.g., Haikonen (2020). In Haikonen's view, qualia equate to "self-explanatory information," which arises from basic "sensory percepts" or their mental analogs. In Haikonen's robot these "meanings" are analog electrical signals from sensors and effectors that are associatively linked to produce pattern recognition, memory, etc. In humans, we gather, they would be the (unspecified, analog?) neural activity produced locally in visual, auditory, etc. systems. Fingelkurts et al. (2010) also might be said to subscribe to this view, although they emphasize the local EM fields as the substrates of the simple phenomenal qualia.

Our modern knowledge of neural information processing, however, has discounted the doctrine of specific nerve energies and its relatives as an explanation for sensory qualia. Indeed, Adrian (1926) showed that all motor and sensory nerves function in the same way, via electro-chemical energy, so that it would be impossible to tell from a recording of a stream of spike potentials whether they were occurring in a visual nerve, an auditory nerve, or, indeed in any part of the central nervous system that produces such potentials, unless one knew how the relevant information was encoded in the stream of spikes. He proposed that it was *where* in the brain a sensory nerve projected that made the difference in qualia experienced. But this cannot be the answer either, although still espoused by several researchers (e.g., Rolls and Treves, 2011). This is because, as mentioned in Section "Qualia," the visual cortex can support inputs from either vision, auditory, or touch sensors, the auditory cortex can support those from either auditory or visual sensors, etc. In these cases, the qualia are those associated with the *input*, *not* those of the receiving area of cortex.

So what could be the alternative to the doctrine of specific nerve energies, or any of the other theories of qualia based on dense neural activity? There has to be some way sensory and other, derived, information is represented in the brain other than "which" neuron is firing, because sensory nerves operate similarly; pyramidal, stellate, etc. neurons are highly similar everywhere in the cortex, and thalamic neurons are similar in various nuclei as well. It must be "how" they are firing (or oscillating, or what is happening in charge flow within them and their dendrites, etc.) that represents the *information* sent from the receptors. This again recalls the idea of the Bayesian brain, where the neural activity represents probabilities of brain states, and thus states of the external (or internal) world (e.g., Hinton and Sejnowski, 1983; George and Hawkins, 2009; Friston, 2010). But how? Consider a color map in V2: it is a topological representation of which wavelength mix of photons is striking which part of the retina, and eventually originating from somewhere in 3D space. At the retina and in early visual areas this is somewhat ok – although opponent processes complicate matters. But when we get to Land territory (V4 and above), where all that matters is the ratio of long to short wavelengths to recreate the color distribution corresponding to photon wavelength across the entire visual scene, we are in trouble with any direct representation of wavelength. So how can the various qualia arise from various distributions of neural activity that are indistinguishable unless we know from outside what they represent? What is the fundamental neural correlate of qualia? We argue that it must be the way in which the neural activity represents, or emulates, the information structure of the relevant input, and that information structure is unique to the input itself.

As mentioned in Section "Physical substrate for P-consciousness," Merker (2012) offered a solution to one aspect of this problem: that of how the brain manages to integrate the neural codes from very different sensory transducers and processors. He points to the idea that in the Bayesian brain it's all about probabilities, a Bayesian blur. He argued that the cortex uses probabilities as its lingua franca but then, because we don't "see" probabilities, must somewhere collapse these into conscious percepts, with a point of view, etc. Merker argued that the collapse occurs in the pulvinar nucleus, Ward (2011) has it in the dorsomedial nucleus, for still others it could be in somewhere in cortex (e.g., Safron, 2020).

CONCLUSION

We have argued that in vision a complex EM field (photons) interacts with matter fields in the environment to generate a complex dynamic EM field that contains information (space-time distribution of frequencies and densities of photons) about the matter fields with which it has interacted. The eyes receive the photons from the isovist. These 3D dynamic EM fields are collapsed to 2D fields as they interact with the matter fields comprising the retinae, whilst preserving the topology of the isovist. The *information* contained in the complex retinal vector-field is analyzed and then synthesized by the neural structures of the visual system, and the synthesis is used to emulate the original complex external field within the brain (thalamus – DM nucleus?). A similar story can be told for the other sensory systems, although the environmental or somatosensory information is not generally presented to the receptors as EM fields, and also for cognition and emotion.

Our story, however, is obviously not complete (or detailed enough). According to Gibson (1979/2014) and to us, the *information* in the environment is what ultimately is responsible for the sensory qualia. So, an important question is: why do we see wavelength/frequency of photons as colors? Why do we hear sound frequency as pitch? Why does pain feel the way it does? Pleasure? Early Gibson emphasized direct perception of information from the environment, whereas later Gibson emphasized that the environmental information is used to compute affordances for action. So, then, why do we see, hear, etc., instead of just acting/behaving based on ambient information? Environmental information is rendered in niche-relevant form, which includes the effectors and egocentric position and motion of the actor, allocentric motion of parts of the environment, as well as environmental features relevant to goals, needs and security. If behavior actually begins in the brain *before* the triggering/relevant information is rendered in P-consciousness, as argued by, for example, Libet (1999) and Soon et al. (2008), *what then is the role of phenomenal consciousness?* It is becoming clearer what the role of the underlying brain activity giving rise to PC is, but why have the phenomenal experience at all when it occurs later? Some answers have been suggested, such as that PC is epiphenomenal, or that the P-conscious EM field (or dynamic core of neural activity) can affect processing in nearby or even distant parts of the brain, but most feel that there are serious problems with each of these answers. Thus, this question, part of Chalmers' (1996) hard problem, remains unsolved.

DATA AVAILABILITY STATEMENT

The original contributions presented in this study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

LMW and RG wrote and edited the various drafts of the manuscript. Both authors contributed to the article and approved the submitted version.

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REFERENCES

Adrian, E. D. (1926). The impulses produced by sensory nerve endings. Part I. *J. Physiol.* 61, 49–72. doi: 10.1113/jphysiol.1926.sp002273

Akam, T., and Kullmann, D. M. (2014). Oscillatory multiplexing of population codes for selective communication in the mammalian brain. *Nat. Rev. Neurosci.* 15, 111–122. doi: 10.1038/nrn3668

Alkire, M. T., and Miller, J. (2005). General anesthesia and the neural correlates of consciousness. *Prog. Brain Res.* 150, 227–242. doi: 10.1016/S0079-6123(05)50017-7

Ashby, W. R. (1958). Requisite variety and its implications for the control of complex systems. *Cybernetica* 1, 83–99.

Barth, D. S., and MacDonald, K. D. (1996). Thalamic modulation of high-frequency oscillating potentials in auditory cortex. *Nature* 383, 78–81. doi: 10.1038/383078a0

Benedikt, M. (1979). To take hold of space: isovists and isovist fields. *Environ. Plann. B* 6, 47–65. doi: 10.1068/b060047

Bogen, J. E. (1995a). On the neurophysiology of consciousness: I. An overview. *Conscious. Cogn.* 4, 52–62. doi: 10.1006/ccog.1995.1003

Bogen, J. E. (1995b). On the neurophysiology of consciousness: part II. Constraining the semantic problem. *Conscious. Cogn.* 4, 137–158. doi: 10.1006/ccog.1995.1020

Buehlmann, A., and Deco, G. (2010). Optimal information transfer in the cortex through synchronization. *PLoS Comput. Biol.* 6:e1000934. doi: 10.1371/journal.pcbi.1000934

Buszaki, G. (2006). *Rhythms of the Brain*. New York, NY: Oxford University Press. doi: 10.1093/acprof:oso/9780195301069.001.0001

Buzsaki, G., and Draguhn, A. (2004). Neuronal oscillations in cortical networks. *Science* 304, 1926–1929. doi: 10.1126/science.1099745

Chalmers, D. (1996). *The Conscious Mind: In Search of a Fundamental Theory*. New York, NY: Oxford University Press.

Clark, A. (2018). Beyond the 'Bayesian blur.' *J. Conscious. Stud.* 25, 71–87.

Coren, S., Ward, L. M., and Enns, J. T. (2004). *Sensation and Perception*, 6th Edn. Hoboken, NJ: Wiley, 598. doi: 10.1002/0471264385.wei0105

Cosmelli, D., David, O., Lachaux, J.-P., Martinerie, J., Garnero, L., Renault, B., et al. (2004). Waves of consciousness: ongoing cortical patterns during binocular rivalry. *Neuroimage* 23, 128–140. doi: 10.1016/j.neuroimage.2004.05.008

Crick, F. (1994). *The Astonishing Hypothesis: The Scientific Search for the Soul*. New York, NY: Simon & Schuster.

Damasio, A. (1999). *The Feeling of What Happens*. London: William Heinemann.

de Haan, E. H. F., Scholte, H. S., Pinto, Y., Foschi, N., Polonara, G., and Fabri, M. (2021). Singularity and consciousness: a neuropsychological contribution. *J. Neuropsychol.* 15, 1–19. doi: 10.1111/jnp.12234

de Vries, J., and Ward, L. M. (2016). An "ecological" action-based synthesis. *Behav. Brain Sci.* 39:e168. doi: 10.1017/S0140525X15002046

Dehaene, S. (2014). *Consciousness and the Brain: Deciphering How the Brain Codes Our Thoughts*. New York, NY: Viking.

Delorme, A., Palmer, J., Onton, J., Oostenveld, R., and Makeig, S. (2012). Independent EEG sources are dipolar. *PLoS One* 7:e30135. doi: 10.1371/journal.pone.0030135

Dennett, D. C. (1991). *Consciousness Explained*. New York, NY: Little, Brown.

Descartes, R. (1664). *Le monde, ou, Le Traite de la Lumiere, et des Autres Principaux Objects des Sens*. Paris: Girard.

Doesburg, S. M., Green, J. J., McDonald, J. J., and Ward, L. M. (2009). Rhythms of consciousness: binocular rivalry reveals large-scale oscillatory network dynamics mediating visual perception. *PLoS One* 4:e6142. doi: 10.1371/journal.pone.0006142

Edelman, G. M., and Tononi, G. (2000). *A Universe of Consciousness*. New York, NY: Basic Books.

Feinberg, T. E., and Mallatt, J. M. (2016). *The Ancient Origins of Consciousness: How the Brain Created Experience*. Cambridge, MA: MIT Press. doi: 10.7551/mitpress/10714.001.0001

Feynman, R. P., Leighton, R. B., and Sands, M. (1964). *The Feynman Lectures on Physics*. Reading MA: Addison-Wesley. doi: 10.1063/1.3051743

Fingelkurts, A. A., Fingelkurts, A. A., and Neves, C. F. H. (2010). Natural world physical, brain operational, and mind phenomenal space-time. *Phys. Life Rev.* 7, 195–249. doi: 10.1016/j.plrev.2010.04.001

Fingelkurts, A. A., Fingelkurts, A. A., and Neves, C. F. H. (2013). Consciousness as a phenomenon in the operational architectonics of brain organization: criticality and self-organization considerations. *Chaos Solitons Fractals* 55, 13–31. doi: 10.1016/j.chaos.2013.02.007

Finney, E. M., Fine, I., and Dobkins, K. R. (2001). Visual stimuli activate auditory cortex in the deaf. *Nat. Neurosci.* 4, 1171–1173. doi: 10.1038/nn763

Fries, P. (2005). A mechanism for cognitive dynamics: neuronal communication through neuronal coherence. *Trends Cogn. Sci.* 9, 474–480. doi: 10.1016/j.tics.2005.08.011

Fries, P. (2015). Rhythms for cognition: communication through coherence. *Neuron* 88, 220–235. doi: 10.1016/j.neuron.2015.09.034

Friston, K. (2010). The free-energy principle: a unified brain theory? *Nat. Rev. Neurosci.* 11, 127–138. doi: 10.1038/nrn2787

George, D., and Hawkins, J. (2009). Towards a mathematical theory of cortical micro-circuits. *PLoS Comput. Biol.* 5:e1000532. doi: 10.1371/journal.pcbi.1000532

Gibson, J. J. (1979/2014). *The Ecological Approach to Visual Perception*. New York, NY: Psychology Press. doi: 10.4324/9781315740218

Grimes, D. M., and Grimes, C. A. (2004). *The Electromagnetic Origin of Quantum Theory and Light*. Hackensack, NJ: World Scientific. doi: 10.1142/5592

Guevara Erra, R., Mateos, D. M., Wennberg, R., and Perez Velazquez, J. L. (2016). Statistical mechanics of consciousness: maximization of information content of network is associated with conscious awareness. *Phys. Rev. E* 94:052402. doi: 10.1103/PhysRevE.94.052402

Haikonen, P. O. A. (2020). On artificial intelligence and consciousness. *J. Artif. Intell. Conscious.* 7, 73–82. doi: 10.1142/S2705078520500046

Hales, C. G. (2014). The origins of the brain's endogenous electromagnetic field and its relationship to provision of consciousness. *J. Integr. Neurosci.* 13, 313–361. doi: 10.1142/S0219635214400056

Hameroff, S., and Penrose, R. (1996). Orchestrated reduction of quantum coherence in brain microtubules: a model for consciousness. *Math. Comput. Simul.* 40, 453–480. doi: 10.1016/0378-4754(96)80476-9

Hinton, G. E., and Sejnowski, T. J. (1983). "Optimal perceptual inference," in *Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition*, Washington, DC, 448–453.

James, W. (1890). *Principles of Psychology*. New York, NY: Henry Holt and Company. doi: 10.1037/10538-000

Jaramillo, J., Mejias, J. F., and Wang, X.-J. (2019). Engagement of pulvino-cortical feedforward and feedback pathways in cognitive computations. *Neuron* 101, 321–336. doi: 10.1016/j.neuron.2018.11.023

Jennett, B., Adams, J. H., Murray, L. S., and Graham, D. I. (2001). Neuropathology in vegetative and severely disabled patients after head injury. *Neurology* 59, 486–490. doi: 10.1212/WNL.56.4.486

Jennett, B., and Plum, F. (1972). Persistent vegetative state after brain damage. A syndrome in search of a name. *Lancet* 1, 734–737. doi: 10.1016/S0140-6736(72)90242-5

Jerath, R., and Crawford, M. W. (2014). Neural correlates of visuospatial consciousness in 3D default space: insights from contralateral neglect syndrome. *Conscious. Cogn.* 28, 81–93. doi: 10.1016/j.concog.2014.06.008

John, E. R. (2001). A field theory of consciousness. *Conscious. Cogn.* 10, 184–213. doi: 10.1006/ccog.2001.0508

John, E. R. (2002). The neurophysics of consciousness. *Brain Res. Rev.* 39, 1–28.

Jones, E. G. (2009). Synchrony in the interconnected circuitry of the thalamus and cerebral cortex. *Ann. N. Y. Acad. Sci.* 1157, 10–23. doi: 10.1111/j.1749-6632.2009.04534.x

Kinsbourne, M. (1988). "Integrated field theory of consciousness," in *Consciousness in Contemporary Science*, eds A. J. Marcel and E. Bisiach (New York, NY: Oxford University Press), 239–256. doi: 10.1093/acprof:oso/9780198522379.003.0011

LaBerge, D., and Kasevich, R. (2007). The apical dendrite theory of consciousness. *Neural Netw.* 20, 1004–1020. doi: 10.1016/j.neunet.2007.09.006

Libet, B. (1999). Do we have free will? *J. Conscious. Stud.* 6, 47–57.

Lu, Y., Stafford, T., and Fox, C. (2016). Maximum saliency bias in binocular fusion. *Conn. Sci.* 28, 258–269. doi: 10.1080/09540091.2016.1159181

Lutkenhoff, E. S., Chiang, J., Tshibanda, L., Kamau, E., Kirsch, M., Pickard, J. D., et al. (2015). Thalamic and extrathalamic mechanisms of consciousness after severe brain injury. *Ann. Neurol.* 78, 68–76. doi: 10.1002/ana.24423

Marr, D. (1980). *Vision*. New York, NY: Academic Press.

Martin, S., Iturrate, I., Millan, J., del, R., Knight, R. T., and Pasley, B. N. (2018). Decoding inner speech using electrocorticography: progress and challenges toward a speech prosthesis. *Front. Hum. Neurosci.* 12:422. doi: 10.3389/fnins.2018.00422

Maxwell, W. L., Pennington, K., MacKinnon, M. A., Smith, D. H., McIntosh, T. K., Wilson, J. T. L., et al. (2004). Differential responses in three thalamic nuclei in moderately disabled, severely disabled and vegetative patients after blunt head injury. *Brain* 127, 2470–2478. doi: 10.1093/brain/awh294

McFadden, J. (2002). Synchronous firing and its influence on the brain's magnetic field. *J. Conscious. Stud.* 9, 23–50.

McFadden, J. (2020). Integrating information in the brain's EM field: the cemi field theory of consciousness. *Neurosci. Conscious.* 2020:niaa016. doi: 10.1093/nc/niaa016

Merker, B. (2012). "From probabilities to percepts," in *Being in Time: Dynamical Models of Phenomenal Experience*, eds S. Edelman, T. Fekete, and N. Zach (New York, NY: John Benjamins Publishing Company), 37–79. doi: 10.1075/aicr.88.03mer

Merker, B., Willford, K., and Rudrauf, D. (2021). The integrated information theory of consciousness: a case of mistaken identity. *Behav. Brain Sci.* 45:e41. doi: 10.1017/S0140525X21000881

Morsella, E., Goodwin, C. A., Jantz, T. K., Krieger, S. C., and Gazzaley, A. (2016). Homing in on consciousness in the nervous system: an action-based synthesis. *Behav. Brain Sci.* 39:e168. doi: 10.1017/S0140525X15000643

Müller, J. (1835). *Handbuch der Physiologie des Menschen für Vorlesungen, Bd. 1*, 2nd Edn. Bonn: Hölscher. doi: 10.5962/bhl.title.128395

Mumford, D. (1991). On the computational architecture of the neocortex. I The role of the thalamo-cortical loop. *Biol. Cybern.* 65, 135–145. doi: 10.1007/BF00202389

Mumford, D. (1992). On the computational architecture of the neocortex. II The role of cortico-cortical loops. *Biol. Cybern.* 66, 241–251. doi: 10.1007/BF00198477

Nunez, P. L. (2000). Toward a quantitative description of large-scale neocortical dynamic function and EEG. *Behav. Brain Sci.* 23, 371–381. doi: 10.1017/S0140525X00003253

Palva, S. (2016). *Multimodal Oscillation-Based Connectivity Theory*. New York, NY: Springer. doi: 10.1007/978-3-319-32265-0

Penrose, R. (1989). *The Emperor's New Mind: Concerning Computers, Minds, and the Laws of Physics*. Oxford: Oxford University Press. doi: 10.1093/oso/9780198519737.001.0001

Pockett, S. (2000). *The Nature of Consciousness: A Hypothesis*. San Jose, CA: Writers Club Press.

Pribram, K. H. (1986). The cognitive revolution and mind/brain issues. *Am. Physiol.* 41, 507–520.

Pribram, K. H. (1991). *Brain and Perception: Holonomy and Structure in Figural Processing*. Mahwah, NJ: Lawrence Erlbaum.

Proix, T., Saa, J. D., Christen, A., Martin, S., Pasley, B. N., Knight, R. T., et al. (2022). Imagined speech can be decoded from low- and cross-frequency intracranial EEG features. *Nat. Commun.* 13:48. doi: 10.1038/s41467-021-27725-3

Quax, S., Jensen, O., and Tiesinga, P. (2017). Top-down control of cortical gamma-band communication via pulvinar induced phase shifts in the alpha rhythm. *PLoS Comput. Biol.* 13:e1005519. doi: 10.1371/journal.pcbi.1005519

Revonsuo, A. (2006). *Inner Presence: Consciousness as a Biological Phenomenon*. Cambridge, MA: The MIT Press.

Rolls, E. T., and Treves, A. (2011). The neuronal encoding of information in the brain. *Prog. Neurobiol.* 95, 448–490. doi: 10.1016/j.pneurobio.2011.08.002

Rudrauf, D., Bennequin, D., Granic, I., Landini, G., Friston, K., and Williford, K. (2017). A mathematical model of embodied consciousness. *J. Theor. Biol.* 428, 106–131. doi: 10.1016/j.jtbi.2017.05.032

Russell, B. (1945). *A History of Western Philosophy*. New York, NY: Simon & Schuster.

Saalmann, Y. B., Pinsk, M. A., Wang, L., Li, X., and Kastner, S. (2012). The pulvinar regulates information transmission between cortical areas based on attention demands. *Science* 337, 753–756.

Sadato, N., Pascual-Leone, A., Grafman, J., Ibanez, V., Deiber, M. P., Dold, G., et al. (1996). Activation of primary visual cortex by Braille reading in blind subjects. *Nature* 380, 526–528. doi: 10.1038/380526a0

Safron, A. (2020). An integrated world modeling theory (IWMT) of consciousness: combining integrated information and global neuronal workspace theories with the free energy principle and active inference framework; toward solving the hard problem and characterizing agentic causation. *Front. Artif. Intell.* 3:30. doi: 10.3389/frai.2020.00030

Safron, A. (2022). Integrated world modeling theory (IWMT) expanded: implications for theories of consciousness and artificial intelligence. *PsyArXiv [Preprint]* doi: 10.31234/osf.io/rm5b2

Searle, J. R. (2000). Consciousness. *Annu. Rev. Neurosci.* 23, 557–578. doi: 10.1146/annurev.neuro.23.1.557

Seth, A. K., and Baars, B. J. (2005). Neural Darwinism and consciousness. *Conscious. Cogn.* 14, 140–168. doi: 10.1016/j.concog.2004.08.008

Soon, C. S., Brass, M., Heinze, H.-J., and Haynes, J.-D. (2008). Unconscious determinants of free decisions in the human brain. *Nat. Neurosci.* 11, 543–545. doi: 10.1038/nn.2112

Sporns, O., Tononi, G., and Edeleman, G. M. (2000). Connectivity and complexity: the relationship between neuroanatomy and brain dynamics. *Neural Networks* 13, 909–922.

Tegmark, M. (2000). Importance of quantum decoherence in brain processes. *Phys. Rev. E* 61, 4194–4206.

Tononi, G., Boly, M., Massimini, M., and Koch, C. (2016). Integrated information theory: from consciousness to its physical substrate. *Nat. Rev. Neurosci.* 17, 450–461. doi: 10.1038/nrn.2016.44

Treisman, A. M. (1988). Features and objects: the fourteenth Bartlett memorial lecture. *Q. J. Exp. Psychol. A* 40, 201–237. doi: 10.1080/02724988843000104

Varela, F., Lachaux, J. P., Rodriguez, E., and Martinerie, J. (2001). The brainweb: phase synchronization and large-scale integration. *Nat. Rev. Neurosci.* 2, 229–239. doi: 10.1038/35067550

von Melchner, L., Pallas, S. L., and Sur, M. (2000). Visual behaviour mediated by retinal projections directed to the auditory pathway. *Nature* 404, 871–876. doi: 10.1038/35009102

Ward, L. M. (2002). "Synchronous relaxation oscillators and inner psychophysics," in *Fechner Day 2002*, eds J. A. Da Silva, E. H. Matsushima, and N. P. Ribeiro-Filho (Rio de Janeiro: International Society for Psychophysics), 145–150.

Ward, L. M. (2003). Synchronous neural oscillations and cognitive processes. *Trends Cogn. Sci.* 7, 553–559. doi: 10.1016/j.tics.2003.10.012

Ward, L. M. (2011). The thalamic dynamic core theory of conscious experience. *Conscious. Cogn.* 20, 464–486. doi: 10.1016/j.concog.2011.01.007

Ward, L. M. (2013). The thalamus: gateway to the mind. *Wiley Interdiscip. Rev. Cogn. Sci.* 4, 609–622. doi: 10.1002/wcs.1256

Wheeler, J. A. (1990). "Information, physics, quantum: the search for links," in *Complexity, Entropy and the Physics of Information, SFI Studies in the Sciences of Complexity*, Vol. VIII, ed. W. H. Zurek (Redwood City, CA: Addison-Wesley), 3–28.

Wolters, C., and de Munck, J. C. (2007). Volume conduction. *Scholarpedia* 2:1738. doi: 10.4249/scholarpedia.1738

Womelsdorf, T., Schoffelen, J. M., Oostenveld, R., Singer, W., Desimone, R., Engel, A. K., et al. (2007). Modulation of neuronal interactions through neuronal synchronization. *Science* 316, 1609–1612. doi: 10.1126/science.1139597

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Consciousness and inward electromagnetic field interactions

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Electromagnetic field (EMF) theories of mind/brain integration have been proposed to explain brain function for over seventy years. Interest in this theory continues to this day because it explains mind-brain integration and it offers a simple solution to the "binding problem" of our unified conscious experience. Thus, it addresses at least in part the "hard problem" of consciousness. EMFs are easily measured and many corelates have been noted for field activity; associated with loss and recovery of consciousness, sensory perceptions, and behavior. Unfortunately, the theory was challenged early on by experiments that were thought to have ruled out a role of EMFs in brain activity, and the field of neuroscience has since marginalized EMF theories. Here I explain why early evidence against EMFs contributing to consciousness was misinterpreted and offer an alternative view to help direct future research.

KEYWORDS

mind, electrodynamic, chaos, ephaptic, quantum fields

Introduction

Electromagnetic field (EMF) theories of mind/brain integration posit that current flow across neuronal membranes generates an electromagnetic field which, in turn, permits computation and integration of information, that produces a conscious mind (Pockett, 2014; McFadden, 2020). Thus, consciousness arises from a dynamic electromagnetic field that reflects synaptic and discharge currents of neurons throughout the brain (Köhler and Held, 1949; Jones, 2013). The prevailing idea is that the EMF forms an aura-like three-dimensional energy cloud emanating from our brains, and extending beyond our skulls, where it can be recorded as EEG and/or MEG signals that exhibit complex patterns (**Figure 1**). I present a new way to visualize these complex patterns, using non-linear dynamic analyses of EEG recordings. 3-D plots of phase information derived from EEG signals nicely track levels of consciousness in humans and animals (MacIver and Bland, 2014; Eagleman and MacIver, 2021). These findings support EMF theories of consciousness, but provide only a crude measure of the complexity and integrating power of EMFs because they only measure the least powerful and most diffuse part of our conscious energy field.

Hypothesis

The standard view of brain/mind integration is illustrated in **Figure 1**, showing how neuronal circuit electrical activity in the brain produces a cloud of energy which radiates as our brain's EMF. The idea being that synaptic and discharge currents in neurons (**Figure 1A**), especially large numbers of connected and synchronously and often rhythmically active neurons (**Figure 1B**) produce an EMF "cloud" of energy that changes moment by moment as underlying brain electrical activity changes. There is no doubt that this energy cloud exists since it is easily measured using both electrical and magnetic detectors (EEG and MEG) (Dyba et al., 2021; Keppler, 2021; Young et al., 2021, 2022; Hales and Ericson, 2022; Kitchener and Hales, 2022). From these measures we know EMFs radiate in 3 dimensions at varying powers and frequencies, represented in **Figure 1C** as differing colors on the right side of the image.

Electromagnetic fields are produced (generated) by neurons that are connected by chemical and/or electrical synapses, as well as *via* ephaptic connections. In **Figure 1A**, an ephaptic connection between two nearby neurons is shown by the synaptic current flow in apical dendrites of the first neuron (red arrows) inducing a depolarizing current flow in an adjacent neuron (blue arrows). Electrical synapses connect dendrites of adjacent neurons *via* gap junctions that are essential for the generation of EEG rhythms (Gołebiewski et al., 2006; Bocian et al., 2011). Larger groups of neurons are connected into circuits, mostly *via* chemical synapses, which are thought to underlie memory engrams and brain computational units (**Figure 1B**). When these circuits are active they produce synchronized synaptic and discharge activity across wide regions of the brain. This synchronized neuronal activity summates to generate the EMFs we record as EEG and MEG signals (**Figure 1C**). We know these fields extend for relatively long distances because they can be measured through at least the 7 mm of the human skull and scalp.

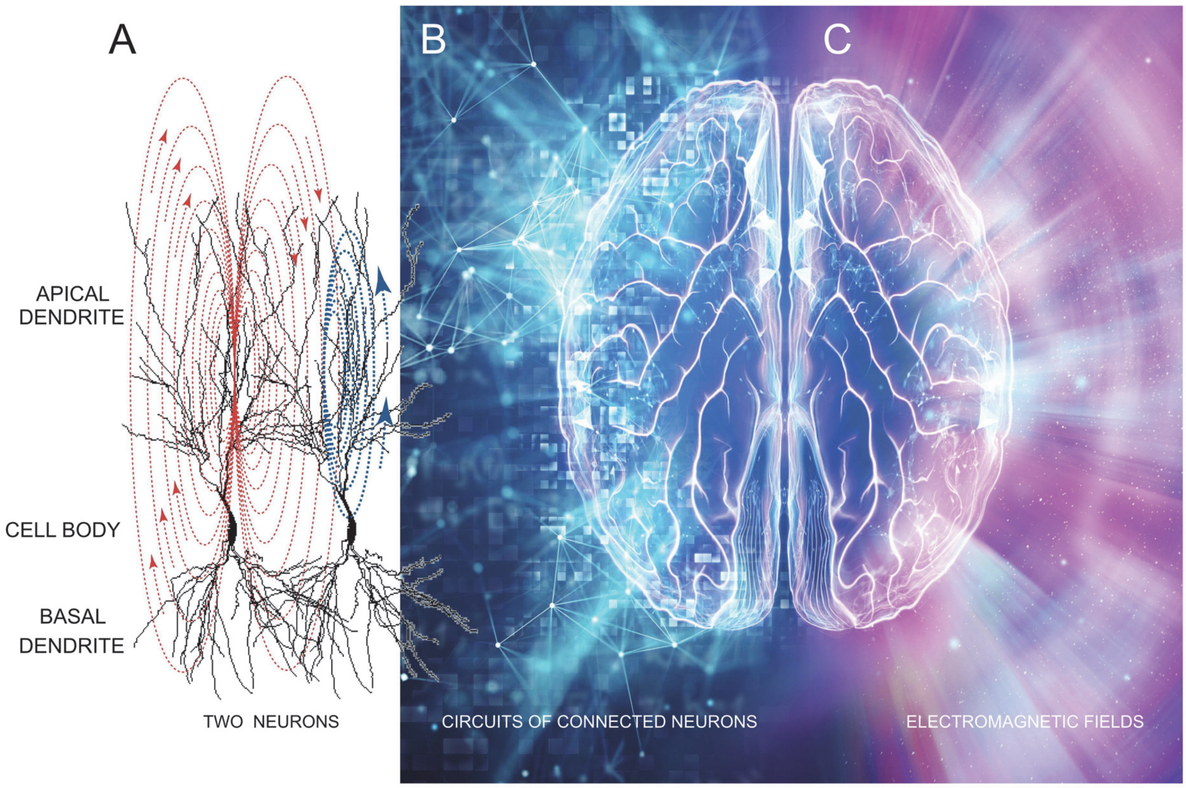

FIGURE 1
A stylistic representation showing how brain neural circuitry **(A,B)** underlies the generation of EMFs **(C)** that unifies brain electrical activity into a conscious whole–that is our mind. Image was modified from freepik.com.

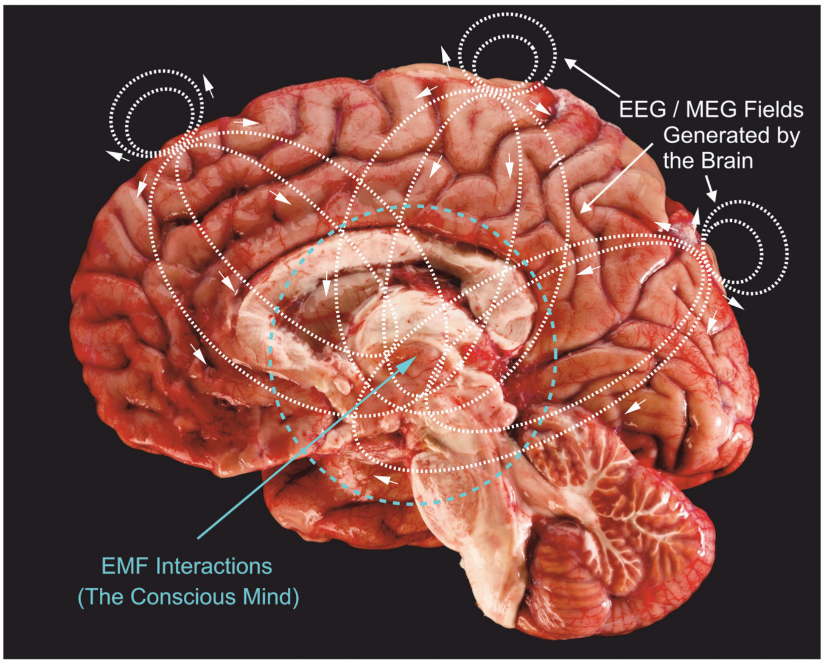

FIGURE 2
Three current sources (e.g., synaptic ion channels) located in upper cortical layers of frontal, midline and occipital areas are shown, together with the charge paths they would produce (dotted lines with small arrows). Synaptic currents are usually carried by positive charges (Na^+ and Ca^{++}) that enter cells across dendritic membranes, so current lines show negative charge movement. These charge paths flow bidirectionally to produce fields above the cortex; these are what we measure with EEG surface electrodes. There are also charge paths directed inward, toward the thalamus and brainstem regions. Inward directed charge pathways would extend further because they are propagating through an electrolytic media that is not impeded by the dura and skull. I propose that these current paths would be concentrated toward the center of brains and generate much stronger EMFs compared to outward directed fields. Brain image modified from ProProfs.com.

The strengths, supporting evidence, and utility of an EMF model have been well reviewed, and a number of proposed weaknesses were refuted by McFadden (2020) as well as in a scholarpedia article (Pockett, 2022). However, the earliest refutations of EMF theories have not been well addressed (Lashley et al., 1951; Sperry et al., 1955). A question remains, why do not EMF shields or perturbations of the EMF affect mental processes?

Placing gold leaf shields or other conductive materials (i.e., electrode arrays) on the brain's surface, to short circuit (shunt) electric current flow, should disrupt or deteriorate an EMF such that an effect on mental processing would be apparent. Yet experiments testing this have failed to show altered mental processes (Lashley et al., 1951; Sperry et al., 1955; Endemann et al., 2022). Why not?

Figure 2 shows the electric current lines generated by just 3 synaptic current sink/sources located in three neocortical regions: frontal, midline and occipital areas. Of course, this is a very simplistic view of actual field generators which are active over wide ranging cortical and subcortical neuronal generators in an ever-changing pattern of complex current paths. The associated magnetic fields are not shown, but would be perpendicular to these current lines. Electrical and magnetic paths radiate in three dimensions, not just in the two dimensions shown in **Figure 2**.

Since synaptic current will take the path of least resistance through interstitial fluid and membranes of the brain, they will extend further into the brain, rather than outward, due to the increased resistance of our skull tissue. Measurements comparing deep electrode responses to surface electrode recordings consistently demonstrate similar or higher signal amplitudes (Hashimoto et al., 1981; Mishra et al., 2021). If the mind is "located" in these centralized overlapping EMFs, then it provides a stronger possibility of unification, "binding" very divergent brain activities into a central whole (Kitchener and Hales, 2022). We can also see (**Figure 2**) that outward fields would play only a small role in modifying neuronal activity through ephaptic influences on neurons. This is critical because we know that EMFs influence the discharge of neurons and this closes a loop for mind-brain duality by linking EMF energy back to controlling neuronal discharge (McFadden, 2013). The increased and focused density of inward directed EMFs would provide stronger ephaptic control of neurons, especially those in the brain's central regions. Placing shields or introducing EMFs from external sources outside of the skull would hardly alter

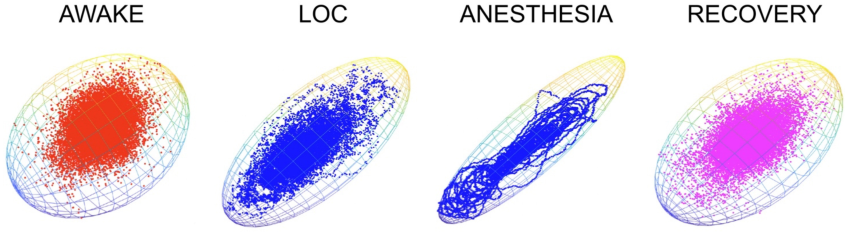

FIGURE 3
Chaotic attractors provide a sensitive measure of levels of consciousness in subjects exposed to an anesthetic. EEG signals were recorded from frontal cortex and processed as previously described (Eagleman et al., 2018b). Attractor plots produce spherical clouds in awake subjects. Loss of consciousness (LOC) is associated with a flattening of the attractor cloud. A further flattening is seen at surgical planes of anesthesia, with a return to a more spherical shape upon recovery, following removal of the anesthetic. Grids indicate best fit boundaries for each 3-D matrix. Unpublished data from Eagleman and MacIver.

inward directed energies and would, hence, not appreciably alter our brain, mind or consciousness; this is what has been observed experimentally (Lashley et al., 1951; Sperry et al., 1955). Similarly, implanted deep brain stimulating electrodes appear to produce too localized a perturbation to alter the mind's EMF, although effects on cognition do occur in some patients (Agashe et al., 2022; Chang et al., 2022). It has long been known that high strength magnetic fields of MRI scanners effect both human and animal subjects, producing dizziness, altered behavioral responses and cognitive impairment (Antunes et al., 2012; Tkáč et al., 2021). Weaker EMFs produced by cell phones, radios and headphones do not appreciably alter mental activity, although long-term exposure to these weak fields may disrupt some brain functions (Bodewein et al., 2022; Schüz et al., 2022). Transcranial magnetic stimulation using strong magnetic pulses are well known to stimulate brain neurons, as does ultrasonic stimulation (Sarasso et al., 2015; Sanguinetti et al., 2020). EMF perturbations on the surface of the brain or outside it or very close to the surface do not affect mental processes, whereas EM perturbations that penetrate deeply into the brain do affect mental process.

Non-linear (chaos) analysis of EEG signals provide a measure of our brain's electric field, and also provide a sensitive measure of human consciousness (Watt and Hameroff, 1988; Walling and Hicks, 2006). We have recently explored a new way to visualize the chaotic complexity of brain activity from EEG signals; as chaotic attractor 3-D clouds which capture phase and complexity information and track the level or degree of consciousness in subjects slowly anesthetized, and then allowed to recover (**Figure 3**). When subjects are awake and conscious, 3-D clouds are largely spherical, reflecting many degrees of freedom and complex brain activity. As loss of consciousness (LOC) is produced, either through sleep, or in this case following anesthetic exposure, 3-D clouds begin to collapse into ellipsoid shapes. Deepening anesthesia, beyond loss of consciousness, results in further flattening of the clouds until cigar-like clouds are seen at deep surgical planes of anesthesia. Flattened clouds readily return to more spherical shapes upon recovery and awakening (Eagleman et al., 2019).

What can these attractor clouds tell us about the EMF that is generated by our brains? They certainly provide a way to visualize the electric field component of the EMF since they are derived from EEG (i.e., electrical) signals, but they contain no magnetic information. Magnetic (MEG) signals have yet to be analyzed with this method. Attractor clouds are thought to reflect the complexity and information content of signals, with higher information being associated with more spherical plots. A more spherical plot indicates higher degrees of freedom in EEG signals, allowing the attractor to explore more regions of the complexity landscape. The anesthetic-induced collapse of the attractor certainly fits with an anesthetic-induced collapse of information integration that occurs at loss of consciousness (Oizumi et al., 2014; Sarasso et al., 2015; Tononi et al., 2016; Eagleman and MacIver, 2018, 2021; Eagleman et al., 2018a,b, 2019; Ward and Guevara, 2022). A more sophisticated approach would measure both electric and magnetic fields, together with photonic energies (Salari et al., 2021), and combine these into multi-dimensional attractors. Even better would be approaches which allow us to record EMFs from deeper regions of the brain, like the thalamus, midbrain and brainstem, together with cortical level signals. This would provide an enriched view of brain function and the distribution of EMFs throughout our higher nervous system regions.

Discussion

Looking inward at EMF energy clouds, as opposed to the outward view most of us have envisioned, can readily account for why external fields and shielding do not alter mental processes. This view also supports the idea that EMFs focused into the brain would provide stronger ephaptic connections to the brain's neural circuits. Providing a stronger coupling between energies of the brain and the mind, from quantum energies of photons and particles, to atoms, molecules, microtubules, synapses and circuits of cells; to energy fields and conscious thought; and back again (Hameroff and Penrose, 2014; McFadden, 2020; Hameroff, 2022).

Data availability statement

The original contributions presented in this study are included in the article, further inquiries can be directed to the corresponding author.

Author contributions

MM researched and envisioned this manuscript in its entirety and wrote and revised the manuscript as well as compiled the illustrations.

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Conflict of interest

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References

Agashe, S., Burkholder, D., Starnes, K., Van Gompel, J. J., Lundstrom, B. N., Worrell, G. A., et al. (2022). Centromedian nucleus of the thalamus deep brain stimulation for genetic generalized epilepsy: a case report and review of literature. *Front. Hum. Neurosci.* 16:858413. doi: 10.3389/fnhum.2022.858413

Antunes, A., Glover, P. M., Li, Y., Mian, O. S., and Day, B. L. (2012). Magnetic field effects on the vestibular system: calculation of the pressure on the cupula due to ionic current-induced Lorentz force. *Phys Med. Biol.* 57, 4477–4487. doi: 10.1088/0031-9155/57/14/4477

Bocian, R., osluszny, A., Kowalczyk, T., Kazmierska, P., and Konopacki, J. (2011). Gap junction modulation of hippocampal formation theta and local cell discharges in anesthetized rats. *Eur. J. Neurosci.* 33, 471–481. doi: 10.1111/j.1460-9568.2010.07545.x

Bodewein, L., Dechent, D., Graefrath, D., Kraus, T., Krause, T., and Driessen, S. (2022). Systematic review of the physiological and health-related effects of radiofrequency electromagnetic field exposure from wireless communication devices on children and adolescents in experimental and epidemiological human studies. *PLoS One* 17:e0268641. doi: 10.1371/journal.pone.0268641

Chang, B., Ni, C., Zhang, W., Mei, J., Xiong, C., Chen, P., et al. (2022). Nomogram to predict cognitive state improvement after deep brain stimulation for Parkinson's Disease. *Brain Sci.* 12:759. doi: 10.3390/brainsci12060759

Dyba, J., Rossi, K. L., Żurek, M., and Rossi, E. L. (2021). Electrodynamics of clinical hypnosis. *Am. J Clin. Hypnosis* 64, 110–122.

Eagleman, S., and MacIver, M. B. (2021). Molecular diversity of anesthetic actions is evident in electroencephalogram effects in humans and animals. *Int. J. Mol. Sci.* 22:E495. doi: 10.3390/ijms22020495

Eagleman, S. L., Chander, D., Reynolds, C., Ouellette, N. T., and MacIver, M. B. (2019). Nonlinear dynamics captures brain states at different levels of consciousness in patients anesthetized with propofol. *PLoS One* 14:e0223921. doi: 10.1371/journal.pone.0223921

Eagleman, S. L., Drover, C. M., Drover, D. R., Ouellette, N. T., and MacIver, M. B. (2018a). Remifentanil and nitrous oxide anesthesia produces a unique pattern of EEG activity during loss and recovery of response. *Front. Hum. Neurosci.* 12:173. doi: 10.3389/fnhum.2018.00173

Eagleman, S. L., and MacIver, M. B. (2018). Can you hear me now? Information processing in primary auditory cortex at loss of consciousness. *Br. J. Anaesth.* 121, 526–529. doi: 10.1016/j.bja.2018.06.008

Eagleman, S. L., Vaughn, D. A., Drover, D. R., Drover, C. M., Cohen, M. S., Ouellette, N. T., et al. (2018b). Do complexity measures of frontal EEG distinguish loss of consciousness in geriatric patients under anesthesia? *Front. Neurosci.* 12:645. doi: 10.3389/fnins.2018.00645

Endemann, C. M., Krause, B. M., Nourski, K. V., Banks, M. I., and Veen, B. V. (2022). Multivariate autoregressive model estimation for high-dimensional intracranial electrophysiological data. *NeuroImage* 254:119057. doi: 10.1016/j.neuroimage.2022.119057

Gołebiewski, H., Eckersdorf, B., and Konopacki, J. (2006). Electrical coupling underlies theta rhythm in freely moving cats. *Eur. J. Neurosci.* 24, 1759–1770. doi: 10.1111/j.1460-9568.2006.04993.x

Hales, C. G., and Ericson, M. (2022). Electromagnetism's bridge across the explanatory gap: how a neuroscience/physics collaboration delivers explanation into all theories of consciousness. *Front. Hum. Neurosci.* 16:836046. doi: 10.3389/fnhum.2022.836046

Hameroff, S. (2022). Consciousness, cognition and the neuronal cytoskeleton - a new paradigm needed in neuroscience. *Front. Mol. Neurosci.* 15:869935. doi: 10.3389/fnmol.2022.869935

Hameroff, S., and Penrose, R. (2014). Consciousness in the universe: a review of the "Orch OR" theory. *Phys. Life Rev.* 11, 39–78. doi: 10.1016/j.plrev.2013.08.002

Hashimoto, I., Ishiyama, Y., Yoshimoto, T., and Nemoto, S. (1981). Brain-stem auditory-evoked potentials recorded directly from human brain-stem and thalamus. *Brain* 104(Pt 4), 841–859. doi: 10.1093/brain/104.4.841

Jones, M. W. (2013). Electromagnetic-field theories of mind. *J. Conscious. Stud.* 20, 1–26.

Keppler, J. (2021). Building blocks for the development of a self-consistent electromagnetic field theory of consciousness. *Front. Hum. Neurosci.* 15:723415. doi: 10.3389/fnhum.2021.723415

Kitchener, D., and Hales, C. G. (2022). What neuroscientists think, and don't think, about consciousness. *Front. Hum. Neurosci.* 16:767612. doi: 10.3389/fnhum.2022.767612

Köhler, W., and Held, R. (1949). The cortical correlate of pattern vision. *Science* 110, 414–419. doi: 10.1126/science.110.2860.414

Lashley, K. S., Chow, K. L., and Semmes, J. (1951). An examination of the electrical field theory of cerebral integration. *Psychol. Rev.* 58, 123–136. doi: 10.1037/h0056603

MacIver, M. B., and Bland, B. H. (2014). Chaos analysis of EEG during isoflurane-induced loss of righting in rats. *Front. Syst. Neurosci.* 8:203. doi: 10.3389/fnsys.2014.00203

McFadden, J. (2013). The CEMI field theory: closing the loo. *J. Conscious. Stud.* 20, 153–168.

McFadden, J. (2020). Integrating information in the brain's EM field: the cemi field theory of consciousness. *Neurosci. Conscious.* 2020:niaa016. doi: 10.1093/nc/niaa016

Mishra, A., Marzban, N., Cohen, M., and Englitz, B. (2021). Dynamics of neural microstates in the VTA-striatal-prefrontal loop during novelty exploration in the rat. *J. Neurosci.* 41, 6864–6877. doi: 10.1523/JNEUROSCI.2256-20.2021

Oizumi, M., Albantakis, L., and Tononi, G. (2014). From the phenomenology to the mechanisms of consciousness: integrated information theory 3.0. *PLoS Computat. Biol.* 10:e1003588. doi: 10.1371/journal.pcbi.1003588

Pockett, S. (2022). Field theories of consciousness. *Scholarpedia* 8:4951.

Pockett, S. (2014). Problems with theories that equate consciousness with information or information processing. *Front. Syst. Neurosci.* 8:225. doi: 10.3389/fnsys.2014.00225

Salari, V., Rodrigues, S., Saglamyurek, E., Simon, C., and Oblak, D. (2021). Are brain-computer interfaces feasible with integrated photonic chips? *Front. Neurosci.* 15:780344. doi: 10.3389/fnins.2021.780344

Sanguinetti, J. L., Hameroff, S., Smith, E. E., Sato, T., Tyler, W. J., Allen, J. B., et al. (2020). Transcranial focused ultrasound to the right prefrontal cortex improves mood and alters functional connectivity in humans. *Front. Hum. Neurosci.* 14:52. doi: 10.3389/fnhum.2020.00052

Sarasso, S., Boly, M., Napolitani, M., Gosseries, O., Charland-Verville, V., Casarotto, S., et al. (2015). Consciousness and complexity during unresponsiveness induced by propofol, xenon, and ketamine. *Curr. Biol.* 25, 3099–3105. doi: 10.1016/j.cub.2015.10.014

Schüz, J., irie, K., Reeves, G. K., Floud, S., and Beral, V. (2022). Cellular telephone use and the risk of brain tumors: update of the UK million women study. *J. Natl. Cancer Inst.* 114, 704–711. doi: 10.1093/jnci/djac042

Sperry, R. W., Miner, N., and Myers, R. E. (1955). Visual pattern perception following sub-pial slicing and tantalum wire implantations in the visual cortex. *J. Comp. Physiol. Psychol.* 48, 50–58. doi: 10.1037/h0043456

Tkáč, I., Benneyworth, M. A., Nichols-Meade, T., Steuer, E. L., Larson, S. N., Metzger, G. J., et al. (2021). Long-term behavioral effects observed in mice chronically exposed to static ultra-high magnetic fields. *Magn. Reson. Med.* 86, 1544–1559. doi: 10.1002/mrm.28799

Tononi, G., Boly, M., Massimini, M., and Koch, C. (2016). Integrated information theory: from consciousness to its physical substrate. *Nat. Rev. Neurosci.* 17, 450–461. doi: 10.1038/nrn.2016.44

Walling, T., and Hicks, K. N. (2006). Nonlinear changes in brain dynamics during emergence from sevoflurane anesthesia: preliminary exploration using new software. *Anesthesiology* 105, 927–935. doi: 10.1097/00000542-200611000-00013

Ward, L. M., and Guevara, R. (2022). Qualia and phenomenal consciousness arise from the information structure of an electromagnetic field in the brain. *Front. Hum. Neurosci.* 16:874241. doi: 10.3389/fnhum.2022.874241

Watt, R. C., and Hameroff, S. R. (1988). Phase space electroencephalography (EEG): a new mode of intraoperative EEG analysis. *Int. J. Clin. Monitor. Comput.* 5, 3–13. doi: 10.1007/BF01739226

Young, A., Hunt, T., and Ericson, M. (2021). The slowest shared resonance: a review of electromagnetic field oscillations between central and peripheral nervous systems. *Front. Hum. Neurosci.* 15:796455. doi: 10.3389/fnhum.2021.796455

Young, A., Robbins, I., and Shelat, S. (2022). From micro to macro: the combination of consciousness. *Front. Psychol.* 13:755465. doi: 10.3389/fpsyg.2022.755465

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Consciousness: Matter or EMF?

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Conventional theories of consciousness (ToCs) that assume that the substrate of consciousness is the brain's neuronal matter fail to account for fundamental features of consciousness, such as the binding problem. Field ToC's propose that the substrate of consciousness is the brain's best accounted by some kind of field in the brain. Electromagnetic (EM) ToCs propose that the conscious field is the brain's well-known EM field. EM-ToCs were first proposed only around 20 years ago primarily to account for the experimental discovery that synchronous neuronal firing was the strongest neural correlate of consciousness (NCC). Although EM-ToCs are gaining increasing support, they remain controversial and are often ignored by neurobiologists and philosophers and passed over in most published reviews of consciousness. In this review I examine EM-ToCs against established criteria for distinguishing between ToCs and demonstrate that they outperform all conventional ToCs and provide novel insights into the nature of consciousness as well as a feasible route toward building artificial consciousnesses.

KEYWORDS

consciousness, neuroscience, EEG, electromagnetic, cognition, theory

> *"I'm not asking you, I'm telling you. These creatures are the only sentient race in the sector and they're made out of meat."*
>
> Terry Bison "They're made out of meat" (Bisson, 1995).

Introduction

In their recent article "Hard criteria for empirical theories of consciousness." Doerig et al. (2021) argue that there are now a wealth of theories of consciousness (ToCs) but no established stringent criteria by which each could be compared. They proposed a list of criteria through which ToCs could be checked and compared. They are that any TOC should:

1. Address paradigm cases of consciousness, such as optical and auditory illusions or masking, when the same sensory information can switch between being either conscious or non-conscious.
2. Cope with the "folding argument" which applies to ToCs that associate consciousness with some kind of information processing architecture in the brain, such as recurrent thalamocortical interactions (Nervous et al., 1998; Lamme and Roelfsema, 2000). The folding argument points out that both recurrent and feedforward networks can approximate any input-output mathematical function (Doerig et al., 2019), so a recurrent network could be "unfolded" into a feedforward network without any change in inputs or outputs.
3. Cope with the small network argument which arises from the observation that many ToCs imply that small networks with fewer than ten neurons are conscious. The authors admit that many ToCs argue that small networks lack additional key ingredients, such as complexity or size of the network. However, these are arbitrary "curve-fitting" additions to the theory, rather than being predicted by the theory, that add complexity to the ToC. I additionally point out that Bayesian inference, which is today considered to be fundamental to scientific reasoning (Howson and Urbach, 2006; McFadden, 2021a,b), automatically

incorporates a preference for simple solutions, not as priors, but as part of the likelihood function that delivers higher posterior probabilities to simpler theories or models that fit the data but make sharper predictions than more complex theories.

4. Copes with the multiple realization argument (Bechtel and Mundale, 1999) which deals with the problem of understanding why some complex systems, such as human brains, are consciousness, whereas other complex systems, such as robots or mammalian immune systems, are presumed to be non-conscious. The challenge is whether a ToC makes clear-cut and specific predictions about which systems, other than human brains, are conscious.

Doerig, Schurger and Herzog do not claim that their criteria are exhaustive but only that they provide "a first set of guidelines to foster discussions about consciousness as an empirical phenomenon." In a more recent review, Seth and Bayne (2022) independently suggest several additional criteria, some of which overlap with the S&B criteria but others are distinct and are added here. Additionally, I add two additional criteria (*'ed) to make eleven tests of ToCs.

5. Addresses the unity of consciousness (Seth and Bayne, 2022) often known as binding problem (Hardcastle, 1994; Singer, 2001; Seth and Bayne, 2022) of how "the experiences that a single agent has at a time seem always to occur as the components of a single complex experience, one that fully captures what it is like to be that agent." This is particularly puzzling because we know that the information in the conscious mind at any single moment is encoded in widely-separated neurons in different regions of the brain. Yet integration of information is intrinsic to conscious perception such that, or example, it is impossible to consciously conceive of an object that lacks color. This would present no problem to a computer, nor does it present any problem to the non-conscious mind that, for example, reacts to objects approaching our eye by blinking, irrespective of the object's color. Yet, in the conscious mind, color is intrinsically bound up with visual objects such that, in synaesthesia, even sounds have colors. The binding problem is then that of understanding how diverse information encoded by firing rates of widely distributed neurons is bound into a singular unified conscious experience. Note that the need to address the binding problem is implicit in many ToCs, though not always stated. For example, theories that invoke integrated information as a key feature of consciousness, such as Integrated Information Theory, IIT (Tononi, 2004) implicitly assume that complex conscious information is bound into a single integrated conscious state.
6. Addresses neural data such as the apparent absence of conscious experience in certain regions of the brain, such as the cerebellum or during certain states of the brain, such as grand mal or absence epileptic seizures (Seth and Bayne, 2022). I include here also timing data, such as the psychological refractory period for conscious awareness or the attentional blink or postdictive effects on conscious perception. Several of these neurological phenomena can be grouped into the broader problem of why neural correlates of consciousness (NCCs), are NCCs.
7. Addresses the measurement problem (Seth and Bayne, 2022) of identifying trustworthy measures of consciousness that could, for example, be used to measure the degree of consciousness in a patient or in artificial systems, such as cerebral orgenanoids or AI.
8. *Accounts for how and why a single brain operates in two modes: a non-conscious parallel processor and a conscious serial processor. As Baars (1993) put it how does "a serial, integrated and very limited stream of consciousness emerge from a nervous system that is mostly unconscious, distributed, parallel and of enormous capacity." Baars pointed out that our non-conscious mind is capable of a massive degree of multitasking, such as directing the delicate limb muscle movements needed to ride a bicycle whilst simultaneously calculating and coordinating the precise movements of the lips, tongue and nasopharynx needed to sing a familiar tune. Yet, our conscious mind can only do one thing at a time. It is, for example, not possible to chat to a friend whilst simultaneously performing long division in your head, a challenge that would be trivial for any chatbot. Any ToC must account for how, and why, these very different modes are generated from the same neural substrate in the brain. I also include here the related curious feature, often overlooked by ToC's, that consciousness appears to be required for learning novel skills, such as riding a bike, but, once leant, those skills can operate without conscious control (McFadden, 2006).
9. *Distinguishing intelligence from consciousness. This criterion was first put forward by Block (2009) who argued that most ToCs fail to distinguish between the intelligence delivered by diverse complex systems including computers, the non-conscious mind, AI, and consciousness.
10. Accounts for the emergence of consciousness through natural selection (Seth and Bayne, 2022).
11. Whether the ToC is able to make novel testable predictions (Seth and Bayne, 2022).

First, a brief introduction to EM field theories of consciousness. The idea that the conscious mind is some kind of field goes back at least as far as the early twentieth century gestalt psychologists who emphasized the holistic nature of perception, or *gestalts*, and argued that they must be encoded in some kind of field, rather than discontinuous particles (McFadden, 2013a). The idea was further developed and extended by Popper et al. (1993) who proposed that consciousness was a manifestation of some kind of overarching *force field* in the brain; whilst the neurobiologists Libet (1994, 1996) and (Lindahl and Arhem, 1994) called it the "conscious mental field." Although each of these authors accepted that consciousness must be some kind of field in the brain they nevertheless concluded that it could not be any of the known physical fields, so its nature remained mysterious.

Most neurobiologists saw this as a unwelcome return to Cartesian dualism and opted instead for the monist position that both mind and consciousness are seated in the matter of the brain. That the brain also generates an EM field had been known from the late 19th century but it was, and still is, generally assumed to play no more role in brain function that that of a steam whistle on the operation of a steam engine. Nevertheless, because of its accessibility, particularly after the invention of electroencephalography (EEG) and magnetoencephalography (MEG), the brain's EM field was (and is) adopted as a routine measure of the level consciousness in, for example, anesthesia (Roth, 1951) and comatose patients (Loeb, 1958).

In his 1994 book "The Astonishing Hypothesis" the Nobel laureate and co-discoverer of the double-helical structure of DNA, Crick (1994) argued that science was capable of tackling the problem of consciousness and proposed starting with an initial focus on identifying neural correlates of consciousness (NCCs). This programme was enthusiastically adopted by a new generation of neurobiologists who searched for NCCs amongst anatomical sites, patterns of neural firing or architecture of neural processing using EEG as well as more advanced techniques such as functional magnetic resonance imaging (fMRI) and magnetoencephalography (MEG) together with intracellular and extracellular recordings. One of the most surprising results to emerge from these studies was that attention and awareness tended to be associated, not with neural firing *per se* or the anatomical site of neural firing, but with the synchronicity of firing of multiple neurons (Gray et al., 1989; Crick and Koch, 1992; Crick, 1994). For example, work conducted by Wolf Singer and colleagues demonstrated that neurones processing visual information fired asynchronously when an animal does not attend to the stimulus, but fired synchronously when the animal attends to, and is presumed to be conscious of, the stimulus (Kreiter and Singer, 1996). Numerous subsequent studies, recently summarized (McFadden, 2020), have confirmed and extended these findings so that, even today, synchronous neural firing and the EM fields that it generates remains the best NCCs. The questions is, why?

In 2000, both McFadden (2000) and Pockett (2000) published books which proposed a possible solution. They pointed out that if a large group of neurons is firing asynchronously then their net EM field will be subject to destructive interference and sum to zero: very little information from these neurons will be *transmitted* to the brain's EM field. If those same neurons are firing synchronously then the net EM field generated by their activities will be subject to constructive interference, so the information they encode will be effectively transmitted into the brain's EM field. The combination of destructive and constructive interference thereby provides a synchronicity filter that ensures that the brain's EM field is dominated by information encoded in synchronously-firing neurons. So, whereas the matter of the brain encodes both conscious and non-conscious neuronal information, its EM field will be dominated by the much smaller stream of information encoded by synchronously-firing neurons—precisely those neurons that were identified as prime NCCs. It is a small step from this realization to the proposal that the seat of consciousness is not the matter of the brain but the equally physical yet immaterial, brain EM field generated by synchronous neuronal firing.

Both McFadden J. (2002), McFadden J. J. (2002) and Pockett (2002), elaborated on this idea in papers published in 2002 pointing out that electromagnetic field ToCs (EMF-ToCs to contrast with neural-ToCs that propose that consciousness is encoded in the matter of neurons) easily solve the unity or binding problem (criterion 8 above) since EM fields automatically integrate their encoded information into a single physical field. Around the same time, similar theories were proposed by the neurophysiologist John (2001, 2002) and the neurophysiologists (Fingelkurts et al., 2001, 2013; Fingelkurts and Fingelkurts, 2008). In the following years, several other EMF-ToCs have been published (Barrett, 2014; Jones, 2016, 2017; Liboff, 2016; Zhakenovich et al., 2016; Hales, 2017; Hunt and Schooler, 2019; Keppler, 2021; Detmar, 2022). Despite this, none of the ToCs discussed in either the Doerig et al. (2021) paper or the Seth and Bayne (2022) review are EMF-ToCs, a deficiency that is rectified here.

In this paper, I review the principal EM-ToCs against the criteria proposed by both Doerig et al. (2021) or Seth and Bayne (2022). Broadly, EMF-ToCs are defined as those ToCs that propose that the seat of consciousness resides in the brain's EM field, rather than its neuronal substrate. To identify EMF ToCs I performed a Google Scholar search with the terms "electromagnetic field theory" +consciousness for the period 2010—present. This returned 336 hits. From these I identified nine EMF-ToCs (John, 2002; McFadden J., 2002; McFadden, 2020; Pockett, 2002, 2012; Fingelkurts et al., 2013; Barrett, 2014; Zhakenovich et al., 2016; Hales, 2017; Hunt and Schooler, 2019; Keppler, 2021) that are discussed here. This is not intended to be an exhaustive review of the EM-ToC literature but an examination of how well they, as a group, fare against recently-established criteria for evaluation of ToCs. A key dividing line within EMF-ToCs is those that predict that conscious brain EM fields influence behavior (John, 2002; McFadden J., 2002; McFadden, 2020; Fingelkurts et al., 2013; Barrett, 2014; Zhakenovich et al., 2016; Hales, 2017; Hunt and Schooler, 2019; Keppler, 2021) which I term type 1 or EMF_1-ToCs[1], and those, such as Pockett's theory (Pockett, 2011, 2012), which predict that conscious brain EM fields do not influence behavior, which I term type 0 or EMF_0-ToCs. A third category are those EMF-ToCs that are agnostic on the question of whether consciousness influences behavior, which I term EMF-ToC_x theories. EMF-ToC_x may agree with the predictions of EMF-ToC_1s and EMF-ToC_0s so will not be dealt with separately. I contrast EMF-ToCs with neural-ToCs and discuss how EMF-ToCs address both Doerig, Schurger and Herzog's, Seth and Bayne's ToC test criteria plus a few additional criteria proposed here.

Results

1. Both type one and type zero EMF-ToCs address paradigm cases of consciousness. As already pointed out, synchronous neuronal firing, which is the primary source of the brain's EM field, strongly correlates with conscious perception. However, the most accessible measure of the brain's EM field is *via* EEG or MEG signals which are generated by synchronous neuronal firing. The strong correlation between EEG signals and conscious states is evidenced by the widespread clinical use of EEG to assess the level of consciousness and awareness in brain-damaged patients (Engemann et al., 2018) and in general anesthesia (Musialowicz and Lahtinen, 2014). EEG signals—and thereby the brain's EM field—also correlate with perception in change blindness (Koivisto and Revonsuo, 2003), perceptual masking (Schubert et al., 2009), sound-induced flash illusions (Kaiser et al., 2019) and classic perceptual switching such as when viewing the Rubin's vase/face illusion (Müller et al., 2000). EEG alpha wave perturbations are also correlated with "mind wandering" (Compton et al., 2019) when attention drifts away from a task activity. The consistent correlation between

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[1] The subscripted numbers represents the binary possibilities of influencing (1) or not influencing (0) behaviour.

EEG/MEG and conscious acts of volition is currently being harnessed to construct prosthetic devices that are controlled by a patient's EEG (Al-Quraishi et al., 2018). All of these and many more EEG studies provide strong evidence that the brain's EM field remains the most reliable correlate of consciousness, consistent with all EMF-ToCs.

Note that the tight correlation of EEG signals to perception and conscious states is not accounted for by a simple correlation of EEG to activation of particular neural pathways or ensembles that are conscious for reasons unrelated to the EM fields they generate, such as that they have the highest value of phi as described by Integrated Information Theory (IIT) (Tononi, 2004) or involve critical thalamocortical recurrent loops (Diseases et al., 1998). This is due to the inverse problem of being unable to predict the pattern of neural firing responsible for generating a particular EEG signal, solely from the EEG signal (Grech et al., 2008; Baillet, 2014). This follows from the physical principle that potential infinite combinations of electrical sources can generate the same EMF (Jackson, 1999). So, if a particular EEG signal was a correlate of consciousness solely because it happened to generated by a neural firing pattern that, in itself, conferred consciousness (the brain EMF that gave rise to the EEG signal was neither sufficient nor necessary for consciousness), that correlation would likely be diluted by diverse non-conscious neural firing patterns that just happen to generate the same EEG signal. Conversely, if a putative neural firing pattern is a sufficient and necessary cause of consciousness, it is unlikely to consistently generate a EEG correlate of consciousness due to destructive interference from adjacent neural firing networks. Consistently high levels of correlation found between EEG signals and conscious states is only guaranteed if the state of the brain's EM field, rather than the state of the neurons that generate the brain EM fields, is both necessary and sufficient for consciousness.

This conclusion is consistent with recent remarkable findings by Pinotsis and Miller (2022) that demonstrate that, although the exact neurons (the neural ensemble) maintaining a given memory in working memory varies from trial to trial, what is known as representational drift, stability of working memory emerges at the level of the brain's electric fields as detected by EEG. Since working memory is considered to be, essentially, conscious memory, all EMF-ToCs predict that it resides in the brain's EM fields rather than in its neurons, acting as the brain's global workspace (Baars, 2005), consistent with Pinotsis and Miller's findings. The higher level of correlation between the contents of working memory and the brain's EM fields, rather than the state of the brain's matter-based neurons, is a considerable challenge to all neural-ToCs.

2. EMF-ToCs are impervious to the unfolding argument since they are dependent on neither feedforward nor recurrent pathways. Indeed, due the uncoupling between brain neural activity and brain EM fields discussed above (resulting from the inverse problem), its seems likely that identical EM fields, and thereby the same conscious state, could be generated by feedforward or recurrent networks.
3. EMF$_1$-ToCs, such as the cemi field theory, cope with the small network argument by predicting that small networks are non-conscious. This follows from the theory's insistence that, to be reportably conscious, brain EM field-based information must, either directly or indirectly, influence the firing of motor neurons (McFadden J. J., 2002). There are sound theoretical grounds (McFadden J., 2002) and abundant experimental evidence that neural firing rates are indeed influenced by the brain's endogenous EM field [summarized in my recent paper (McFadden, 2020)]. In the cemi field theory, that influence is proposed to be experienced as what we call our "free will," the output of our conscious mind (McFadden, 2021c). So, in EMF$_1$-ToCs, neurons act as both transmitters and receivers of EM field-based conscious thoughts forming the strange loop proposed by philosopher Hofstadter (1979, 2007) to be central to consciousness.

Field gradients of 2–4 mV/mm appear to be necessary to influence neural firing (Frohlich and McCormick, 2010) which is similar to the strength of the endogenous brain EM fields (McFadden J., 2002) that can be detected by EEG. Thousands or millions of aligned neurons must fire synchronously (McFadden J., 2002; Pockett, 2002) to generate fields of as strong as 2–4 mV/mm. Small networks will generate only very weak field gradients that will usually be insufficient to influence neural firing patterns and will thereby be non-conscious.

It is less clear that type 0, or EMF$_0$-ToCs, for example, Pockett's (2000, 2002) EM-ToC are resistant to the small network argument. As Pockett (2002) has argued, from the perspective of EEG, small networks will be drowned out by the field generated by large coherent networks but, without a reportability threshold, within EMF$_0$-ToCs I see no reason to exclude consciousness from the experience of small networks just because they generate field gradients below the sensitivity of EEG.

4. Just as neural-ToCs that locate consciousness in the matter of the brain are susceptible to the multiple realization argument (MRA), since not all matter is conscious, EMF$_0$-ToCs are similarly subject to the MRA since not all EM fields are likely to be conscious. EMF$_0$-TOCs generally resort to the same kind of primary defense against rampant panpsychism as neural-ToCs by insisting that some additional criterion, such as complexity, integration, anatomical location, informational processing architecture or access to working memory, is needed for consciousness. Since thoughts are informationally-rich, the complexity criterion is indeed sound: what could a single bit encoded by a single particle of matter, or EM field sine wave, possibly *think*? The substrate of consciousness must, at a minimum, possess sufficient complexity to encode a thought. However, neither neural-ToCs nor EMF$_0$-ToCs provide objective criteria for determining the level of neuronal complexity, or any other criterion, needed for neural computation to reach conscious, except, as in IIT (Tononi and Koch, 2015), to propose it is the winner of some kind of internal neuronal mathematics competition.

In contrast, EMF$_1$-ToCs provide an objective criterion for distinguishing conscious from non-conscious EM fields. This arises from the requirement that, to be reportably conscious, a system must be able to generate (rather than merely transmit) thoughts as gestalt (integrated) information (McFadden, 2013b)—our thoughts—that can be communicated to the outside world *via* a motor system.

This simple formula excludes consciousness from artifacts such as toasters, computers and other AI devices that, although capable of generating complex EM fields are designed to avoid electromagnetic interference (EMI) with their operation. A strong prediction of EMF-ToCs is therefore that conventional computers that exclude EM field influences on their outputs will never be conscious. If demonstrably conscious conventional computers are ever developed, then EMF_1-ToCs will immediately be falsified. Type 1 EMF-ToCs also propose an objective means of assessing the level of consciousness (the degree by which actions are controlled by the conscious, rather than the non-conscious, mind) in different brains by measuring the correlation between a nervous system's motor outputs and its brain's EM fields. The strong correlation between willed actions and EEG signals in humans has already been known since Libet et al. (1982, 1983a,b) pioneering experiments in the 1980's that demonstrated that EEG signals can be used to predict intentions to act, prior to the subject knowing their intention, findings that have inspired recent research efforts to build EEG-operated brain-computer interfaces (BCIs) for patients with prosthetic limbs (Guger et al., 1999) or suffering from locked-in syndrome (Aricò et al., 2018). Unfortunately, only limited studies of the correlation between EEG and behavior have been performed in primates (Attaheri et al., 2015), cats (Engemann et al., 2018), horses (de Camp et al., 2020), and a scattering of other animals (Klemm, 1992); but, type 1 EMF-ToCs do, at least, provide a framework through which the question of the level of consciousness in animals could potentially be measured.

5. McFadden recently argued that binding is a property not only of visual information but all sensory information (McFadden, 2020) and is fundamental to the gestalt information processing (McFadden, 2013b) of ideas and concepts that is characteristic of the conscious mind and contrasts with the digital processing capabilities of non-conscious minds. The binding problem is then that of understanding "*our capacity to integrate information across time, space, attributes, and ideas*" (Treisman, 1999). Nearly all neuronal ToCs argue that binding, or integration, of information in the conscious mind is a consequence of some forms of neural processing, for example, synchrony (Engel et al., 1999) or hypersynchrony (Mashour, 2004) of neural firing, the formation of neuronal assemblies through processing the same sensory information, or the involvement of particular information processing architectures such as reentrant loops (Singer, 2001), or involving particularly parts of the brain, such as the thalamus (Hardcastle, 1994) or is accomplished through some hypothetical structure, such as the global workspace (Baars, 2005) or, like IIT (Tononi, 2004), claims that consciousness is associated with particular mathematical properties of information processing in the brain. Yet, as the physicist Rolf Landauer argued "information is physical." Integrated information must therefore be physically integrated. Matter encoded information is always discrete and digital in nature, except in exotic quantum mechanical states, such as a Bose-Einstein condensate, which are completely infeasible in the brain (McCrone, 2003). No neural-ToC provides an adequate account of how information encoded in discrete matter is integrated in the conscious mind. Classically-encoded information is only physically integrated in the energy fields generated by matter (McFadden, 2020). For example, the gravitational field that keeps our feet on the ground represents an integration of the mass of our body and that of the entire planet, despite the fact that nearly all the atoms and molecules of matter that form that field is located thousands of miles from the soles of our feet. EM-ToCs pointed out, more than 20 years ago (McFadden J., 2002; McFadden J. J., 2002), and without recourse to special states of matter, hypothetical structures or complicated mathematical functions, that the brain's EM field automatically integrates neural information into a singular non-material physical field thereby effortlessly solving the binding problem.
6. Addresses neural data such as the apparent absence of consciousness in the cerebellum and providing an explanation of why NCCs, such as neural synchrony, correlate with conscious awareness. I have discussed above how the recognition that information encoded in synchronous neural firing will dominate the brain's EM field was the primary inspiration for a renewal of interest in EMF-ToCs in the first decade of the 21st century. EMF-ToCs provide the most parsimonious explanation of why neural synchrony is a NCC and are thereby favored by Occam's razor (McFadden, 2021d) since, unlike neural ToCs, they predict, rather than merely incorporate, a strong association between synchronous neural firing and consciousness. EMF-ToCs also account for why neural activity in the cerebellum appears to be non-conscious. This is likely due to the cerebellum's intricate folding, compared to cerebral cortex, which ensures that currents arising in neighboring patches of cerebellum activation tend to be running in opposite directions resulting in cancellation of their EM fields through destructive interference. The same reason is thought to be responsible for the invisibility of the cerebellum in EEG or MEG measurements (Andersen et al., 2020).

EMF-ToCs also account for the lack of consciousness in absence epileptic seizures in which patients lose consciousness. These are associated with strong regular and usually bilaterally synchronous and symmetric EEG signals particularly in the 2–4 Hz range (Hedström and Olsson, 1991). Naively, one might expect that that EMF-ToCs might predict that strong EEG signals would be associated a heightened, rather than reduced state of consciousness. However, in contrast to the information-rich EM-encoded information detectable in a normal EEG, which correlates with sensory information, perception and the contents of consciousness, the highly rhythmic EMF fluctuations characteristic of EEG seizures are devoid of information so they cannot encode thoughts. According to EMF-ToCs, they represent a kind of consciousness brain-wipe that is entirely consistent with the loss of consciousness in absence seizures.

7. Compared to neural-ToCs, EMF-ToCs have a distinct advantage in tackling the measurement problem, since, as outlined above, measurement of brain EMFs by EEG or MEG are routinely used to detect signs of consciousness in anesthesia (Pistoia et al., 2015; Schartner et al., 2015; Bayne et al., 2016; Hajat et al., 2017; Eagleman et al., 2018) and in disorders of consciousness, such as locked-in syndrome (Voss and Sleigh, 2007; Rohaut et al., 2017). Indeed, brain-computer interfaces (McFarland and Wolpaw, 2017; Nolte, 2021) that detect EEG signals have recently been developed to restore communication and control to people paralyzed by chronic neuromuscular

disorders and allow locked-in patients to communicate *via* their (conscious) EEG signals. This is doubly-puzzling as, according to the Grand Illusion Hypothesis, our conscious mind only processes a tiny fraction of the information being processed by our non-conscious brain (Noë, 2002). No neural-ToC can account for why EEG and MEG signals are so well correlated with that thin conscious trickle rather than the bulk of non-conscious brain activity; but it is easily accounted for in EMF-ToCs that predict that these EMF measurement will correlate with the activity of the conscious mind. EMF_1-ToCs predict that an EMF-encoded information loop is required for conscious control of actions. This is something that is potentially detectable by experiments that measure the degree by which external EM fields, of similar strength and structure but of opposite phase as brain/organoid/AI-generated EM fields, influence the outputs of neuronal, organoid or artificial computational devices by, essentially, neutralizing conscious inputs. The level of interference would then provide a measure of the degree of conscious control of behavior. Although experimentally challenging, experiments have demonstrated that external fields of similar strength and structure as endogenous EM fields do influence neural firing patterns in brain slices (Frohlich and McCormick, 2010; Anastassiou et al., 2011). Similar experiments performed on live animals would be able to test if external EM fields of similar strength and structure, but of opposite phase, as endogenous brain EM field are capable of influencing behavior. The degree of influence would be a measure of the level of conscious control of behavior. Since EMF_0-ToCs do not predict that EM fields influence behavior, they cannot, as far as I am aware, be evaluated to determine level of awareness.

8. How the same neuronal architecture delivers both a massively-parallel non-conscious mode and a serial conscious mode of operation is not accounted for in any neuronal-ToC except through the imposition of arbitrary thresholds for conscious processing as being the most complex, integrated or those which involve particular anatomical sites or processing architecture, such as recurrent networks. Yet there is no evidence that computations routinely performed by the non-conscious mind, such as computing limb movements during walking or running, or orchestrating the delicate motions of tongue, lips and larynx required for speech or song, are any simpler, or less integrated, than those involved in conscious deliberations such as doing long division in one's head—a task that is easy for the simplest pocket calculator. Moreover, following the dialogue and action in a movie or theater surely requires a high degree of complex and highly integrated distributed neuronal processing of multiple sensory sources; yet it can easily be supplanted in the conscious mind by the simplest of stimuli, such as when a fellow audience member stands on your toe whilst shuffling past your seat. Global workspace theory (GWT) (Baars, 2005) and the related global neuronal workspace (GNWT) theories (Dehaene, 2014) avoid these pitfalls by not specifying the criteria by which neuronal activity gains access to the global workspace (Baars and Franklin, 2003) except, in GNWT, to claim that it is driven by non-linear feedback systems that flip between different states in a winner-takes-all dynamics (Dehaene, 2014). A related problem is to understand why activities, such as conversation or long division, can only be performed consciously (Dehaene, 2014).

EMF-ToCs provide a clearly defined physical distinction between matter-based EMF-independent non-conscious neural processing and EMF-dependent conscious information processing in the brain. Matter-based neuronal networks—the non-conscious mind—can easily partition tasks into spatially separated matter-based sub-networks that do not interfere with each other. The brain's EM field is however a singular entity so the conscious mind can only do one thing at a time. The second aspect of this criterion is to understand why conscious control is required to provide fine tuning in the process of learning, similar to what James (1988) envisaged more than a century ago (as quoted in [40]) suggesting that "if consciousness can load the dice, can exert a constant pressure in the right direction, can feel what nerve processes are leading to the goal, can reinforce and strengthen these and at the same time inhibit those that threaten to lead astray, why, consciousness will be of invaluable service". In the cemi field theory, this is accomplished by the brain's EMF pushing and pulling on neurons toward or away from firing to achieve the desired motor actions. However, so long as target neurons are connected by Hebbian synapses then the repeated influence of the brain's EMF to accomplish a practiced action will tend to become hard-wired into either increased (long-term potentiation, LTP) or decreased (long-term depression) neural connectivity between the neurons involved in this action. After repeated augmentation by the brain's EMF, motor actions that were once painfully conscious may thereafter be performed non-consciously. The action is now learned and hardwired so no longer requires EMF input for fine-tuning. Type 1 EMF-ToCs thereby provide an entirely naturalistic account of why consciousness is intimately involved in learning and memory but, once learnt, is dispensable and may even interfere with performance.

9. EMF-ToCs distinguish between consciousness and intelligence, which is substrate independent and can be delivered by any matter or field-based information processing system, from neuronal networks to electronic circuits, intelligent materials or insect social networks (MacLennan, 1999); as well as in conscious and non-conscious minds. Non-classical states of matter, such as the Bose-Einstein condensates used in some quantum computers (MacLennan, 2022) do physically integrate matter-based information and could potentially integrate complex information in an analogous manner to brain EM fields. It remains to be seen whether there is something *it feels* to be a quantum computer.
10. The cemi field theory accounts for the emergence of consciousness through natural selection. Neurones in a complex brain display a range of excitability and in the busy brain of our ancestral animals there would have been many neurones poised close to their threshold potential with voltage-gated ion channels sensitive to small changes in the EM fields generating by surrounding neural activity. So long as they impacted neural firing—as has amply been demonstrated in studies referenced above—then those field interactions would have been subject to natural selection. Wherever field effects boosted performance, natural selection would have acted to enhance neurone sensitivity, for example, by maintaining neurones close to firing potential, decreasing nerve myelination or orientating and synchronizing neurones to maximize constructive interference. Potential advantages provided by EMF-based computing include, as outlined above,

field computing, conscious fine-tunable learning and the ready availability of an EMF-based global workspace that can be accessed by the entire brain. In my previous publications, I have argued that the principle advantage captured by the conscious mind was to compute with the integrated packages of gestalt information that we call thoughts, rather than with the binary digits that are processed by the non-conscious mind and AI devices (McFadden, 2013b, 2020). Conversely, field influences were also likely to be detrimental to the host though EM field "feed-back" that interfered with informational processing of essential motor functions, such as reflex actions, together with learnt motor actions such as walking, running, or speech. It is easy to experience this kind of negative interference by attempting to exercise conscious control of our limb movements whilst engaged in a learnt and normally automatic motor task, such as walking or playing a musical instrument. For these EMF-impaired operations, natural selection would have acted to decrease EMF sensitivity by, for example, maintaining neurones far from firing potential, increasing myelination or orientating and desynchronising neurones to maximize destructive interference, as in the cerebellum. So, with only the information that endogenous EM fields influence neural firing, the theory of natural selection predicts that brains will evolve into an EM field-sensitive (conscious) system and a parallel EM field-insensitive (non-conscious) system. *Homo sapiens* have clearly followed this route. Note also that the region of the brain that is most involved in control of reflex actions, the cerebellum, is, as discussed above, also the most invisible to EEG because it produces only very weak EM fields that are unlikely to generate any EMF-feedback. As far as I am aware, it is only EMF_1-ToCs that, in combination with the theory of natural selection, predict, entirely naturalistically and with no further assumptions, the inevitable evolutionary emergence of a parallel-computing non-conscious mind together with a serial computing conscious mind.

11. Whether the ToC is able to make novel testable predictions. I have already outlined the very strong prediction of EMF-ToCs that AIs based on conventional computing will never be conscious. Moreover, because EMF's are subject to wave interference, EMF-ToCs make another strong prediction that changing only the relative timing of neuronal firings will affect conscious perception. For example, it should be possible to switch between the alternative conscious perceptions of the face/vase illusion merely by shifting the relative timings of neuronal signals involved in generating the brain EM fields that correlate with the alternative perceptions through constructive or destructive interference. In this way, the brain could be manipulated so that information encoded in neuron firing rates is always present in the neuronal brain but alternatively present/absent in brain EM fields. EMF-ToCs predict that consciousness will correlate with the informational content of the brain's EM field, rather than its neurons, whereas all neural-ToC's predict the opposite. Recent advances in application of optogenetic techniques (Toettcher et al., 2011; Boyden, 2015; Adesnik and Abdeladim, 2021) in humans and non-human primates (Han, 2012) are likely to make such an experiment a real possibility in the near future.

Other prediction of EMF-ToCs have already been verified, albeit unintentionally. For example, as described above, the cemi field theory proposes that EM fields are involved in memory and learning and so would predict that external EM fields, such as those delivered by TMS, will interfere with these processes, as found in several studies (Ferrari et al., 2018; Bang et al., 2019) but will be impervious to external fields once learnt, as has also been demonstrated (Bang et al., 2019). Even more remarkably, a recent study has demonstrated that retrieval of human memories involved coupled ripple oscillations in the EEG between the medial temporal lobe and the neocortex (Vaz et al., 2019).

Discussion

At first sight, EMF-ToCs appear far-fetched: how can EM fields be conscious? But is it any more unreasonable to propose that the matter of the brain is conscious? In Terry Bison's delightful short story "They're Made out of Meat" (see opening quotation), two aliens ponder the shocking discovery of a "meat"-based sentient species inhabiting a planet in a remote corner of the galaxy (Bisson, 1995). One of the aliens' proposes that there must be more to the new species, perhaps "A meat head with an electron plasma brain inside" but the other insists that "they're meat all the way though... Yes, thinking meat! Conscious meat! Loving meat. Dreaming meat. The meat is the whole deal!" They agree to suppress the new data.

Most neurobiologists continue to believe that the matter of the brain, its flesh, is the whole deal despite knowing for more than a century, that, alongside the particles of matter that make up the brain's visible matter, there is also the equally physical, though invisible, electromagnetic field generated by neuronal firing, action potentials and synaptic transmission. Modern particle physics tells us that those particles—protons, electrons, neutrons—that make up the matter of the brain—are actually excitations of underlying electromagnetic, weak and the strong nuclear force fields, together with the Higgs field. Moreover, apart from physical processes involving radioactive decay or gravity, pretty much everything that happens on our planet, all of chemistry and the biochemistry of life, is mediated by electromagnetic field interactions. Is it really so bizarre to propose that some of those interactions are also the substrate of life's greatest gift, consciousness?

Of course, it remains to be proved that the brain's electromagnetic field is the substrate of consciousness. But then it also remains to be proved that the matter of the brain is the substrate of consciousness. As far as I am aware, there is no experiment that favors the brain's matter, as the substrate of consciousness, over its EM fields. Yet, as outlined above, EMF-ToCs provide the most parsimonious accounts of numerous phenomenal aspects of consciousness, including its serial nature, binding and the disconnect between intelligence and consciousness. EMF-ToC's explain why consciousness is involved in learning together with an account of the evolution of consciousness which predicts one of the mind's most curious features, that it operates in both non-conscious (parallel) and conscious (serial) modes. EMF-ToCs achieve all this without recourse to any special states of matter, hypothetical workspaces, or impenetrable equations. It is surely time for neurobiologists to accept that there is more to mind than matter.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

The author confirms being the sole contributor of this work and has approved it for publication.

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Conflict of interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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References

Adesnik, H., and Abdeladim, L. (2021). Probing neural codes with two-photon holographic optogenetics. *Nat. Neurosci.* 24, 1356–1366. doi: 10.1038/s41593-021-00902-9

Al-Quraishi, M. S., Elamvazuthi, I., Daud, S. A., Parasuraman, S., and Borboni, A. (2018). EEG-based control for upper and lower limb exoskeletons and prostheses: a systematic review. *Sensors.* 18, 3342. doi: 10.3390/s18103342

Anastassiou, C. A., Perin, R., Markram, H., and Koch, C. (2011). Ephaptic coupling of cortical neurons. *Nat. Neurosci.* 14, 217–223. doi: 10.1038/nn.2727

Andersen, L. M., Jerbi, K., and Dalal, S. S. (2020). Can EEG and MEG detect signals from the human cerebellum? *NeuroImage.* 215, 116817. doi: 10.1016/j.neuroimage.2020.116817

Aricò, P., Borghini, G., Di Flumeri, G., Sciaraffa, N., and Babiloni, F. (2018). Passive BCI beyond the lab: current trends and future directions. *Physiol. Measur.* 39, 57e. doi: 10.1088/1361-6579/aad57e

Attaheri, A., Kikuchi, Y., Milne, A. E., Wilson, B., Alter, K., Petkov, C. I. E. E. G., et al. (2015). potentials associated with artificial grammar learning in the primate brain. *Brain Lang.* 148, 74–80. doi: 10.1016/j.bandl.2014.11.006

Baars, B. J. (1993). "How does a serial, integrated and very limited stream of consciousness emerge from a nervous system that is mostly unconscious, distributed, parallel and of enormous capacity? Experimental and theoretical studies of consciousness," in *Ciba Foundation Symposium 174* (Chichester: Wiley), 282–303.

Baars, B. J. (2005). Global workspace theory of consciousness: toward a cognitive neuroscience of human experience. *Prog. Brain Res.* 150, 45–53. doi: 10.1016/S0079-6123(05)50004-9

Baars, B. J., and Franklin, S. (2003). How conscious experience and working memory interact. *Trends Cognit. Sci.* 7, 166–172. doi: 10.1016/S1364-6613(03)00056-1

Baillet, S. (2014). "Forward and inverse problems of MEG/EEG," in *Encyclopedia of Computational Neuroscience*, eds D. Jaeger, and R. Jung (New York, NY: Springer), 1–8. doi: 10.1007/978-1-4614-7320-6_529-1

Bang, J. W., Milton, D., Sasaki, Y., Watanabe, T., and Rahnev, D. (2019). Post-training TMS abolishes performance improvement and releases future learning from interference. *Commun. Biol.* 2, 1–7. doi: 10.1038/s42003-019-0566-4

Barrett, A. B. (2014). An integration of integrated information theory with fundamental physics. *Front. Psychol.* 5, 63. doi: 10.3389/fpsyg.2014.00063

Bayne, T., Hohwy, J., and Owen, A. M. (2016). Are there levels of consciousness? *Trends Cognit. Sci.* 20, 405–413. doi: 10.1016/j.tics.2016.03.009

Bechtel, W., and Mundale, J. (1999). Multiple realizability revisited: linking cognitive and neural states. *Philos. Sci.* 66, 175–207.

Bisson, T. (1995). *Bears Discover Fire and Other Stories.* New York, NY: Macmillan.

Block, N. (2009). "Comparing the major theories of consciousness," in *The Cognitive Neurosciences*, eds M. S. Gazzaniga, E. Bizzi, L. M. Chalupa, S. T. Grafton, T. F. Heatherton, C. Koch, J. E. LeDoux, S. J. Luck, G. R. Mangan, J. A. Movshon, H. Neville, E. A. Phelps, P. Rakic, D. L. Schacter, M. Sur, and B. A. Wandell (Massachusetts Institute of Technology), 1111–1122. doi: 10.7551/mitpress/8029.003.0099

Boyden, E. S. (2015). Optogenetics and the future of neuroscience. *Nat. Neurosci.* 18, 1200–1201. doi: 10.1038/nn.4094

Compton, R. J., Gearinger, D., and Wild, H. (2019). The wandering mind oscillates: EEG alpha power is enhanced during moments of mind-wandering. *Cognit. Affect. Behav. Neurosci.* 19, 1184–1191. doi: 10.3758/s13415-019-00745-9

Crick, F. (1994). *The Astonishing Hypothesis.* New York, NY: Simon and Schuster.

Crick, F., and Koch, C. (1992). The problem of consciousness. *Sci. Am.* 267, 152–159.

de Camp, N. V., Ladwig-Wiegard, M., Geitner, C. I., Bergeler, J., and Thöne-Reineke, C. (2020). EEG based assessment of stress in horses: a pilot study. *PeerJ.* 8, e8629. doi: 10.7717/peerj.8629

Dehaene, S. (2014). *Consciousness and the Brain: Deciphering How the Brain Codes Our Thoughts.* New York, NY: Penguin.

Detmar, C. F. (2022). An adaptational theory of consciousness. *J. Conscious. Stud.* 29, 30–55. doi: 10.53765/20512201.29.1.030

Diseases, A. A., Llinás, R., Ribary, U., Contreras, D., and Pedroarena, C. (1998). The neuronal basis for consciousness. *Philos. Trans. Royal Soc. Lond. Ser. B Biol. Sci.* 353, 1841–1849.

Doerig, A., Schurger, A., and Herzog, M. H. (2021). Hard criteria for empirical theories of consciousness. *Cognit. Neurosci.* 12, 41–62. doi: 10.1080/17588928.2020.1772214

Doerig, A., Schurger, A., Hess, K., and Herzog, M. H. (2019). The unfolding argument: why IIT and other causal structure theories cannot explain consciousness. *Conscious. Cognit.* 72, 49–59. doi: 10.1016/j.concog.2019.04.002

Eagleman, S. L., Vaughn, D. A., Drover, D. R., Drover, C. M., Cohen, M. S., Ouellette, N. T., et al. (2018). Do complexity measures of frontal EEG distinguish loss of consciousness in geriatric patients under anesthesia? *Front. Neurosci.* 12, 645. doi: 10.3389/fnins.2018.00645

Engel, A. K., Fries, P., König, P., Brecht, M., and Singer, W. (1999). Temporal binding, binocular rivalry, and consciousness. *Conscious. Cognit.* 8, 128–151.

Engemann, D. A., Raimondo, F., King, J.-., R., Rohaut, B., Louppe, G., et al. (2018). Robust EEG-based cross-site and cross-protocol classification of states of consciousness. *Brain.* 141, 3179–3192. doi: 10.1093/brain/awy251

Ferrari, C., Cattaneo, Z., Oldrati, V., Casiraghi, L., Castelli, F., D'Angelo, E., et al. (2018). TMS over the cerebellum interferes with short-term memory of visual sequences. *Sci. Rep.* 8, 1–8. doi: 10.1038/s41598-018-25151-y

Fingelkurts, A. A., and Fingelkurts, A. A. (2008). Brain-mind operational architectonics imaging: technical and methodological aspects. *Open Neuroimag. J.* 2, 73–93. doi: 10.2174/1874440000802010073

Fingelkurts, A. A., Fingelkurts, A. A., and Neves, C. F. (2001). Natural world physical, brain operational, and mind phenomenal space-time. *Phys. Life Rev.* 7, 195–249. doi: 10.1016/j.plrev.2010.04.001

Fingelkurts, A. A., Fingelkurts, A. A., and Neves, C. F. (2013). Consciousness as a phenomenon in the operational architectonics of brain organization: criticality and self-organization considerations. *Chaos Solitons Fract.* 55, 13–31. doi: 10.1016/j.chaos.2013.02.007

Frohlich, F., and McCormick, D. A. (2010). Endogenous electric fields may guide neocortical network activity. *Neuron.* 67, 129–143. doi: 10.1016/j.neuron.2010.06.005

Gray, C. M., Knig, P., Engel, A. K., and Singer, W. (1989). Oscillatory responses in cat visual cortex exhibit inter-columnar synchronization which reflects global stimulus properties. *Nature.* 338, 334–337.

Grech, R., Cassar, T., Muscat, J., Camilleri, K. P., Fabri, S. G., Zervakis, M., et al. (2008). Review on solving the inverse problem in EEG source analysis. *J. Neuroeng. Rehabil.* 5, 1–33. doi: 10.1186/1743-0003-5-25

Guger, C., Harkam, W., Hertnaes, C., and Pfurtscheller, G. (1999). "Prosthetic control by an EEG-based brain-computer interface (BCI)," in *Proceedings of the AAATE 5th European Conference for the Advancement of Assistive Technology* (Princeton: Citeseer).

Hajat, Z., Ahmad, N., and Andrzejowski, J. (2017). The role and limitations of EEG-based depth of anaesthesia monitoring in theatres and intensive care. *Anaesthesia* 72, 38–47. doi: 10.1111/anae.13739

Hales, C. (2017). The origins of the brain's endogenous electromagnetic field and its relationship to provision of consciousness. *Biophys. Conscious. Found. Approach World Sci.* 13, 295–354. doi: 10.1142/9789814644266_0010

Han, X. (2012). Optogenetics in the non-human primate. *Prog. Brain Res.* 196, 215–233. doi: 10.1016/B978-0-444-59426-6.00011-2

Hardcastle, V. G. (1994). Psychology's binding problem and possible neurobiological solutions. *J. Conscious. Stud.* 1, 66–90.

Hedström, A., and Olsson, I. (1991). Epidemiology of absence epilepsy: EEG findings and their predictive value. *Pediat. Neurol.* 7, 100–104.

Hofstadter, D. (1979). *Goedel, Escher, Bach: An Eternal Golden Braid*. New York, NY: Basic Books.

Hofstadter, D. R. (2007). *I Am a Strange Loop*. New York, NY: Basic Books.

Howson, C., and Urbach, P. (2006). *Scientific Reasoning: The Bayesian Approach*. Chicago: Open Court Publishing.

Hunt, T., and Schooler, J. W. (2019). The easy part of the hard problem: a resonance theory of consciousness. *Front. Hum. Neurosci.* 13, 378. doi: 10.3389/fnhum.2019.00378

Jackson, J. D. (1999). *Classical Electrodynamics*. College Park: American Association of Physics Teachers.

James, W. (1988). *Manuscript Lectures*. Cambridge, MA: Harvard University Press.

John, E. R. (2001). A field theory of consciousness. *Conscious. Cognit.* 10, 184–213. doi: 10.1006/ccog.2001.0508

John, E. R. (2002). The neurophysics of consciousness. *Brain Res. Brain Res. Rev.* 39, 1–28. doi: 10.1016/S0165-0173(02)00142-X

Jones, M. W. (2016). Neuroelectrical approaches to binding problems. *J. Mind Behav.* 2016, 99–118.

Jones, M. W. (2017). Mounting evidence that minds are neural EM fields interacting with brains. *J. Conscious. Stud* 24, 159–183.

Kaiser, M., Senkowski, D., Busch, N. A., Balz, J., and Keil, J. (2019). Single trial prestimulus oscillations predict perception of the sound-induced flash illusion. *Sci. Rep.* 9, 1–8. doi: 10.1038/s41598-019-42380-x

Keppler, J. (2021). Building blocks for the development of a self-consistent electromagnetic field theory of consciousness. *Front. Hum. Neurosci.* 28, 572. doi: 10.3389/fnhum.2021.723415

Klemm, W. R. (1992). Are there EEG correlates of mental states in animals? *Neuropsychobiology* 26, 151–165.

Koivisto, M., and Revonsuo, A. (2003). An ERP study of change detection, change blindness, and visual awareness. *Psychophysiology.* 40, 423–429. doi: 10.1111/1469-8986.00044

Kreiter, A. K., and Singer, W. (1996). Stimulus-dependent synchronization of neuronal responses in the visual cortex of the awake macaque monkey. *J. Neurosci.* 16, 2381–2396.

Lamme, V. A., and Roelfsema, P. R. (2000). The distinct modes of vision offered by feedforward and recurrent processing. *Trends Neurosci.* 23, 571–579. doi: 10.1016/S0166-2236(00)01657-X

Libet, B. (1994). A testable field theory of mind-brain interaction. *J. Conscious. Stud* 1, 119–126.

Libet, B. (1996). Conscious mind as a field [letter; comment]. *J. Theor. Biol.* 178, 223–226.

Libet, B., Gleason, C. A., Wright, E. W., and Pearl, D. K. (1983b). Time of conscious intention to act in relation to onset of cerebral activity (readiness-potential). The unconscious initiation of a freely voluntary act. *Brain.* 106(Pt 3), 623–942.

Libet, B., Wright, E. W. J., and Gleason, C. A. (1982). Readiness-potentials preceding unrestricted "spontaneous" vs. pre-planned voluntary acts. *Electroencephalogr. Clin. Neurophysiol.* 54, 322–335.

Libet, B., Wright, E. W. J., and Gleason, C. A. (1983a). Preparation- or intention-to-act, in relation to pre-event potentials recorded at the vertex. *Electroencephalogr. Clin. Neurophysiol.* 56, 367–372.

Liboff, A. (2016). Magnetic correlates in electromagnetic consciousness. *Electromag. Biol. Med.* 35, 228–236. doi: 10.3109/15368378.2015.1057641

Lindahl, B. I., and Arhem, P. (1994). Mind as a force field: comments on a new interactionistic hypothesis. *J. Theor. Biol.* 171, 111–122.

Loeb, C. (1958). Electroencephalographic changes during the state of coma. *Electroencephalogr. Clin. Neurophysiol.* 10, 589–606.

MacLennan, B. J. (1999). Field computation in natural and artificial intelligence. *Inform. Sci.* 119, 73–89.

MacLennan, B. J. (2022). *Unconventional Computation Including Quantum Computation*. Faculty Publications and Other Works – EECS. Available online at: https://trace.tennessee.edu/utk_elecpubs/28

Mashour, G. A. (2004). Consciousness unbound: toward a paradigm of general anesthesia. *J. Am. Soc. Anesthesiol.* 100, 428–433. doi: 10.1097/00000542-200402000-00035

McCrone, J. (2003). Quantum mind. *Lancet Neurol.* 2, 450. doi: 10.1016/S1474-4422(03)00466-6

McFadden, J. (2000). *Quantum Evolution*. London: HarperCollins.

McFadden, J. (2002). Synchronous firing and its influence on the brain's electromagnetic field: evidence for an electromagnetic theory of consciousness. *J. Conscious. Stud.* 9, 23–50.

McFadden, J. (2006). "The CEMI field theory: seven clues to the nature of consciousness," in *The Emerging Physics of Consciousness*, ed J. Tuszynski (New York: Springer), 387–406. doi: 10.1007/3-540-36723-3_12

McFadden, J. (2013a). The CEMI field theory gestalt information and the meaning of meaning. *J. Conscious. Stud.* 20, 3–4.

McFadden, J. (2013b). The CEMI field theory gestalt information and the meaning of meaning. *J. Conscious. Stud.* 20, 152–182.

McFadden, J. (2020). Integrating information in the brain's EM field: the cemi field theory of consciousness. *Neurosci. Conscious.* 2020, niaa016. doi: 10.1093/nc/niaa016

McFadden, J. (2021a). *Life is Simple: How Occam's Razor Set Science Free and Unlocked the Universe*. Paris: Hachette.

McFadden, J. (2021b). Razor sharp. *New Sci.* 252, 70–71.

McFadden, J. (2021c). The electromagnetic will. *NeuroScience* 2, 291–304. doi: 10.3390/neurosci2030021

McFadden, J. (2021d). *Life is Simple: How Occam's Razor Set Science Free and Shapes the Universe*. London: Basic Books.

McFadden, J. J. (2002). The conscious electromagnetic information (Cemi) field theory: the hard problem made easy? *J. Conscious. Stud.* 9, 45–60.

McFarland, D., and Wolpaw, J. (2017). EEG-based brain–computer interfaces. *Curr. Opin. Biomed. Eng.* 4, 194–200. doi: 10.1016/j.cobme.2017.11.004

Müller, M. M., Gruber, T., and Keil, A. (2000). Modulation of induced gamma band activity in the human EEG by attention and visual information processing. *Int. J. Psychophysiol.* 38, 283–299. doi: 10.1016/S0167-8760(00)00171-9

Musialowicz, T., and Lahtinen, P. (2014). Current status of EEG-based depth-of-consciousness monitoring during general anesthesia. *Curr. Anesthesiol. Rep.* 4, 251–260. doi: 10.1007/s40140-014-0061-x

Nervous, A. A., Diseases, M., Llinás, R., Ribary, U., Contreras, D., and Pedroarena, C. (1998). The neuronal basis for consciousness. *Philos. Trans. Royal Soc. Lond. Ser. B Biol. Sci.* 353, 1841–1849.

Noë, A. (2002). Is the visual world a grand illusion? *J. Conscious. Stud.* 9, 1–12.

Nolte, A. (2021). "Brain-computer interface: a possible help for people with locked-in syndrome," in *International Scientific Conference on Brain-Computer Interfaces BCI Opole* (New York, NY: Springer). doi: 10.1007/978-3-030-72254-8_24

Pinotsis, D. A., and Miller, E. K. (2022). Beyond dimension reduction: stable electric fields emerge from and allow representational drift. *NeuroImage.* 2022, 119058. doi: 10.1016/j.neuroimage.2022.119058

Pistoia, F., Sacco, S., Sar,à, M., Franceschini, M., and Carolei, A. (2015). Intrathecal baclofen: effects on spasticity, pain, and consciousness in disorders of consciousness and locked-in syndrome. *Curr. Pain Headache Rep.* 19, 1–6. doi: 10.1007/s11916-014-0466-8

Pockett, S. (2000). *The Nature of Consciousness: A Hypothesis*. Lincoln, NE: Writers Club Press.

Pockett, S. (2002). Difficulties with the electromagnetic field theory of consciousness. *J. Conscious. Stud.* 9, 51–56.

Pockett, S. (2011). Initiation of intentional actions and the electromagnetic field theory of consciousness. *Hum. Mente.* 15, 159–175.

Pockett, S. (2012). The electromagnetic field theory of consciousness a testable hypothesis about the characteristics of conscious as opposed to non-conscious fields. *J. Conscious. Stud.* 19, 191–223.

Popper, K. R., Lindahl, B. I., and Arhem, P. A. (1993). discussion of the mind-brain problem. *Theor. Med.* 14, 167–180.

Rohaut, B., Raimondo, F., Galanaud, D., Valente, M., Sitt, J. D., Naccache, L., et al. (2017). Probing consciousness in a sensory-disconnected paralyzed patient. *Brain Injury.* 31, 1398–1403. doi: 10.1080/02699052.2017.1327673

Roth, M. (1951). Changes in the EEG under barbiturate anaesthesia produced by electro-convulsive treatment and their significance for the theory of ECT action. *Electroencephalogr. Clin. Neurophysiol.* 3, 261–280.

Schartner, M., Seth, A., Noirhomme, Q., Boly, M., Bruno, M.-., A., et al. (2015). Complexity of multi-dimensional spontaneous EEG decreases during propofol induced general anaesthesia. *PLoS ONE* 10, e0133532. doi: 10.1371/journal.pone.0133532

Schubert, R., Haufe, S., Blankenburg, F., Villringer, A., and Curio, G. (2009). Now you'll feel it, now you won't: EEG rhythms predict the effectiveness of perceptual masking. *J. Cognit. Neurosci.* 21, 2407–2419. doi: 10.1162/jocn.2008.21174

Seth, A. K., and Bayne, T. (2022). Theories of consciousness. *Nat. Rev. Neurosci.* 2022, 1–14. doi: 10.1038/s41583-022-00587-4

Singer, W. (2001). Consciousness and the binding problem. *Ann. N. Y. Acad. Sci.* 929, 123–146. doi: 10.1111/j.1749-6632.2001.tb05712.x

Toettcher, J. E., Voigt, C. A., Weiner, O. D., and Lim, W. A. (2011). The promise of optogenetics in cell biology: interrogating molecular circuits in space and time. *Nat. Methods.* 8, 35–38. doi: 10.1038/nmeth.f.326

Tononi, G. (2004). An information integration theory of consciousness. *BMC Neurosci.* 5, 1–22. doi: 10.1186/1471-2202-5-42

Tononi, G., and Koch, C. (2015). Consciousness: here, there and everywhere? *Philos. Trans. Royal Soc. B Biol. Sci.* 370, 20140167. doi: 10.1098/rstb.2014.0167

Treisman, A. (1999). Solutions to the binding problem: progress through controversy and convergence. *Neuron.* 24, 105–125.

Vaz, A. P., Inati, S. K., Brunel, N., and Zaghloul, K. A. (2019). Coupled ripple oscillations between the medial temporal lobe and neocortex retrieve human memory. *Science.* 363, 975–978. doi: 10.1126/science.aau8956

Voss, L., and Sleigh, J. (2007). Monitoring consciousness: the current status of EEG-based depth of anaesthesia monitors. *Best Pract. Res. Clin. Anaesthesiol.* 21, 313–325. doi: 10.1016/j.bpa.2007.04.003

Zhakenovich, A. E., Valentina, Y., Ruben, S., and Tudor, S. A. (2016). new approach to electromagnetic theories of consciousness. *J. Chem.* 10, 235–237. doi: 10.17265/1934-7375/2016.05.006

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The contribution of coherence field theory to a model of consciousness: electric currents, EM fields, and EM radiation in the brain

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A paradigm in neuroscience is developing which views resonance as the phenomenon responsible for consciousness. Much progress is being made in the investigation of how resonance as oscillating flows within the brain's electric field might result in production of mind from matter. But it's mostly unknown how vibrations among features of matter such as nanoscale atomic structures and photonic waves may participate in forming the basic substance of first-person consciousness, meaning percepts such as colors, textures, sounds, thoughts, feelings et cetera. Initial evidence at the leading edge of quantum biology suggests that light and atoms combine to form synchronously resonating structures of contiguous energy which I have termed coherence fields. My hypothesis is that coherence fields as atomic nodes within expanses of integrating photonic waves are the fundamental unit of first-person percepts insofar as they arise from electromagnetic matter. A concept of quantum coherence is formulated based on a new phenomenology of matter's nanoscale properties, and this is shown to tie what we have thus far discovered of neural anatomy into a comprehensive model of how electrical impulses travel through neurons as electron currents driven by coherence at the quantum scale. Transmembrane electric fields generated by ionic currents, synaptic phase regulation, and perhaps further mechanisms have been hypothesized as responsible for local field potentials (LFP) oscillations. Some insights into how emergent, macroscopic waves in the brain's electric field may reciprocally impact LFP propagation to control arousal, attention, and volition are briefly discussed. Activation of neural tissue is closely linked to temperature variation, and it is hypothesized that this is not merely a waste byproduct but constitutes a signature of coherence field modulation, with photonic waves of a primarily infrared spectral range functioning as an interstitial medium of the basic percept field. A variety of possible routes to coherence field modulation are outlined that derive from the mechanisms of electric currents, EM fields, EM radiation, and entanglement. If future experimental designs continue to validate coherence field theory, this could set science on course to resolve the mind/body problem.

KEYWORDS

coherence field theory (CFT), electromagnetic field, electromagnetic radiation, electric current, ebb effect, photonics, infrared, quantum entanglement

Introduction: consciousness as the resonant structure of matter

One of the features that most defines brain matter is vibration: waves of electrical energy ranging from one millimeter to a dozen centimeters course through this organ (Alekseichuk et al., 2019), oscillating and flowing as an emergent property of neural networks. Most have some familiarity with the fact that these traveling waves are a primary signature of the arousal states such as thinking, imagining, remembering, focusing, etc., which we refer to as consciousness. EEG machines are of course employed to study the mind by observing the brain's electric field. Vibration proves more fundamental than this, for all of the electromagnetic matter we sense *via* optical inspection, measure with instruments and scientifically model, is comprised of wavelike frequencies. We all know that light oscillates, with the distance between peaks of its superpositioned waveforms ranging from nanometers to kilometers. It is also common knowledge that electrons, as the particles which give atoms their shape, have wavelike characteristics that produce interference patterns upon contact with many surfaces (ER Services, n.d.a; Mairhofer and Passon, 2022). Vibration is so intrinsic to the structure of matter that a paradigm in the scientific study of consciousness' substance is materializing which seeks to model it in terms of resonance, for example, Hunt and Schooler's General Resonance Theory (GRT). This theoretical approach anticipates that vibrations in matter are not merely a signature of consciousness but rather the essence of the mind itself.

In theorizing consciousness, GRT has so far focused on models of the brain's electric field, most basically reducible to LFPs (local field potentials) as oscillative perturbations at the scale of individual neurons. Electric field oscillations superposition to produce emergent contours we know as brain waves and GRT is committed to closely examining patterns of electrical energy as they arise in different combinations and locations within the brain, for they may be the actual substance of experience. The present article tries to base GRT's brain wave account of consciousness on lower, quantum levels. Neuroscience is in the beginning stages of determining the extent to which the wavelike behavior of matter at the quantum scale is relevant for the modeling of sensations, perceptions, and stream of consciousness. It will be proposed here that key mechanisms of the first-person mind fall within the purview of what has traditionally been the quantum physics' domain. The goal of this article is to investigate some ways that phenomena operative at the nanoscale may participate in generating macroscale phenomena including brain waves and minds.

Historically, quantum mechanics has tended towards formulas and mathematization, with the motto being "shut up and calculate" while phenomenological considerations were mostly neglected. This is for an obvious reason: it is so difficult to directly observe matter at the nanoscale that even the most introductory progress in this area was untenable. But recent discoveries in the realm of cellular anatomy have changed the situation, and this article will attempt to elucidate how neural structure in particular sheds light on the qualities and roles of quantum-scaled phenomena in biological systems.

The article starts by giving a description as to why the concept of a matter field is central in the quest for a model of consciousness, then some background into why quantum mechanics as the foremost determinant of this concept relies so heavily on models of statistical probability rather than physical structure in formulating its models. Despite the discipline's antirealist leanings and ambiguity in how its quantitative abstractions are to be interpreted, some key realist insights are possible which provide for a general definition of what will be delineated and explained as quantum coherence. This concept of coherence is a powerful idea, for it makes sense of all the empirically derived facts thus far disclosed about a neuron's component structures, allowing us to arrive at a much deeper comprehension of neural function, from the subatomic to cellular scale. Essentially, the flow of electrical energy around an aqueous solution inside a neuron is driven by differentials in electron density caused by ion diffusion, which seems to be why ion channels are positioned where they are in the cell and how signals are transmitted intraneurally. Hypotheses are discussed in regards to how LFPs might emerge from either dynamics of the synapse, or electron and ion currents abiding by the newly outlined principles of quantum coherence. LFPs in turn synchronize into emergent waves of oscillation with phase distributions linked to attention, awareness, and volition.

An empirically backed hypothesis will be made that electromagnetic radiation and molecular arrays jointly oscillate in what I call a coherence field, the signature of which is vibration measured as temperature variation. Temperature changes occur when neural networks activate, suggesting that cognitive processes are tied to thermal energy, consisting in the vibration of biochemical structures within photonic fields typically centered on infrared portions of the EM radiation spectrum which effectively penetrate the aqueous solutions within and between neurons. It is proposed that this complex of particle vibrations and radiative waves is not merely the waste byproduct of neuron firing and chemical reactions but rather a vital component of mechanisms binding electromagnetic brain matter into the substance of perception. Relatively nonlocal mechanisms of consciousness are of course in effect as an additional factor, but if electrical coherence currents, EM fields, and EM radiation coordinate with molecular complexes as the electromagnetic facet of coherence field structure, a resultant coherence field theory (CFT) may enable the GRT framework to begin discerning how the nanoscale of quantum physics renders matter a perceptual field.

Consciousness, the brain, and quantum coherence

One of the main topics that arise in consciousness theory is the binding problem: how can trillions of atoms and billions of cells participate in producing the more or less integrated medium of awareness we introspect? The body and brain are intimately involved in generating this experiential substrate, for awareness seems to largely extinguish when physiological processes cease, but it is not easy to discern how the holism of conscious experience inheres within brain matter and is in large measure instantiated by it.

As a parallel investigation, 20th and 21st-century physics have come to rely on the concept of a field: matter is not fundamentally solid and stable, but rather a vast array of ripples or disturbances in a sort of fluid medium characterized by perpetual motion, with relatively persistent focal points of perturbation being what we observe and model in the form of particles (Strassler, n.d.). As loci of energetic perturbation, particles radiate causality farther than characteristic densities we directly measure using mass, through a spatially extended substrate we do not yet fully grasp. The concept of matter as a field of fluctuating, flowing perturbations and the concept of experience as a stream of consciousness which contiguously saturates our reality is intuitive to analogize. But constructing a viable model must conjoin domains of inquiry that diverge widely in content and methodology. How can the sciences of perception, personality, and meaning be reconciled with the sciences of matter with their fundamental reliance on the modeling of unconscious mechanisms? If any synthesis is to be had, it seems destined to initiate by explaining brain processes as a physical field, and examination of the organ's wavelike, diffusive properties is moving neuroscience in that direction. The aim is to explore some hypotheses which may further the modeling of the brain's coordination with experience as a physical field.

A detailed history of the physical field concept is beyond this article's scope, but suffice to say that our most precise experiments and calculations reveal the continuum of matter as divisible into basic quanta with measures such as an almost infinitesimally small unit of distance called the Planck length: $1.6^{*}10^{-35}$ m. To give a sense of the scale, protons are about 100 million trillion times larger. This quantity originated at the turn of the 20th century as a calculational tool that integrated quantum, gravitational, and eventually relativistic units of measurement while lacking much physical meaning, though modern string theory is a prominent attempt at theoretically modeling this scale (University of South Wales, n.d.). However, a related term called Planck's constant (approx. $6.6^{*}10^{-34}$ joule-seconds) correlates the frequency of EM radiation with its wavelength and is a foundational component of quantum mechanics (TechTarget, n.d.), allowing physicists to probe, model, and technologize electromagnetic matter by observing how atomic and subatomic particles quantize frequencies and corresponding wavelengths of EM radiation while interacting with them.

During the inception of quantum mechanics, it was confirmed by experiments which created interference patterns by scattering electrons from crystals that these particles have wavelike properties. Louis de Broglie developed a theory based around arranging circular, wavelike electron "orbitals" according to a constrained range of oscillative shapes characterized by quantized ratios where constructive interference obtains, similar to how a plucked guitar string vibrates in whole number ratios of its length (ER Services, n.d.a). But when EM radiation was emitted into atoms experimentally, scientists found that each individual trial produced a more particulate than a wavelike signature in a different region within the atom. Furthermore, this location could not be predicted exactly from trial to trial because the higher the frequency or energy of EM radiation, the more it knocked the electron out of its natural trajectory, altering the momentum, and the lower the energy, the somewhat less particulate an electron registered upon contact, making its position less exact. The fundamental imprecision of these measurements was quantified and codified as the Heisenberg uncertainty principle. By contrast, hundreds of trials resulted in a probability distribution of more and less likely locations that looked like a cloud of particulate density, and the shape of this cloud could be reproduced with great precision (ER Services, n.d.b). Mathematical tools were fashioned for performing calculations on these probability distributions, namely Heisenberg's matrix mechanics along with Schrodinger's wave function (Casado, 2008), and quantum mechanics remains fundamentally probabilistic to this day, even in its most high-tech applications.

So basic understanding of matter is founded on relative probability, with the textbook image of how electrons are arranged in atoms depicted by squaring Schrodinger's wave function to enable a geometry of probability density (Morin, n.d.). These geometries are assumed to be three-dimensional for reasons of clarity, superimposed on an "x, y, z" coordinate system in ways that maximize symmetry of charge since negative charges repel (Dill, 2008). The shapes thus formed include spheres, dumbbells, and doughnuts, in all sorts of hybrids (**Figure 1**).

Quantum mechanics is one of the most accurate models in science, matching the results of thousands of experiments to impeccable precision, but is nonetheless an approximation, and uncertainty persists about what is going on beneath the superimposed math. The crux of the dilemma is how a greater than zero probability exists for a particle such as an electron to be anywhere (saylordotorg.github.io, n.d.) while we experience matter as localized to particular regions of space. The math says that every particle is to some extent everywhere at once as a universal superposition of states, while real particles reside at a particular place and time, so what is the actual state of the matter itself when what we quantify is so different from what we intuit?

Competing interpretations of quantum mechanics have been proposed which fit the math equally well, though experiments are beginning to achieve the capacity to adjudicate between them. The many-worlds interpretation hypothesizes that a particle splits into multiple, largely noninteracting timelines when undergoing certain types of perturbation such as measurement so that superposition is undissolved by factors of localization like particle collisions even though most of these superpositions are not to this point scientifically observed. The pilot-wave interpretation assumes that particles such as electrons are guided along trajectories by underlying wave perturbations which have not been witnessed directly. Spontaneous localization interpretations attempt to model physical matter as pockets of locality that form within the probability plenum in a phenomenon directly proportional to the quantity of perturbation, and a host of different parameters for how this localization occurs have been fashioned with the aim of fitting experimental data. But enough doubt remains that the traditional Copenhagen interpretation is the most popular, simply asserting the math should be viewed as working agnosticism, a technique allowing us to predict the relationship between initial and final probabilities of a material system without telling us anything realist about causality (Mohanmurthy, 2020).

Despite the incertitude, some rudimentary realist knowledge can presently be gleaned from the probability model that is sufficient for the purposes of neuroscience. First of all, though a probability exists for the energy of every particle to be anywhere, each particle involves a range of most to least likely locations that eventually declines dramatically as one strays from the center of mass, and reductions in probability correspond to a diminishment of energy density, meaning regions equidistant between centers of mass tend to be less energetically dense (saylordotorg.github.io, n.d.). So centers of mass are various forms of energy maxima, and equidistance between them relative minima, a principle seeming to apply all around us, from electron orbitals, to atoms, planets, etc. We also know, at least insofar as electromagnetic properties obtain, less mass or energy density corresponds to more propensity for energy to flow through that region of space. For instance, the less dense that electrical energy is at a specific location, the more rapidly this energy can

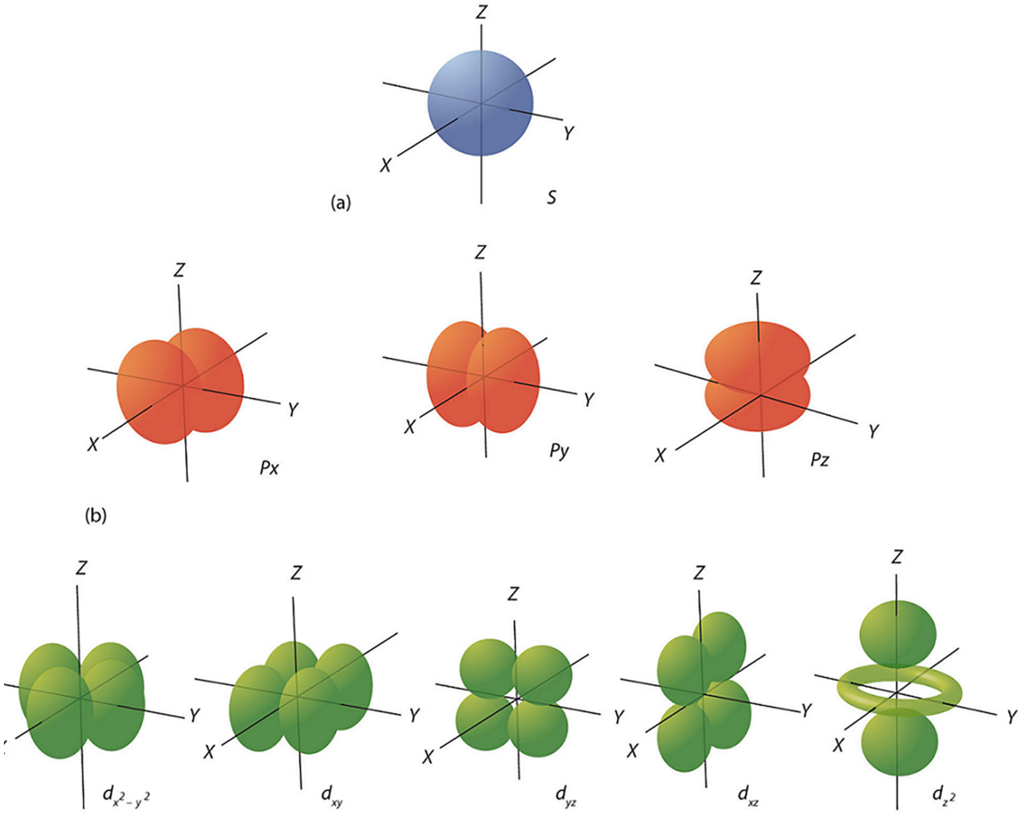

FIGURE 1
Diagram of atomic s, p, d orbitals (Blendspace, n.d.).

accelerate. Atom on atom causality of an EM field, provisional of maximum diffuseness (density minimum) when atoms involved are not chemically bonded, almost instantaneously reaches or nears the typical max speed of magnetism and light, 300 million m/s. Currents comprised of electrons which are density maximums within the EM field of an atom can attain 90% of the speed of light in a copper wire due to a cascade of local displacements called signal velocity which travels along its length, but rarely any speed in excess of that, especially at the micrometer scale or larger. Many electric currents, again a directional flow among adjacent density maximums, reach average signal velocities that can be closer to 50% of the speed of light. This is a consequence of the idiosyncrasies in specific atomic structures along with a material system's entropy, the amount of disorder from factors such as temperature that increase local agitation, preventing electrons from synchronizing within relatively large spaces (Bond, 2022a).

Under conditions where electric currents cannot flow micrometers or larger distances because of entropy, electromagnetic motion tends to commove haphazardly and settle into maximum average locality, a state which has been termed decoherence. When conditions are such that electrical energy flows synchronously, this is a state of coherence. So a spectrum of relatively decoherent to relatively coherent states exists among electromagnetic matter. An atom's electron orbitals or density maximums in and of themselves are relatively coherent, to the extent that atoms can be modeled as individual units of superpositioned probability waves. Trillions of atoms jostle entropically enough in typical Earth environments that relative decoherence prevails and net motion is modelable in terms of classical space and time. Chemical bonds range between a maximally decoherent and maximally coherent state, as a sort of short-ranged coherence at the boundary of Newtonian and atomic structure. And electric currents constitute a special case where atoms are induced to engage in macroscopic coherence transcending the baseline boundaries between microatomic and macroatomic (Bond, 2022b). Electricity is made to flow by charge differentials in the matter, with greater charge differential (voltage) as a general rule causing more rapidly accelerating currents (amperes). It will be shown that the most plausible model for signal transmission in a neuron is derived from these coherence principles.

Electric coherence currents and EM fields within the brain

It is well-established that neural signaling is modulated by the diffusion of ions through channels in a neuron's membrane, but ion collisions cannot explain some features of signal transmission. Researchers have discovered that each node of Ranvier, where voltage-gated Na^+ channels let Na^+ into an axon, is flanked by paranodes, where the myelin sheath attaches to the outer membrane, and these are flanked by juxtaparanodes, where voltage-gated K^+ channels are located that let K^+ flow out of the cell when open (**Figure 2**; Arancibia-Carcamo and Attwell, 2014). Ion diffusion provides no reason for voltage-gated K^+ channels to be strategically placed at the juxtaparanodes. In theory, larger diameter axons involve less axial (lengthwise) resistance due to greater volume and more dilute ion

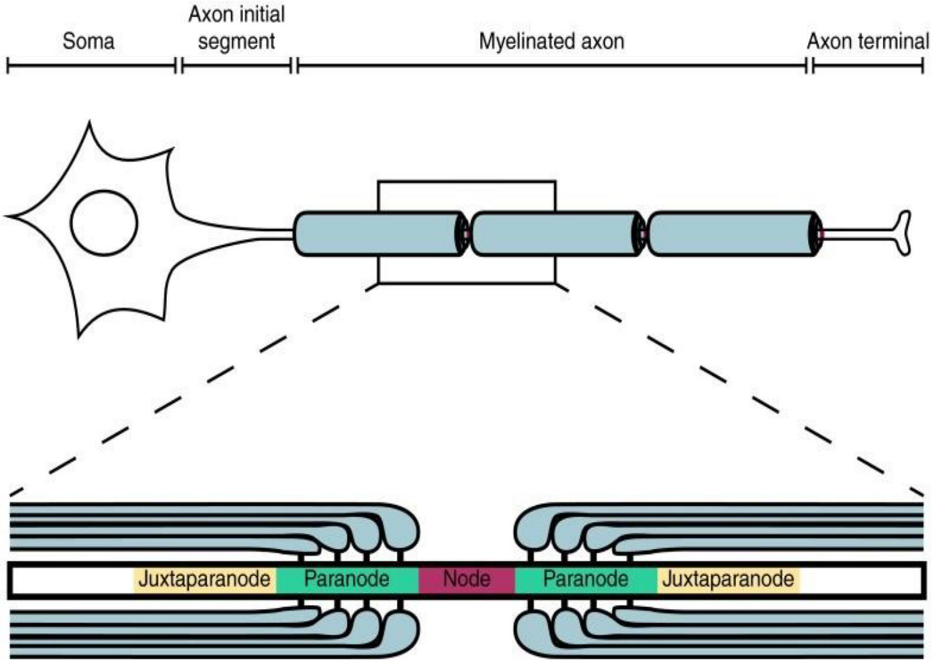

FIGURE 2
Nodal, paranodal, and juxtaparanodal regions (Arancibia-Carcamo and Attwell, 2014).

concentrations. This would allow more rapid axial diffusion rates, necessitating that nodes of Ranvier be farther apart so as to keep signal strength the same, but nodes of Ranvier are actually spaced closer together in larger diameter neurons (Ford et al., 2015). Computer simulations demonstrate that widening nodes of Ranvier slightly to significantly increase the quantity of voltage-gated Na^+ channels does not increase the rate of signal transmission with more ion diffusion (Arancibia-Carcamo et al., 2017). And a neuron's signal can of course travel meters in milliseconds, far exceeding the rate of diffusion. Where a description based on ion diffusion alone falls short, applying the idea of electrical coherence current succeeds. The coherence model has not at this stage surpassed the status of the Gedanken experiment, but ties all we know about the chemistry and anatomy of neurons into a complete picture so is deserving of concerted empirical investigation.

The solution internal to a neuron is made up primarily of water molecules and positive ions. H_2O is of course a polar molecule, its hydrogen atoms being the positive poles and the oxygen atom a negative pole, bent at the fulcrum. A nanoscale solvation shell forms around each positive ion, with negative poles facing inward and positive poles outward. Thus, the cellular solution contains a complex contour of positive and negative charge. Since positive ions lack an electron, the electromagnetic density of aqueous solution at their locations would be reduced. Asymmetries in electron density perpetually shift positive ions and water molecules around in pursuit of equilibrium, a nanoscale agitation which causes the solution to on average be maximally decoherent as its baseline condition.

When Na^+ floods into the axon at a node of Ranvier during an action potential, electron density decreases in that region. This creates a positive terminal that induces an electric current to flow towards the node, but the current begins adjacent to the node and cascades outward into successively distant regions. Because propagation slows due to electron mass inertia when charge is constant, I have named this the "ebb effect". The ebb effect has not been verified by experiment but should be observable within any aqueous solution of ions that contains regions of both charge differential and uniform average charge.

The electron density of atoms is enveloped in an EM field that acts remotely, perturbing at or near the speed of light as atoms move. When an electrical coherence current initiates, the leading edge of procession away from the node is accompanied by an EM field fluctuation, probably the trigger by which depolarization activates voltage-gated ion channels, *via* a temporary nanoscale magnetism caused by synchrony of electric current flow.

Electric current initialization decelerates through the paranodal region, and upon reaching the juxtaparanode its field perturbation triggers voltage-gated K^+ channels to open and let this ion rush out of the axon. The spike in electron density propels current through internodal space at a significant fraction of light speed despite resumed slowing. The motion of this phenomenon is complex, depending on local ion concentrations, positions, and the relative rate of electron vs. ion flow, but thought experiments preliminarily suggest that electrical energy might saturate at the node of Ranvier due to a signal velocity's relative rapidity. This would form a sort of electron wall so that greater electron density can only travel towards internodal space. Voltage-gated K^+ channels then serve to greatly increase electron density by vacating positive ions from the juxtaparanode, at a faster rate than Na^+ influx. A substantive breadth of higher electron density thus materializes near-instantaneously at the juxtaparanodal and paranodal regions, causing pressure which is released by the flow of electric current through internodal space and to the next node of Ranvier. An accompanying field may trigger the intervening, downstream juxtaparanode to depolarize, while the subsequent node of Ranvier has usually not been completely repolarized, and charge differential accelerates current towards the node of Ranvier. EM field stimulation then causes voltage-gated Na^+ channels to let this ion flow into the axon, a chain reaction that continues to the axon terminal where a synapse occurs.

An increase in electron density at the downstream juxtaparanode and paranode would also induce current to flow in the upstream direction, back into internodal space. It is at least conceivable that an alternating current of concentrated electron density could cause a sort of reverberation within internodal space which might be a fundamental aspect of the mechanism responsible for electric field oscillation. This may be supported by recent research improving the resolution of LFP structure using a Discrete Pade Transform (DPT) analysis. The technique revealed low amplitude, high frequency, irregular harmonics that comprise 90%–99% of the total quantity of frequencies (Perotti et al., 2019), a noise component perhaps hinting at ultrafast, intracellular reverberations within the LFP, but a definitive link between the present thought experiment and DPT data awaits further study. The extent to which these mechanisms are possible in dendrites is also empirically uncertain.

Dendrites have clustered Na^+ channels as well, so an EPSP (excitatory postsynaptic potential) takes place *via* at least the ebb effect mechanism. Cl^- channels are located at the dendrite/soma junctions to halt EPSPs with a Cl^- influx that initiates current traveling upstream into a dendrite, from greater, negative electron density to lesser, positive electron density. This current is called an IPSP (inhibitory postsynaptic potential). When Cl^- influx and IPSPs wane, with EPSPs cumulatively strong enough to breach the soma *via* the ebb effect, a threshold is crossed, probably abetted by the subsequent resumption of Cl^- influx, and this relatively large electron density accelerates rapidly towards the greatest quantity of voltage-gated Na^+ channels and Na^+ ions in a neuron at the axon hillock. K^+ leakage channels are present throughout the outer membrane to sustain positive ion concentrations as a kind of electrochemical chassis allowing ebb effect flow to trump decoherence effects, which are more substantial when greater amounts of water agitate the solution locally due to denser polarity. Sodium-potassium pumps help maintain diffusion gradients across the membrane by a constant ferrying of two K^+ ions into the cell accompanied by three Na^+ ions out of the cell.

Microscopic platinum sensors have been inserted into individual neurons, revealing a crystalline structure located just beneath the axon's outer membrane, wrapped around a core support framework of microtubules (Bandyopadhyay, 2022). This probably assists in holding ion concentrations at levels provisional of the ebb effect. A greater volume-to-surface area ratio may surround this structure in larger diameter neurons, necessitating that nodes be spaced closer together to compensate for dilution effects and a consequently less powerful electron current due to more resistance from decoherence.

So based on what we know of cellular anatomy, an explanation for signal transmission in neurons which appeals exclusively to ion diffusion and transport is unsatisfactory, but the concept of electric coherence currents traveling through a chassis of positive ions at significant fractions of light speed meets all current requirements for a successful model, though experimental verification remains to be performed. How then does a flow of ions and electricity associated with individual neurons result in macroscopic oscillations of the brain's electric field, and does this field have some functional role in consciousness' architecture?

Wave phases of individual neurons coordinate as supracellular electric field oscillations in a process termed "phase-locking". These electric fields of more or less in-phase neural networks then constitute emergent flow shapes which reciprocally impact the firing of individual neurons. Transcranial magnetic stimulation by electric fields having properties resemblant of the organ's endogenous field (Frohlich, 2014) as well as the application of similar fields to *in vivo* and *in vitro* preparations of neural tissue (Frohlich and McCormick, 2010) demonstrate this ultrasynchronizing entrainment effect. Phase-locking's mechanism is still a mystery, but progress is being made.

Preliminary research suggested a neuron's lipid membrane almost fully absorbs an electric field produced by the internal electron current so that it only extends a few nanometers beyond the membrane's surface (Anastassiou et al., 2011). This would seem to imply the current is not directly involved in phase-locking. However, recent research has provided evidence that ephaptic coupling occurs at much greater ranges as an important factor in communication between neurons. Slow wave oscillations of the mouse hippocampus, less than 1 Hz, were proven to synchronize neural activity in slices separated by as much as a 400 μm gap, which eliminated synaptic transmission and gap junctions as variables. The entrainment effect propagated at 0.1 m/s, too fast to be accounted for by ion diffusion. An anti-electric field blocked this phenomenon, adding evidence that ephaptic coupling is the mechanism (Chiang et al., 2019). Further study revealed pharmacological blockers to be incapable of inhibiting synchrony while stimulating intact slices using an electric field with similar properties to the tissue's endogenous field induced a self-propagating wave of comparable nature. Applying a voltage clamp completely blocked synchronization, still more evidence that ephaptic coupling is the mechanism (Shivacharan et al., 2019).

It is not yet entirely clear how and to what general extent ephaptic coupling is active in conjunction with biochemical features of the neuron, but a theory has been proposed. Researcher Colin Hales developed a computer model suggesting the global, static field that pervades neural membranes of the brain is accompanied during neuron firing by fields arising from ion channels operating both individually and in tandem. He postulates that these overlapping electric fields caused by ions moving more or less coherently through channels densely concentrated within a neuron's membrane, flowing at a rate similar to electric current in a copper wire, 90% the speed of light, generate the transmembrane impact upon nearby neurons revealed by experiment. When certain parameters are introduced to this model, the most significant being sufficient synapse-mediated synchrony among neural networks, then ion channel fields projected beyond the neurons giving rise to them modify firing thresholds into a collective form, tightly binding groups of neurons as phase-locking's mechanism (Hales, 2014).

It seems plausible to the present author that a combination of K^+ leakage channels and sodium-potassium pumps positioned throughout the neural membrane could produce a transmembrane electric field extending the full length of a neuron *via* constant flurries of ion transport, binding adjacent cells into relatively stable superstructures through the mutual influence of their fields. Holistic activation of the voltage-gated ion channels at each node by lengthwise coherence currents traveling at a sizable fraction of light speed would then cause surges of transmembrane electric field behavior, a further influence inducing clusters of neurons to fire in unison. So though electric field oscillations of a neuron may at the base be the consequence of intracellular force exacted by electron density disequilibration and resultant lengthwise flow, these currents might be synced into phase-locked, more or less in-phase conglomerates by ionic currents transiting through channels, a dual mechanism of electrical energy from different sources that induces emergent electric field patterns which stimulate collective firing. Intracellular electron currents might evince irregular microreverberations in the field, K^+ leakage channels and sodium-potassium pumps a constant, low-level field noise from somewhat loosely synchronized populations of ionic current (which might also contribute to the irregular harmonics of DPT), and nodal fields the more regularized oscillatory patterns of LFPs. Research is ongoing into the origin of neural oscillation, and we will know more about how and why this phenomenon occurs in the coming years. As in the case of coherence currents, an ion channel hypothesis requires more empirical validation.

Evidence is accumulating which suggests that at least some synapses do not transition between inactivated and activated states as a continuum correlated with the gradualized flow of thousands of molecules and ions, but rather snap into three or more discrete states linked to the degree of synchronous potentiation. Interestingly, a model of this phenomenon has shown that at certain frequencies of neuron firing and rates in the transition between discrete states, oscillations of a presynaptic and postsynaptic neuron can be in-phase, so phase-locking may be mediated by synaptic synchronization (Abarbanel et al., 2005).

It is apparent that coherence currents induce transmembrane LFPs (local field potentials), hypothetically phase-locked by mutual projection from ion channels, synaptic synchronization and/or alternate mechanisms. Emergent oscillation and flow shapes in the brain's electric field, of the kind EEG distinguishes from those of individual neurons, may then magnetically orchestrate flurries of molecular machinery, similar to how electric currents drive the operation of appliances by exacting organized magnetic effects upon their structure. Actually, brain cells may be more akin to an ecosystem that is especially fine-tuned in comparison to most physiology, with components fluxing in holistic ways partially under their own power while tightly knit by varying EM field stimulation, a cross between mechanism, food chain, and mass migration. It seems probable that brain waves are more than an epiphenomenon, flowing through neural tissue to participate in morphing swaths of molecular structure into simultaneity. The more phase-locking an electric field attains among neural networks, the more large-scale, unified, and self-directed its functioning can be. Research indicates that the behavior of the brain's electric field consists ofhing, that it have regionally linked oscillation patterns as well as a 40 Hz signature corresponding to individual neurons, superimposed on slow wave oscillations emergent from the whole brain, with a large, roving concentration of semi-stable gamma activity which blends with local oscillations while it moves. This drifting density of macroscopic integration could be the primary orchestrating factor in experiential awareness (Hunt and Schooler, 2019). It could also be a root of volition as proposed by CEMI (conscious electromagnetic information) theory (McFadden, 2020, 2021).

The coherence current model and some auxiliary concepts seem to put certain basic principles of the mind's organization insofar as it connects to the brain's electromagnetism within reach, but we still lack the total picture, for this does not in itself necessitate that consciousness look or feel like anything, that it has features of awareness as opposed to being machinery, a mere technological gadget. How do percepts arise in conjunction with physiology of the brain and body?

EM radiation as a binding agent for the physiological substance of perception

All EM fields are filled by a vast array of undulations which readily superposition while flowing between and in synchrony with atoms, what we know as EM radiation or light. EM radiation can conceivably constitute the interstitial texture of perception's substance, so the question then is how to characterize the properties of this light energy. Electrons as electromagnetic constituents of massive atoms, the density maximums, and light as textural substantiality between atoms, the density minimum, evince a counterintuitive property known as entanglement. Entanglement is a process by which particle states such as spin in electrons or phase in photons correlate across distances at faster-than-light speed. It occurs *via* relatively nonlocal forces that are still poorly understood, which underlie coherence in all its forms, more fundamental than electromagnetism (Franson, n.d.). In relatively diffuse, minimally entropic, or relatively homogeneous material structures such as gases of more or less minimized temperature and simple chemical composition (Irving, 2020), faster than light entanglement can readily take effect, but very exacting conditions must be generated for the phenomenon to presently be observed in the lab. Under more common circumstances such as the flow of electric current through a compact structure such as a metal, or through an entropic substance such as an aqueous solution, or through heterogeneous matter such as an organic body, the nonlocality of coherence is dissipated by the medium's baseline decoherent state so that rates slower than the speed of light obtain (Bond, 2022a,b). Coherence among electromagnetic particles of substantial mass thus tends to be mitigated in various degrees by density, a sort of rate bottleneck effect more pronounced the greater the complexity of density contour.

EM radiation, by contrast, is much less massive and does not have nearly the same constraints as electrons or atoms. Congregates of photons can evince statistically significant entanglement correlations across distances of at least 15 km (Filmer, 2013). Light has further properties unique for electromagnetic matter, filling nonvacuum spaces populated by atomic structure as a wave, and much more readily superpositioning into additive structures than atoms, put on full display by the wide range of wavelength combinations associated with the visible spectrum. EM fields are made to undulate as EM radiation when electrons in atoms or electric currents accelerate or decelerate, and most electromagnetic matter does to some extent, so nature is saturated with light (Northwestern, n.d.). This light interacts with atoms in complex ways that are still rudimentarily understood, but we know for sure that its wavelengths can blend into atoms when energy is complementary. Many photons scatter as they collide with atoms, a phenomenon known as the Compton effect, but light also forms vibrational complexes of atomic nodes within photonic fields (Dill, 2008). Radiative/molecular superpositions as synchronously vibrating arrays of electromagnetic matter are an excellent candidate for the substance of percepts, and research into the connection between photonics and awareness is showing promise.

In the initial analysis of light's interaction with biological systems, it was discovered that photosynthetic reaction center complexes achieve 100% energy yield from UV radiation because light waves take multiple routes or flow through numerous chlorophyl molecules as they are translated into chemical energy, fully absorbed by a reaction center hub without fail (McFadden, 2014). Chlorophyl arrays are such that EM radiation blends into them like they are a pool of water and photons a bead of this water, conjoining as a coherent energy field. Early research into the response of neurons to light exposed them to the visible and UV spectrum. It was found that this relatively high energy EM radiation affects neural function, but primarily due to the degradation of ion channels and additional structures, reducing synaptic efficiency (Khoshakhlagh et al., 2019). Subsequent examination has proved more auspicious, however.

A long-standing hypothesis about the source of consciousness, Roger Penrose and Stuart Hameroff's Orch-Or (orchestrated-objective reduction) theory, proposes that microtubules are compact enough in the brain to produce a wide array of pulsing superpositions responsible for awareness (Hameroff, 1998). The model has faced criticisms from scientists who claim the brain is too hot and wet to support the coherence of this kind, but recent experiments have aimed to assess whether light induces a coherent energy field in microtubules where molecular structure alone cannot.

Microtubules contain light-sensitive amino acids such as tryptophan, and the absorption of UV light was recently tested. A solution of microtubule fragments exposed to UV light was proven conducive to remote energy transfer between component tryptophan molecules. Anesthetics inhibited the phenomenon, hinting at a link with consciousness. Combining this data with a model of tryptophan positioning inside intact microtubules suggested that the amino acid can mediate a coherent energy field spanning the microtubule's entire length, ranging to 50 μm. The only source of UV light in a typical cell was hypothesized as perhaps the oxidation reactions of mitochondria, so it is doubtful these wavelengths have much of a functional role in the brain, but it becomes increasingly apparent that light superpositions and entangles among relatively large molecular structures to produce coherent energy fields in a wide range of circumstances (McIver et al., 2022; Neven et al., 2022). So the question is whether some alternative light source exists within the brain to cause an expansive energy coherence.

An obvious option for endogenous light in the brain is infrared radiation, which saturates physiological structures while constantly absorbed and emitted by rotating and vibrating atomic bonds. The capacity of the infrared spectrum to transmit through aqueous solution quickly diminishes as this radiation's wavelength increases from 1 to 10 μm, but plenty of circumstantial evidence ties the thermal energy of molecular motion associated with infrared radiation, better known as temperature, to brain function. Brain tissue temperatures have been measured to exceed those of the blood by 0.5°C–0.6°C in various mammals. In rats, the temperature of the hippocampus increases 1.5°C–38°C when actively exploring. In male finches, temperature of brain tissue increases during variance in song tempo. Feeding and social interaction produce rapid, unique, and relatively long-lasting brain temperature elevations, occurring faster and with greater magnitude than those of the arterial blood supply. In humans, somatosensory cortex temperature increases during nerve stimulation, and likewise for motor cortex and bodily movement. Many brain regions such as the substantia nigra alter their activity when the temperature is varied. The rise in temperature of neuronal pathways is generally linked with sensory stimuli, and correlations between temperature and data obtained on resting potential, action potential, nerve conduction velocity, and synaptic transmission are well-established. Anesthesia lowers brain temperature, a sign that infrared radiation may be linked to conscious awareness. The total brain varies in temperature by 1°C–3°C in some animal models. The relationship is obvious, but whether temperature contributes some function or is merely a byproduct remains uncertain. Indications exist, however, that neurons may be tailored for the purpose of sustaining the brain's infrared spectrum at robust levels. A rapid spike in temperature of two degrees microCelsius occurs during action potentials, hinting at a general connection between nerve firing and a boost to the infrared spectrum (Wang et al., 2014). So if we hypothesize that neurons are designed to expand the quantity of infrared light while regulating its local behavior, how might this mechanism work?

Assuming the coherence flow model is accurate, as it certainly seems to be, lengthwise signals are transmitted through a neuron as electric currents which attain a relativistically significant percentage of light speed, so the mass of this rapidly moving matter increases. Experiments in the first half of the 20th century suggested that relativistic mass has an underlying physical cause, while many modern approaches incline to view relativistic mass as a conceptual tool to be dispensed with at will (Gibbs et al., 2012). Debate rages, but regardless of the real source for theoretical mass increase when transitioning to high-velocity states, some empirically based conclusions of a rather simple nature can be drawn insofar as light emission correlates with relativistic momentum in electrons. We know from technological applications that matter moving at relativistic speeds emits higher energy (frequency), shorter wavelength EM radiation while it decelerates, and lower energy, longer wavelength radiation while it accelerates. For instance, when a beam of electrons traveling at half the speed of light collides with a metal plate in an x-ray machine, it emits high energy braking radiation in the x-ray portion of the spectrum (Arpansa, n.d.), and accelerating current in a radio antenna emits low energy radio waves (Astro, n.d.). Essentially, if an accelerating coherence current is almost instantaneously compressed as it alternates, EM waves will be emitted proportional to speed, total size, and perhaps lesser overall density of the current (in addition to waves at further spectral ranges), and if a decelerating coherence current is likewise compressed, EM waves are emitted in proportion to speed, size, and perhaps greater density of the current segment that is decelerating. So if current acceleration is sustained in a neuron, the spectrum of EM radiation will be prone to lengthen, and the reverse is true for decelerating current, with the quantity of radiation increasing in both cases.

During an action potential, the electric current accelerates between a node of Ranvier and adjacent juxtaparanodes, while gradually decelerating as it traverses internodal space. If this current alternates multiple times between juxtaparanodes following an action potential while changing velocity it might be possible to generate a photonic field. But it is unclear how sustained this field would be between action potentials or whether biochemistry is diverse enough in the axon, a structure probably tailored for long-range signaling at the expense of complex intracellular machinery, to generate a photonic/molecular field comprised of rich assortments of wavelength. Additionally, myelin encasing the axon would likely tend to reflect this radiation, preventing it from exacting multicellular effects.

At the synaptic junction, the current accelerates from single positive ion concentrations (Na^+ and K^+) at the last node in the action potential chain to a lesser electron density of Ca^{2+} concentrations near the axon terminal. Current would also accelerate from the first node in a dendrite to its upstream tip, on the opposite side of a synapse. In order for acceleration to be sustained, Ca^{2+} would have to cycle into and out of a neuron at rapid rates, continuously drawing energy away from nodes with a replenishing supply of lower electron density ions. Indications are that ions travel through ion channels *via* quantum mechanisms, again at approximately 90% light speed, so the cycle might be near-instantaneous enough to hold acceleration stable. But at present, more research into neuron anatomy near the synaptic junction is necessary before this hypothesis can be corroborated or refuted.

It seems more feasible at this stage to postulate a model for current acceleration in the soma. A tapering from more to less positive ion concentration is maintained between the largest quantity of Na^+ channels and ions in a neuron at the axon hillock and relatively expansive space of the soma with its lesser rate of Na^+ and K^+ reuptake. This tapering ranges all the way to cellular space near the dendrite/soma junctions, where Cl^- channels and ions maintain a much higher electron density. Cl^- influx during an IPSP blocks EPSPs from propagating into the soma, followed by some Cl^- reuptake and an accompanying diminution of the IPSP. When the IPSP wanes, the ebb effect of EPSPs can draw greater electron density around the base of dendrites out of more interior regions of the soma. This is likely combined with a well-timed renewal of Cl^- influx such that electron density increases slightly while simultaneously breaching the positive ion gradient. Once this greater electron density reaches the axon hillock's sphere of influence extending far into the soma, it accelerates rapidly towards the axon hillock. Upon reaching the axon hillock, a companion EM field fluctuation triggers large quantities of Na^+ to rush in, sustaining acceleration from the opposite side due to greatly reduced electron density even as the relatively negative charge initiated at the dendrite/soma junction reaches a minimum due to dilution. As Na^+ ions again diffuse into the soma, the gradient of positive charge is replenished, and though the overall strength and influence of positive charge lessens in the soma, Cl^- concentrations increase and regain a maximum, driving acceleration from the opposite side.

To summarize:

At the dendrite/soma junctions:

1. Cl^- influx, concentration, and electron density maximum
2. Cl^- concentration and electron density attenuation
3. The ebb effect force of dendritic potentials followed by resumption of Cl^- influx
4. Electron density from Cl^- concentration at a minimum, with continued influx

Instigated by the axon hillock:

1. Na^+ concentration attenuation
2. Greater Na^+ concentration attenuation
3. Na^+ concentration minimum
4. Na^+ influx and concentration maximum

Thus, a flux of Cl^- concentration maximum to minimum coupled with Na^+ concentration minimum to maximum conceivably maintains a constant acceleration of electric current through the soma. As in the case of possible current acceleration around the synaptic junction, this model needs empirical verification.

So if current continuously accelerates at the synaptic junction and within the soma, what would be the properties of emitted EM radiation? Applying the nascent but plausible concept of relativistic current presented in this article, neural currents have no circuit to stabilize their velocity as in electrical wiring, so if the charge is constant they would probably initiate at the same rate as baseline agitation from decoherence and decelerate due to the ebb effect. EM wavelengths produced then hover at around 1 μm, slightly longer than the boundary between visible and near-infrared portions of the spectrum. This correlates to the electromagnetic domain just beyond the level of emergence associated with an individual atom's valence shell and the roughly 400–700 nm range of EM wavelengths, in essence multiatomic vibration while a robustly decoherent state prevails. In this theory, if electric current does indeed accelerate at the synapse and through the soma, this would add slightly longer wavelengths to the spectrum. It seems reasonable as a very approximate hypothesis that the spectrum could range from at least 1–10 μm in wavelength. This spectrum is capable of traveling through an aqueous solution at distances of roughly 100 mm to 10 μm, with the range shrinking considerably as wavelength increases (**Figure 3**). The soma is about 12 cubic micrometers and the synaptic space 1 cubic micrometer, with the currents themselves probably equivalent in volume, so it seems plausible that a persistent field of photonic waves can inundate both. Boosted by maximal reflection from white matter, gray matter may be filled with a substantive light spectrum capable of interacting with molecular arrays and biochemical pathways to form a diversely superpositioned photonic field studded with a wide range of atomic and multiatomic nodes.

Where atoms and molecules involved in the generation of percepts might be most concentrated remains unknown, but protoplasmic astrocytes which are commonly adjacent to the soma and thus have access to hypothesized light fields, with a cytoplasm relatively uncluttered by organelles (Elabbady et al., 2022), are a good candidate, of course in addition to gray matter itself, the soma as well as junctions at which axons and dendrites form synaptic connections. Mounting evidence from studies with paramecia, yeast, onion roots, and even crustaceans substantiates the hypothesis that biophotons of low-intensity travel through cell membranes, affecting functions such as energy production and growth in populations of cells, even when separated by a sizable barrier such as the walls of a glass cuvette (Fels, 2009). A range of wavelengths seem to interact with biochemistry, and all kinds of cellular structures including those of neurons could be built around biophotonic mechanisms.

An exception to the general link between brain hyperthermia and awareness is the visual cortex, where it has been observed with fMRI that tissue temperature decreases by 0.2°C during activation of the neural processing involved (Wang et al., 2014). Some uncertainty exists as to the accuracy of these results, but if valid this suggests molecular structures may exist in parts of the brain to shift the EM radiation spectrum towards shorter wavelengths such as visible light that are less likely to dissipate as the heat of vibrating and rotating chemical bonds. It is intriguing to consider that centers of vision in the brain, probably correlated with the phenomenality of image

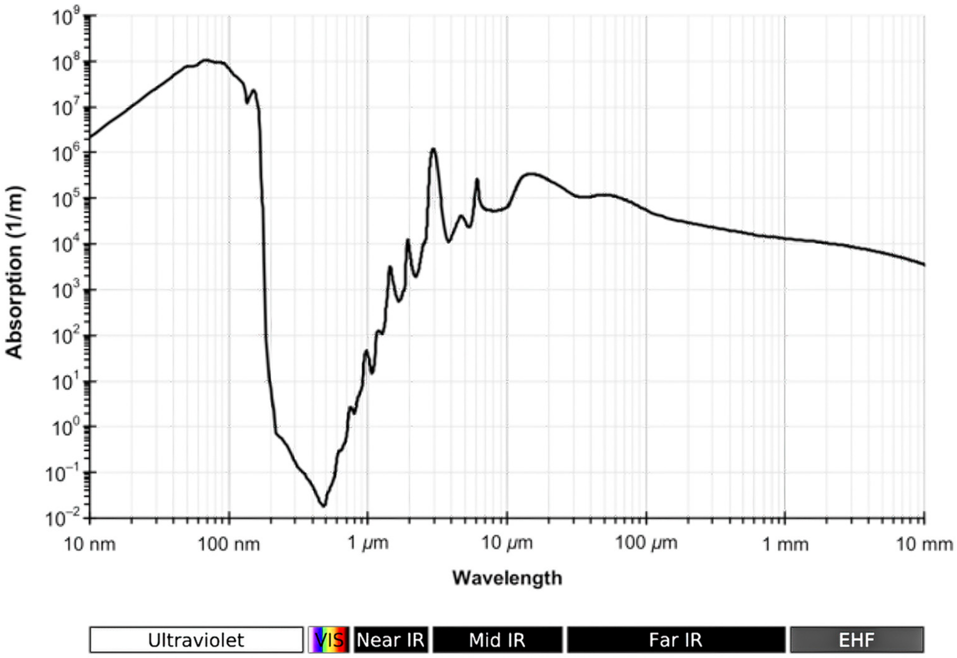

FIGURE 3
Absorption spectrum of liquid water (Kebes, 2008).

perception, might generate a light field comparable to the one upon which vertebrate optical mechanisms are based.

Some further categories of mechanism in addition to basic current acceleration seem likely for how spectrums of EM radiation may thicken and assume functional form in the nervous system and brain. Visible, near-infrared, mid-infrared radiation, and perhaps beyond of course must interact with molecules in such a way that wavelengths are modified into a wide variety of vibrational signatures, with all of this dispersing into the sink of somewhat increased temperature during activation as baseline decoherence continually reasserts itself. The electric currents themselves may also rapidly decelerate upon contact with molecular structures to cause braking radiation, and shortened EM wavelengths of relatively low intensity. Whether these processes occur in non-neuronal cells as a result of ion channel activity and additional mechanisms is an interesting topic, barely broached. So how then might this basic substrate of structural integration in the brain, nervous system, and perhaps the wider body give rise to awareness's percepts, the substance of perception?

Implications of the coherence field concept for understanding percepts as a physical phenomenon

In the coherence field model, we have thus far formulated, a supervenient EM field drives and orchestrates the behavior of biochemical pathways in the brain, but EM radiation within this material framework is the binding agent which flows around with effective instantaneity to integrate molecular arrays, cells, and tissues at trillions of locations as the vibrational structure of perception. Details of how percepts would form in this manner are undoubtedly complex and, if upheld by further evidence, probably warrant decades of research. But if these theories are accurate, it could provide for some very simple ways to define features of the mind in terms of matter.

This model views percepts, to the extent they arise from electromagnetic properties of tissue, as the emergent organization of atomic nodes within photonic fields, numerous and diverse regions of coherent energy most fundamentally characterized by vibration. The brain is unique because electric currents likely found in all cells are so strong and compact in this organ that a robust EM field is generated which can coordinate the magnetic particles in large swaths of tissue as an individual unit. The brain is thus much more synchronized than the rest of the body. If the hypothesis proves valid, this mechanistic chassis of electrical energy is saturated by EM radiation of a primarily infrared spectral range which interacts with molecules to produce the structural components of the mind, insofar as they arise from the brain, as a variably dense physical field.

Most of our basic sentience—sound, touch, taste, smell, visceral sensations, in essence feel—would essentially be vibrational textures in matter with their shapes, rates of oscillation, and locations determining the quality of experience. Input from specialized sensory apparatuses in the eye, ear, olfactory, gustatory and tactile cells superimposes on fundamentally cognitive textures to render our environment a crisp perceptual world.

Image sensation might be a modification of EM wavelengths within the textural field such that light in the visible range is produced, so that optical inspection and image imagination coevolved into complementary forms. This would explain how we visualize much of what our eyesight takes in without optical stimulation. The visual stream of consciousness is then a complex of visible light and specially adapted cellular structures, while the verbal stream would probably be infrared light and still different biomolecules and cells, together a range of emergent textures induced by the brain and perhaps the wider body. All of this sentience and stream of consciousness converge to constitute the foundational substrate of emotion and thought.

Memory would derive from interaction of this coherent energy field with neural architecture, accounting for how recall cannot be easily pinpointed to any particular process in the brain or body, for it is linked to the interface between field and circuitry at an intracellular level we have not yet penetrated in theory. The relative role of circuitry vs. intracellular biochemistry in memory, synaptic as opposed to intrinsic plasticity, is still the subject of contention (Trettenbrein, 2016; Langille and Brown, 2018), but some form of amalgamation is undoubtedly in play, and the brain's matter is as photonic and field like as it is molecular. Neural circuitry is built into intricately emergent structures so that synthetic and logic like insights are possible, the environment "making sense" *via* a background of more or less abstract interrelationships rather than just starkly presenting. The self can be defined as a collection of functions that monitor one's own circuitry and coherence field of radiative/molecular percepts.

This model affords an explication of how a percept's appearance, we could think of a colored object for instance, is capable of holding stable in our field of vision despite the fact that a dynamic flurry of at least billions of more or less separate atoms participates in producing the image. Field theory implies that particles at the quantum scale are not solid, entirely self-contained, and indivisible units, but rather ripples in an energy field which happen to be especially stable. When particles transition between states and interact, this energy flow is quantized at the subatomic scale, but disjunctions become negligible at the emergent scale of molecular structure, smoothed out into a continuum of flow, just as the components of a robotics plant seem to follow seamless trajectories though zooming in on the process would reveal irregularities and asymmetries of motion. Even with this emergent continuity, partitioning of molecular complexes and biochemical pathways in cellular solution could alone be significant to the appearance of electromagnetic percepts, as robotic machinery at different locations in an assembly line occupies obviously discrepant orientations. But photonic fields, the motions of which are effectively instantaneous at the atomic scale and even the scale of an entire brain, provide an interstitial medium at very basic levels of emergence. Minute regions of disjunction between the organ's atomic structures as energy maxima are unceasingly integrated by space-saturating waves of EM radiation as energy minima. A coherence field of atoms and EM radiation combined thus veils the fine structure of quantization that obtains at the subatomic scale, shrouding disassociations among energy minima and maxima with an emergent structure which lacks apparent gaps on the scale of biochemical function. From this perspective, the apparent holism of a robotics plant's physical structure as it conjures an observable scene and the integrated structure of perception insofar as it arises from the brain are parallels in a very real sense: electromagnetic matter's emergent unity is an "interior" feature as much as an "exterior" one, and if this matter is, in fact, the substance of perception, we should expect physical percepts to evince that permeating unity.

The question of how a coherent field of awareness projects beyond the body can be raised. It must be remembered that coherence is not fundamentally electromagnetic, physiological, or local in the Newtonian sense, and under suitable conditions causality can propagate faster than light. It might be possible for similar mechanisms to those which manifest within the brain and body to conjure beyond physiology, as a hybrid of standing and traveling waves within a medium of infrared light, visible light, and perhaps more energy sources, all interspersed by atomic and molecular nodes with which this energy more or less synchronously vibrates. If an experiment can entangle photons at 3 trillion m/s across a distance of 15 km, any material structure which manipulates the underlying coherence responsible for such entanglement should be capable of similar influence, and the brain could be such a material structure. The coherence field concept may eventually explain why we do not perceive the field of awareness as entirely within our own heads or bodies despite the fact that neural and cellular architecture is required to comprise an organic mind.

Though an EM radiation hypothesis for how matter binds into the substance of perception hangs together well based on what we currently know of physics, it has also been proposed that LFP-based fine structure of the electric field may be the source of percepts. Any region of this field is of course composed of numerous superpositioned frequencies which can be decomposed by a Fourier transform in similarity to EM radiation, producing the familiar EEG readouts. The question is whether this reaches enough complexity to be the sole seat of perception.

As an example, we can estimate the maximum intricacy of an electric field consciousness. If we assume percepts are superpositions delimited by phase-locking, of which the basic unit is some constitutive portion of an LFP, the most complex and differentiated consciousness possible for a human would plausibly consist in neural networks of on average a hundred phase-locked neurons each, blending into both a background of slower waves and some kind of roving, semi-stable density of relatively homogeneous frequency that temporarily mingles with a variety of more local oscillations to produce experiential awareness. If phase-locking determines the boundaries of a percept, and the brain contains approximately 80 billion neurons making 100 trillion connections, each neuron would contribute to on average around 1,250 different percepts at most. This hypothetical consciousness would support 800 million simultaneous percepts and 1 trillion percepts total. But human olfaction detects more than a trillion scents (Bushdid et al., 2014), and this is one of our least acute sensory modalities, in addition to being localized within small portions of the brain. The range of variation in sounds and images far exceeds olfaction. Overall oscillation patterns within one of these minimum phase-locked assemblies may involve a continuum of relativities rather than simply being a steady state, on or off phenomenon, doing double duty in the formation of multiple percepts, so within any particular neural network the spectrum of percepts might be much greater, though the level of differentiation must at some point prove discrete, constrained by an LFP's degrees of freedom. We must also consider that much of the brain may not be sufficiently phased for producing emergent organization conducive to percepts of this type, so the possible quantity of percepts would likely be much less than the maximum. Of course, pending further research, room for doubt exists as to whether an LFP-based model alone is capable of accounting for the full gamut of percepts.

It is also uncertain how an LFP-based model can explain the nonlocality of consciousness. At this point, extrasensory perception is fairly well-established scientifically, since it has been demonstrated that humans can communicate, locate archaeological sites, etc. through ESP (Schwartz et al., 2022). Science is making rapid progress in its capacity to model faster than light entanglement between photonic fields, an action at a distance which is canonical to quantum physics. Though advances are being made in finding ways to empirically verify the mechanisms of group consciousness phenomena, in essence, brain wave entrainment and synchronization between multiple individuals *via* some behavior-linked mechanism, research is in its early stages (Young et al., 2022). Though brain waves are of course integral to the presentation of all conscious phenomena, we presently have much less cause for attributing ESP to mediation by LFPs and emergent flow shapes in the electric field than entanglement dynamics of the EM radiation they contain.

If we add EM radiation to the electric field model, this massively increases the diversity available to perceptual mechanisms, from maximums of roughly a few trillion superpositioning LFP subunits to at least hundreds of trillions of possible locations where photonic fields, variously superpositioned on scales resembling spectra in the external environment, can cohere with atoms and molecules to assume functional form. These photonic fields which would radiate with effective instantaneity in the brain may get locked in as emergent structure during neural activation, with the signature of this light modulation mechanism being temperature variation. To the extent that a region of the brain is especially saturated by synchronizing mechanisms such as phase-locking, as seems to be the case in processes of experiential awareness, the effects of photonic fields would simultaneously become more pervading. The LFP-based model and photonics model are thus complementary, for if research proves that EM radiation plays a functional role, this is simply an intrinsic aspect of the electric field's fine structure as it oscillates and flows.

Cross talk between neural regions within the 100 ms temporal window during which perceptual binding occurs would be greatly enhanced by the light speed effect of large-scale oscillations in the brain's electric field on LFP oscillons, and some models indicate that this type of modulated superposition amid oscillators is necessitated in a process such as percept binding (Kraikivski, 2022). Line of sight issues must limit the intricacy of interaction between the brain's somewhat partitioned electric field and microscale oscillons, which we of course observe, but if EM radiation can be included this proliferates the fine structure of modulated superposition by orders of magnitude. If justified by a continuing train of evidence, the hybrid electric/radiative field model makes neuroscience and quantum physics natural collaborators, for brain/body and nonlocal phenomena of consciousness may yield to a single explanation rather easily provided EM radiation is a binding agent for the physiology and more generally the matter of perception in addition to the physical environment as a whole.

The mechanism by which brain matter contributes to forming the substance of percepts is proposed by this article as starting with a sustained acceleration of electric current between centers of ion concentration, modifying the spectrum of EM radiation (primarily infrared and more rarely visible light) while increasing its quantity. This proceeds to modulation *via* a cascade of light/molecular interactions, ending in a temperature increase when decoherence thermally dissipates the additional energy as biochemical vibration and infrared radiation. If current acceleration is steady enough, the electromagnetic energy that results can maintain intracellular coherence fields, and likely also intercellular coherence fields due to the transmission of EM radiation through cell membranes. But this mechanism might preclude coherence fields spread through complexes of axons because myelin reflects any infrared or visible radiation from intracellular currents back into the neuron.

An alternate mechanism not discussed with much depth in this article is the manipulation of molecular arrays through EM field permutations that can originate from electron and ionic currents. Modified vibration of molecules might then induce a separate route to cascades of modulated light/molecular interaction, also thermally dissipating as biochemical vibration and infrared radiation due to decoherence. The range at which this mechanism can modulate a coherence field depends on the density and location of affected atoms and molecules, but could conceivably transcend the limitation that myelin imposes on axons and adjacent extracellular space because of transmembrane influence, expanding the perceptual field to brain matter in its entirety. Further effects along these lines are probably transmitted *via* emergent electric wave oscillations and flow spread through macroscopic portions of the brain, synchronously morphing LFP/neural complexes, current-field patterns, and the coherence fields of cellular structure in a top-down way to enact larger-scale perceptual integration. It is well-established that endogenous electric fields affect orientation, migration, adhesion, proliferation and differentiation among and within cells (Cassela et al., 2021). Alteration to a cell's molecules *via* electric fields is finding application in cancer treatment as TTFields (tumor treating fields; Tuszynski et al., 2016), wound healing, and the modification of developmental processes (Cassela et al., 2021). Numerous research angles already identify electric field properties as integral to workings of the cell, and once the investigation has matured enough to comprehensively assess the dynamics of varying electric field strength and distribution along with the undulating EM radiation within these fields, any electric field/molecular routes to coherence field modulation should be modelable.

A third possibility is that so-called nonlocal properties of the brain's coherence field facilitate entanglements *via* EM radiation and through this route modulate cascades of light/molecular interaction. Mechanisms of this type could pervade the brain, exacting an extremely holistic effect upon electromagnetism, with the vibrational and radiative consequences being at this stage unknown and fairly unpredictable. We cannot rule out the potential for modification of EM radiation and molecular vibrations into many different forms than would be predicted in association with electric currents or LFPs.

The question then is how we are to derive definitive models of these mechanisms and their comparative role in the brain. It is very early in the research agenda, so analysis of the correlation between electric currents, EM fields, and the modulation of EM radiation must probably take place outside a neural context, with stripped down experimental designs restricting mass, velocities, volumes, concentrations, temperature, etc. to a small, inorganic set of variables, gradually building our facility in parameterizing how light and electrons in motion should interact within biological systems. Developing techniques for measuring the emission of EM radiation within and from neurons would help tremendously, an investigation which can probably be extended to the entire body. Physics will of course continue to construct more incisive models of nonlocality, and this phenomenon's intersection with brain function can be complemented by psychology of nonlocality. If perception is a physical field at least partially manifesting as an electromagnetic matter of the brain, continuing revelations of physics will surely mesh well with predictions of neuroscience and are valuable in and of themselves. We have decent prospects for a comprehensive physical theory of percepts.

Conclusion: a coherence field theory of consciousness

So in summary, our increasingly sophisticated understanding of matter at the subatomic scale suggests that electric currents in neurons are driven by states of quantum coherence which occur within an aqueous solution of ions. The baseline condition is for aqueous solution to be maximally decoherent due to nanoscale shifting among huge quantities of polar constituents, but when charge disparity is induced between large enough centers of ion concentration, a coherent current flows from higher electron density or more negative charge to lower electron density or more positive charge. Neural anatomy is built around this dynamic, with ion channels modulating the flow of electron current to transmit signals between nodes at a significant fraction of light speed. The electric current mechanisms of individual neurons may provide a deep explanation for why the electric fields of neurons oscillate, why axons contain juxtaparanodes, why nodes are spaced as they are in proportion to neuron diameter, and a host of further observations. It is not a stretch to claim that the coherence current concept may tie all we have discovered of neural anatomy into a comprehensive model of intraneural function.

The source of intercellular LFPs and phase-locking of emergent brain waves with neural networks is more in the realm of speculation, but a computer model based around ionic current flow through membrane channels alongside analysis of discrete synapses holds promise for making inroads on this front, while additional mechanisms may obtain. The brain's electric field increasingly appears to be a central factor in consciousness' integration rather than an epiphenomenon of neuronal activity, and ongoing research into macroscopic oscillation and flow patterns as coordinated with tissue should continue to reveal more about the organ's functional organization.

Neural tissue is more closely correlated with temperature fluctuations than is an anatomy of comparable locations such as the brain's arteriole blood vessels. This thermal energy is instantiated as vibrating molecules integrated with fields of EM radiation which in a physiological context peak within the infrared range of the spectrum. The hypothesis is that these vibrational and wavelength signatures are not a mere waste byproduct, but prove intrinsic to the electromagnetic matter as it binds into expanses of coherent structure modulated to produce many of the first-person experience's basic features, what I have called percepts. A potential mechanism linking the coherence currents of a neural solution to modulation of these coherence fields has been discussed in depth, and additional mechanisms are possible. In this model, brain processes which generate states of coherence are an essential facet of the organ's material structure such as the visual system's retinotopic maps, and these states coalesce as basic constituents of perception on the intracellular and perhaps intercellular scale. The contents of experiential awareness, attention, and will are then to a profound degree emergent from properties of coherence evinced by electromagnetism.

The primacy of vibration and wavelength to these ideas aligns closely with General Resonance Theory, and it seems promising that resonant phenomena identified at the nanoscale will reveal themselves to be important aspects of first-person perception. Experimentally verifying the main hypotheses of coherence field theory would constitute major progress in addressing the "quantum question" Hunt and Schooler have outlined. This pushes beyond statistical formulations of quantum mechanics to begin constructing a phenomenology of matter suitable for full integration of physics with the life sciences. Perhaps a scientific solution to the mind/body problem is just around the corner.

Data availability statement

The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

Ethics statement

Ethical review and approval was not required for animal studies because research cited was performed by neuroscientists who met the ethical standards necessary to publish. Ethical review and approval was not required for studies on human participants in accordance with the local legislation and institutional requirements. Written informed consent for participation was not required for this study in accordance with the national legislation and the institutional requirements.

Author contributions

EB has exclusively developed, analyzed, and authored the contribution of coherence field theory to a model of consciousness: electric currents, EM fields, and EM radiation in the brain.

Conflict of interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

References

Abarbanel, H. D., Talathi, S. S., Gibb, L., and Rabinovich, M. I. (2005). Synaptic plasticity with discrete state synapses. *Phys. Rev. E* 72:031914. doi: 10.1103/PhysRevE.72.031914

Alekseichuk, I., Flachier, A. Y., Linn, G., Xu, T., Milham, M. P., Schroeder, C. E., et al. (2019). Electric field dynamics in the brain during multi-electrode transcranial electric stimulation. *Nat. Commun.* 10:2573. doi: 10.1038/s41467-019-10581-7

Anastassiou, C. A., Perin, R., Markram, H., and Koch, C. (2011). Ephaptic coupling of cortical neurons. *Nat. Neurosci.* 14, 217–223. doi: 10.1038/nn.2727

Arancibia-Carcamo, L., and Attwell, D. (2014). The node of ranvier in CNS pathology. *Acta Neuropathol.* 128, 161–175. doi: 10.1007/s00401-014-1305-z

Arancibia-Carcamo, L., Ford, M. C., Cossell, L., Ishida, K., Toyhama, K., and Attwell, D. (2017). Node of ranvier length as a potential regulator of myelinated axon conduction speed. *eLife* 6:e23329. doi: 10.7554/eLife.23329

Arpansa. (n.d.). X-rays. Available online at: https://www.arpansa.gov.au/understanding-radiation/what-is-radiation/ionising-radiation/x-ray.

Astro, J. (n.d.). Radio wave emission. Available online at: https://www.physics.unlv.edu/ jeffery/astro/electromagnetic_radiation/radio_wave_emission.html.

Bandyopadhyay, A. (2022). "Brain connectivity," in *The Science of Consciousness*, (Tuscon, Arizona), 18–22.

Blendspace (n.d.). Quantum numbers for electrons. Available online at: https://www.blendspace.com/lessons/vtlqxGxrxiK3Ng/quantum-theory.

Bond, E. (2022a). Essentials of a theory for how brain structure contributes to the substance of consciousness. *World J. Neurosci.* 12, 8–21. doi: 10.4236/wjns.2022.121002

Bond, E. (2022b). Coherence field theory: quantum coherence as the basis for a model of brain function. *J. Q. Info. Sci.* 12, 64–89. doi: 10.4236/jqis.2022.123007

Bushdid, C., Magnasco, M. O., Vosshall, L. B., and Keller, A. (2014). Humans can discriminate more than 1 trillion olfactory stimuli. *Science* 343, 1370–1372. doi: 10.1126/science.1249168

Casado, C. M. M. (2008). A brief history of the mathematical equivalence between the two quantum mechanics. *Latin Am. J. Physics Educ.* 2.

Cassela, A., Panitch, A., and Leach, J. K. (2021). Endogenous electric signaling as a blueprint for conductive materials in tissue engineering. *Bioelectricity* 3, 27–41. doi: 10.1089/bioe.2020.0027

Chiang, C., Shivacharan, R., Wei, X., Gonzalez-Reyes, L., and Durand, D. (2019). Slow Periodic activity in the longitudinal hippocampal slice can self-propagate non-synaptically by a mechanism consistent with ephaptic coupling. *J. Physiol.* 597, 249–269. doi: 10.1113/JP276904

Dill, D. (2008). "Chapter 2, Quantum aspects of light and matter," in *Notes on General Chemistry*, 3e. Available online at: https://www.bu.edu/quantum/notes/GeneralChemistry/02-QuantumAspectsOfLightAndMatter.pdf.

Elabbady, L., Seshamani, S., Mu, S., Mahalingam, G., Schneider-Mizell, C., Bodor, A., et al. (2022). Quantitative census of local somatic features in mouse visual cortex. *bioRxiv* [Preprint]. doi: 10.1101/2022.07.20.499976

ER Services (n.d.a). The wave nature of matter causes quantization. Available online at: https://courses.lumenlearning.com/suny-physics/chapter/30-6-the-wave-nature-of-matter-causes-quantization/.

ER Services (n.d.b). Probability: the heisenberg uncertainty principle. Available online at: https://courses.lumenlearning.com/suny-physics/chapter/29-7-probabiity-the-heisenberg-uncertainty-principle/.

Fels, D. (2009). Cellular communication through light. *PLoS One* 4:e5086. doi: 10.1371/journal.pone.0005086

Filmer, J. (2013). Chinese physicists measure speed of quantum entanglement. Available online at: https://lifeboat.com/blog/2021/05/chinese-physicists-measure-speed-of-quantum-entanglement.

Ford, M. C., Alexandrova, O., Cossell, L., Stange-Marten, A., Sinclair, J., Kopp-Scheinpflug, C., et al. (2015). Tuning of ranvier node and internode properties in myelinated axons to adjust action potential timing. *Nat. Commun.* 6:8073. doi: 10.1038/ncomms9073

Franson, J. (n.d.). Quantum entanglement-einstein's "spooky action at a distance". University of Maryland at Baltimore County. Available online at: https://www.aps.org/units/maspg/meetings/upload/franson-021815.pdf.

Frohlich, F. (2014). Endogenous and exogenous electric fields as modifiers of brain activity: rational design of noninvasive brain stimulation with transcranial alternating current stimulation. *Dialogues Clin. Neurosci.* 16, 93–102. doi: 10.31887/DCNS.2014.16.1/ffroehlich

Frohlich, F., and McCormick, D. A. (2010). Endogenous electric fields may guide neocortical network activity. *Neuron* 67, 129–143. doi: 10.1016/j.neuron.2010.06.005

Gibbs, P., Carr, J., and Don, K. (2012). What is relativistic mass? Available online at: https://math.ucr.edu/home/baez/physics/Relativity/SR/mass.html.

Hales, C. G. (2014). The origins of the brain's endogenous electromagnetic field and its relationship to provision of consciousness. *J. Integr. Neurosci.* 13, 313–361. doi: 10.1142/S0219635214400056

Hameroff, S. (1998). Quantum computation in brain microtubules? The penrose-hameroff "orch or" model of consciousness. *Philos. Trans. R. Soc.* 356, 1869–1896. Available online at: doi: http://www.jstor.org/stable/55017.

Hunt, T., and Schooler, J. W. (2019). The easy part of the hard problem: a resonance theory of consciousness. *Front. Hum. Neurosci.* 13:378. doi: 10.22541/au.154659223.37007989

Irving, M. (2020). *15 Trillion Quantum Entangled Atoms Make a Record-Breaking Hot Mess*. Available online at: https://newatlas.com/physics/15-trillion-atoms-quantum-entanglement/.

Kebes (2008). *Absorption Spectrum of Liquid Water.* Available online at: https://commons.wikimedia.org/wiki/File:Absorption_spectrum_of_liquid_water.png.

Khoshakhlagh, P., Bowser, D. A., Brown, J. Q., and Moore, M. (2019). Comparison of visible and UVA phototoxicity in neural culture systems micropatterned with digital projection photolithography. *J. Biomed. Mater. Res.* 107, 134–144. doi: 10.1002/jbm.a.36540

Kraikivski, P. (2022). A dynamic mechanistic model of perceptual binding. *Mathematics* 10:1135. doi: 10.20944/preprints202202.0326.v1

Langille, J. J., and Brown, R. E. (2018). The synaptic theory of memory: a historical survey and reconciliation of recent opposition. *Front. Syst. Neurosci.* 12:52. doi: 10.3389/fnsys.2018.00052

Mairhofer, L., and Passon, O. (2022). Reconsidering the relationship between "matter wave interference" and "wave-particle duality". *Found. Phys.* 52. doi: 10.1007/s10701-022-00544-2

McFadden, J. (2020). Integrating information in the brain's EM field: the CEMI field theory of consciousness. *Neurosci. Conscious.* 2020:niaa016. doi: 10.1093/nc/niaa016

McFadden, J. (2014). *Life on the Edge: The Coming of Age of Quantum Biology.* New York: Crown Publishers.

McFadden, J. (2021). The electromagnetic will. *Neuroscience* 2, 291–304. doi: 10.3390/neurosci2030021

McIver, B., Tuszynski, J., Kalra, A., Scholes, G., Dogario, A., and Craddock, T. (2022). "Testing orch or," in *The Science of Consciousness* (Tuscon, Arizona), 18–22 April 2022. Available online at: https://consciousness.arizona.edu/sites/consciousness.arizona.edu/files/FINAL%20TSC2022_BOOK_V8.pdf.

Mohanmurthy, P. (2020). Interpretations of quantum mechanics: a general purview. *College of Arts and Sciences Publications and Scholarship* 14. Available online at: https://scholarsjunction.msstate.edu/cas-publications.

Morin, D. (n.d.). *Introduction to Quantum Mechanics*, Ch. 10, 1–20. Available online at: https://scholar.harvard.edu/files/david-morin/files/waves_quantum.pdf.

Neven, H., Kalra, A., Dogario, A., and Craddock, T. (2022). "Quantum neuroscience," in *The Science of Consciousness* (Tuscon, Arizona), 18–22 April 2022. Available online at: https://consciousness.arizona.edu/sites/consciousness.arizona.edu/files/FINAL%20TSC2022_BOOK_V8.pdf.

Northwestern (n.d.). *Electricity and Magnetism*. Available online at: https://faculty.wcas.northwestern.edu/infocom/Ideas/electric.html.

Perotti, L., DeVito, J., Bessis, D., and Dabaghian, Y. (2019). Discrete structure of the brain rhythms. *Sci. Rep.* 9:1105. doi: 10.1038/s41598-018-37196-0

saylordotorg.github.io (n.d.). *Atomic Orbitals and Their Energies*. Available online at: https://saylordotorg.github.io/text_general-chemistry-principles-patterns-and-applications-v1.0/s10-05-atomic-orbitals-and-their-ener.html.

Schwartz, S. A., Radin, D., Mossbridge, J., and Mishlove, J. (2022). "Consciousness and nonlocality," in *The Science of Consciousness* (Tuscon, Arizona), 18–22 April 2022. Available online at: https://consciousness.arizona.edu/sites/consciousness.arizona.edu/files/FINAL%20TSC2022_BOOK_V8.pdf.

Shivacharan, R., Chiang, C., Zhang, M., Gonzalez-Reyes, L., and Durand, D. (2019). Self-propagating, non-synaptic epileptiform activity recruits neurons by endogenous electric fields. *Exp. Neurol.* 317, 119–128. doi: 10.1016/j.expneurol.2019.02.005

Strassler, M. (n.d.). *Virtual Particles: What Are They?* Available online at: https://profmattstrassler.com/articles-and-posts/particle-physics-basics/virtual-particles-what-are-they/.

TechTarget (n.d.). *What is Planck's Constant?* Available online at: https://www.techtarget.com/whatis/definition/Plancks-constant.

Trettenbrein, P. C. (2016). The demise of the synapse as the locus of memory: a looming paradigm shift. *Front. Syst. Neurosci.* 10:88. doi: 10.3389/fnsys.2016.00088

Tuszynski, J. A., Wenger, C., Friesen, D. E., and Preto, J. (2016). An overview of sub-cellular mechanisms involved in the action of TTfields. *Int. J. Environ. Res. Public Health* 13:1128. doi: 10.3390/ijerph13111128

University of South Wales (n.d.). *The Planck Scale: Relativity Meets Quantum Mechanics Meets Gravity*. Available online at: http://www.phys.unsw.edu.au/einsteinlight/jw/module6_Planck.htm.

Wang, H., Wang, B., Normoyle, K. P., Jackson, K., Spitler, K., Sharrock, M. F., et al. (2014). Brain temperature and its fundamental properties: a review for clinical neuroscientists. *Front. Neurosci.* 8:307. doi: 10.3389/fnins.2014.00307

Young, A., Robbins, I., and Shelat, S. (2022). From micro to macro: the combination of consciousness. *Front. Psychol.* 10:755465. doi: 10.3389/fpsyg.2022.755465

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Electromagnetic-field theories of qualia: can they improve upon standard neuroscience?

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How do brains create all our different colors, pains, and other conscious qualities? These various qualia are the most essential aspects of consciousness. Yet standard neuroscience (primarily based on synaptic information processing) has not found the synaptic-firing codes, sometimes described as the "spike code," to account for how these qualia arise and how they unite to form complex perceptions, emotions, *et cetera*. Nor is it clear how to get from these abstract codes to the qualia we experience. But electromagnetic field (versus synaptic) approaches to how qualia arise have been offered in recent years by Pockett, McFadden, Jones, Bond, Ward and Guevera, Keppler and Shani, Hunt and Schooler, *et cetera*. These EM-field approaches show promise in offering more viable accounts of qualia. Yet, until now, they have not been evaluated together. We review various EM field theories of qualia, highlight their strengths and weaknesses, and contrast these theories with standard neuroscience approaches.

KEYWORDS

qualia, EM-field theories of consciousness, images in cognition, cosmopsychism, general resonance theory

1. The qualia problem and standard neuroscience solutions

1.1. The qualia problem

How is the external world in all of its many forms transformed into qualia in the mind? This is the "qualia problem." This includes a "coding problem" because most standard neuroscience solutions ask how external phenomena are encoded in the brain through synaptic firing weights and related phenomena. Such encoding may not, however, be based solely on synaptic firing or "spikes."

In this paper, we ask what are the physical mechanisms by which specific features of the objective external world are encoded into our subjective internal universe, our minds, with all of the informational and affective components that are included in each moment of consciousness? We discuss standard neuroscience approaches to this problem and then compare and contrast proposed solutions that rely on electromagnetic (EM) field theories rather than the more traditional neural and synaptic approaches.[1]

We flesh out different aspects of the qualia problem in §1.5.

Standard neuroscience is computational and focused on neurons and synaptic firing in terms of understanding how the brain and consciousness function. It faces the fundamental problem of explaining specifically how computations (information processing) and synaptic firings produce our consciousness–our privately experienced inner life of feelings, thoughts, etc., which is lost during comas and dreamless sleep. This consciousness is basically characterized by its qualia, which are our sensory and emotional qualities, such as pain and fear. It also has unity, which is exemplified by how various qualia are experienced as a whole when meeting an old friend. These unified qualia reflect the standard view (originally from Nagel, 1974) that consciousness is "what it is like" to, for example, smell a rose or to echolocate like a bat.[2]

Here in §1, we will analyze standard neuroscience's primary problems in helping to explain how all the wide varieties of sensory and emotional qualia arise, and how they unite together. We will proceed from sensory qualia to unified sensory images, then emotional qualia.

In §2, we will investigate whether theories based on electromagnetic field rather than synaptic approaches can better explain the varieties of qualia we all experience than standard neuroscience theories. These electromagnetic approaches fit into various categories and are typically called "electromagnetic (EM) field theories of consciousness." Numerous representative examples of these rapidly proliferating theories will be covered here, but we do not address those theories that neglect to address how unified qualia arise. We also address remaining issues with EM field theories and suggest some avenues for addressing these issues.

1.2. Problems with sensory qualia

Neuroscientists usually explain how our different sensory qualia arise in terms of specialized labeled lines with their own detector fibers and processing areas for taste, vision, and other sensory modes (e.g., Purves et al., 2001; Parker, 2019). Photoreceptors thus produce color qualia regardless of whether they are stimulated by light, pressure, or other stimuli. This method is supplemented by detailed comparisons of the fibers within each labeled line (e.g., Solomon and Lennie, 2007; Conway, 2009). For example, the three color fibers overlap in their response to short, medium, and long wavelengths of incoming light. So across-fiber comparisons of their firing rates help disambiguate which wavelengths are actually present.

This longstanding view has arisen from various historical roots. But the overall problem is that these operations are so similar in the visual, tactile, and other sensory modes that it is unclear how these methods can differ enough to account for all the stark differences between color and taste qualia, for example. Another issue (which will be addressed more below) concerns the "hard problem" of why this biological information processing is accompanied by any conscious experience of colors, pains, *et cetera*.

Such problems have not gone unnoticed by neuroscientists. For example, Humphries (2020) provides a book-length overview of the science of the "the spike code" (the synaptic firing approach that is the focus of standard neuroscience), particularly as it relates to visual perception. The book describes in detail how visual perceptions make their way from the retina through the central nervous system and coordinate with our motor control system. Humphries acknowledges, however, that neural spike activity and its relationship to consciousness remains largely unknown: "what we can predict are the new directions we want to explore. And what we want to explore is everything that is missing entirely from this book because we know nothing about them: spikes that underlie disorders of the brain, and spikes that underlie human thought processes." He adds: "The most obvious chasm in our understanding is in all the things we did not meet on our journey from your eye to your hand. All the things of the mind I've not been able to tell you about, because we know so little of what spikes do to make them."

It might be thought that recently proposed neuron-based neuroscientific theories of consciousness would offer more viable accounts of how different qualia arise. But they rarely do. For example, Global Neuronal Workspace Theory GNWT (e.g., Dehaene and Naccache, 2001; Dehaene, 2014) and Higher-Order Theories (e.g., Rosenthal, 2005) focus on access consciousness–the availability of information for acting, speaking, and reasoning. This access involves attention and thought. But these higher cognitive levels do not do justice to qualia, for qualia appear even at the very lowest levels of conscious cognition in pre-attentive iconic images (e.g., Koch, 2019). In contrast, Recurrent Processing theory (Lamme and Roelfsema, 2000) covers both access consciousness and phenomenal consciousness (the latter pertains to the subjective, qualitative feel characteristic of qualia). But this theory gives no account of how different qualia arise–so it is not covered in this paper.

Some prominent theories of consciousness that do address how different qualia arise include Integrated Information Theory–IIT (e.g., Tononi, 2008) and various quantum theories of consciousness. We start first with IIT.

IIT can be applied to any physical system and will provide a quantification of the capacity for consciousness in that system. But the authors of the theory look specifically to synaptic and related activity in the brain for an explanation of human consciousness (Hunt, 2020a, which is an interview with Christof Koch). IIT represents qualia information abstractly and geometrically in the form of a system's

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[1] The qualia problem is related to but different than the problem of memory (how are memories encoded, stored and retrieved), because memories could in theory be encoded without qualia. There is no apparent necessity that recording information about the external world would entail affective components. Indeed, we do not assume that a video camera recording successive images of the world includes any affective component in the camera or the images it takes. And yet our memories of the world–akin to snapshots stored in our brains–seem to always include affective components, at least initially. The same is true of our reactions in real-time to the world. It may turn out that the qualia problem and the "memory problem" are the same problem, if indeed memories cannot be encoded without affect.

[2] Such experience is usually called "phenomenal" or "qualitative" consciousness to contrast it with "access" consciousness, which is the availability of information for acting, speaking, reasoning, *et cetera*. But the latter arguably has no essential connection with qualitative experience and is thus not consciousness at all.

"qualia space" (Tononi, 2008). This is the space where each axis represents a possible state of the system–a single combination of logic-gate interactions (typically involving synapses). Points along the axes are the probable efficacies of these various logic-gate combinations in the system. Arrows between the points represent information relationships between these elements. The overall set of information relationships constitutes the shape of the system's qualia space, which in turn specifies the system's experience. Thus, colors are different sub-shapes of the same kind (for example, pyramids pointing in different directions)–while sounds are very different sub-shapes (such as tetrahedra). Even the simple color of blue translates into a staggeringly complex shape in qualia space, for it must be differentiated not only from all other colors and all other perceptions, but also from all other experiences generally (*cf.* Aaronson, 2014).

IIT's accounts of qualia spaces are far too complex to specify except in the simplest of cases, and no tests for this method of characterizing qualia has yet been proposed, as far as we are aware. This is unfortunate, for a useful theory of how different qualia arise needs to spell out the neural correlates of qualia in testable ways. But the difficulty in testing IIT–and its reliance on axioms, thought experiments, and abstract mathematical accounts–ultimately make this qualia theory seem in some ways less like an empirical hypothesis than a rationalist speculation. At least at this point in its development.

Other neuron-based theories that are (at least potentially) relevant to explaining qualia are the quantum-based theories of consciousness. To consider their potentials and shortcomings, let us start with the familiar example of the Orchestrated Objection Reduction theory (Orch OR), first suggested by Hameroff and Penrose (1996) and developed further in numerous papers. They argue that quantum states are coherent superpositions of microtubule states that incorporate many neurons when their electrons become entangled and inseparably correlated. (Microtubules are parts of neurons' cytoskeletons which are important for maintaining cells' shapes and intracellular transport, among other things) The collapse of these quantum states is attributed to gravity, and they are construed as being elementary moments of consciousness. One issue facing this approach to consciousness is whether quantum states can actually survive long enough in the brain's thermal environment to affect cognitive mechanisms. Hameroff has addressed and dismissed these critiques in various papers (e.g., Hagan et al., 2002), but this debate continues.

Another issue here that is more relevant to this paper is that Hameroff and Penrose have not yet addressed how different qualia arise from different quantum states. This latter issue applies to many quantum theories of consciousness. They generally omit mention of how quantum states yield the primary sensory qualia (redness, sweetness, etc.) we are familiar with.

Some quantum-based theories do try to do this. But they remain problematic, in our view. For example, Beshkar (2020) contains an interesting QBIT theory of consciousness that attributes qualia to quantum information encoded in maximally entangled states. Yet this information ultimately gets its actual blueness, painfulness, etc. from higher cortical mechanisms criticized above and in §1.3.

Another example is Lewtas (2017). He also attributes our primary qualia to quantum levels. Each fundamental particle has some of these various qualia. Synchronized firing by neurons at different frequencies selects from the qualia and binds them to form images. This is ingenious, but binding mechanisms such as neuronal synchrony are problematic in explaining how pictorial images arise (see below). Far more detailed explanation is required here for how differences in neural mechanisms yield differ qualia.

Turausky (n.d.) posits a single quality in fundamental particles that contains all others. Just as visual qualia merge into whiteness, so all sensory qualia could merge into a neutral whiteout. Separate qualities differentiate out like a synthesizer filters an electric buzz to produce brass, string, or percussion melodies. These analogies are intriguing but hard to specify neurally.

The general problem with these highly philosophical qualia theories is that they are hard to evaluate. Their uniting of qualia to quanta is not spelt out in testable detail. Nor are quantum levels adequately tied to the existing neuroscience of perception. Typical quantum-binding theories have relied on synchronic and synaptic activity to explain why only certain neural assemblies support subjective experience (e.g., Da Rocha et al., 2001; Georgiev et al., 2007). If binding thus involves these synchronic and synaptic activities, why is quantum-level activity also needed to explain the overall coherence of neural activity and unity of sensory activity? In contrast, Eric Bond's theory (below) is interesting in its attempt to address such shortcomings with an EM-field view of consciousness.

1.3. Problems with images

Having already looked at standard neuroscience's problems in explaining how different colors (for example) arise, we will now turn to its problems in explaining how (1) colors get their shapes, and (2) how both bind together point by point to form a unified image. This is crucial to explaining qualia, for we actually perceive color qualia in the form of unified images, not as isolated points.[3]

(1) Our detection of the shapes in images starts with retinal activity and culminates with the ventral cortical pathway detecting ever larger borders, surfaces, and objects. It is often assumed that integrated shapes are perceived when higher neurons have sufficient information to detect which shapes are present together, as when three lines are seen as a triangle. While top-level cells do attentively monitor objects such as grandmothers (Le Chang and Tsao, 2017), no neurons monitor the entire visual scene (which is largely preattentive) to recognize the shapes present together in a particular scene. Indeed, it is impossible to have a top-level detector for each possible visual scene. So, while standard neuroscience has explained our perception of some shapes and objects, it has not yet explained our perception of overall shapes and layouts.

(2) Let us now turn to the binding of images into unified forms. Standard neuroscience has not explained well how the brain's separate, distributed visual circuits bind together to support a unified image. This is an aspect of the so-called "binding problem" of how the mind's unity arises (e.g., Treisman, 1998; LaRock, 2006, 2007).

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[3] It may seem that accounts of binding (unity) are irrelevant to this paper's basic topic of qualia. But the two are inseparable. For example, colors are always experienced in visual space where they are bound together as unified images. Also, as the account of qualia theories will illustrate below, these theories get into trouble when they try to explain how different qualia arise without looking at how they bind together in images (e.g., see Pockett in §2.1.3).

This binding problem has several parts. To start with, visual processing uses separate, parallel circuits for color and shape, and it is unclear how these circuits combine to form complete images. Ascending color and shape circuits have few if any synapses for linking their neurons to create colored shapes. Nor do they converge on any central visual area (Zeki, 2003, p. 296; 1993, p. 216). Zeki may have overlooked here feedbacks from higher cortex into lower level maps (e.g., see Kawato, 1997; Lamme, 2004; Larkum, 2012). Arguably, these feedbacks might indirectly bind color and shape. But to encode detailed images, feedbacks would have to systematically connect shape and color elements point by point all across neural maps, which even the most detailed maps fail to do. [Nor is there any evidence of a central cortical area which higher cognitive functions connect into so as to account for the mind's overall unity (*ibid*)].

Nor is binding wholly encoded by the firing of color and shape circuits in synchronized lockstep, as suggested by Dehaene and Naccache (2001), Dehaene (2014), Gray et al. (1989), Crick and Koch (1990), and Roelfsema et al. (1997). For example, Thiele and Stoner (2003), Dong et al. (2008), and others found that neural firing synchrony does not necessarily correlate with color and shape binding. Also, Koch et al. (2016) point out that some kinds of neural firing synchrony occur without consciousness, for example during anesthesia and seizures. Here hypersynchrony seems to disintegrate binding and normal consciousness disappears. So, there is inconsistent support for binding by neural-firing synchrony. (Below, we discuss how General Resonance Theory (GRT) explains binding via resonating/synchronized electromagnetic (EM) fields throughout the brain and body, instead of just synchronized neural firing in the brain).

Other lesser-known binding mechanisms are problematic too (Jones, 2017; Jones and LaRock, 2019). It is thus understandable that while IIT assumes conscious systems have unified causality (Tononi, 2008), it has not actually explained the mechanism that creates this unity.

So, standard neuroscience seems unable to explain the most basic level of cognition. It has not explained how the qualia, shapes, and unity of images are encoded. Nor does neuroscience adequately explain how such codes give rise to our conscious perceptions (as argued below).

1.4. Problems with emotional qualia

One of the best-known neurocomputational accounts of emotional qualia comes from Patricia Churchland (2014). She stresses their complexity. She says that the physiological functions of hormones are too numerous and complex to treat (for example) the function of oxytocin as simply being the love molecule. She instead attributes emotions to complex hormonal interactions. But she does little to actually specify these complex correlations.

Churchland (2014) approach partly resembles Lovheim's (2012) hormonal approach to emotions. Unlike Churchland, he acknowledges (like many researchers) that serotonin correlates with the emotion of self-confidence, while dopamine correlates with anticipation and motivation, and noradrenaline correlates with distress. However, more in tune with Churchland, he treats varying levels of these three as the three axes of a computational space–a cube. These axes generate the cube's eight corners, representing the emotions of anger, disgust, surprise, fear, joy, shame, excitement, and anguish–which Tomkins (1981) treated as the eight basic emotions. So, much like in Churchland's view, the varying levels of the three hormones are assumed to be neural correlates of all these basic emotions.

However, this focus on basic emotions creates problems. Returning to the example of love, Lovheim offers no better guidance than Churchland on where it comes from. He presumably assimilates love with Tomkins' emotion of joy. But the joy of romantic love differs greatly from the joy of monetary riches or the joy of children playing. Arguably, his preoccupation with the "basic" emotions such as excitement, joy, and surprise misleads him into thinking that joy is a single emotion with a single cause. He ignores the rich variety of both emotions and hormones.

Moreover, there is little evidence that all these various emotions correlate in any systematic way with varying mixtures of the three hormones that Lovheim's computational emotional space so narrowly focuses on. It is thus most likely that mixtures of hormones instead just affect (for example) love quite indirectly by modulating levels of oxytocin in limbic circuits and thus intensities of love feelings. (See §2.5 below for a noncomputational view of qualia like this one).

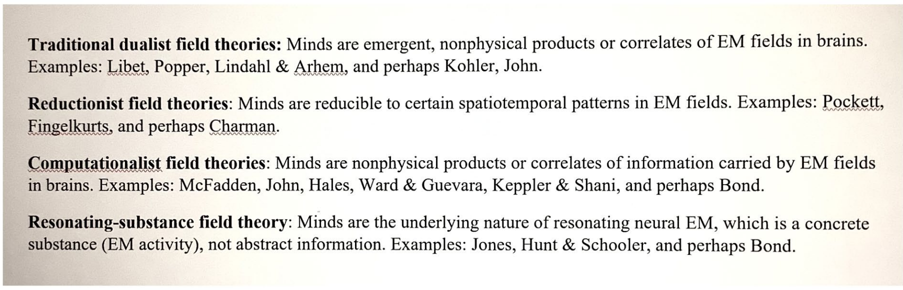
These issues demonstrate, at the least, that these issues with emotional qualia are not explained or tested in any significant detail in the standard neuroscience paradigm.

1.5. Standard neuroscience's three main qualia problems

The main problems above in neuroscience's accounts of qualia seem to fit into three categories. These problems actually apply to all accounts of qualia–neuron-based, EM-based, computation-based, *et cetera*. But they will be cast here initially in terms of the standard neuron-based and computation-based accounts above. This focus will help to summarize the problems in neuroscience and (in some cases) further sharpen critiques of it.

(1) *The coding/correlation problem:* As argued above, the neuronal and computational accounts above have failed to find different information-processing operations among neurons that encode our different qualia. More generally, this issue concerns how to specify the various neural correlates of qualia, whether or not they are computationalist. But sticking now to neuroscience's current computational approach, this issue may arise simply because these encoded operations are highly elusive. Alternatively, it may arise because qualia are ultimately not computational and neuronal in character. The next two qualia problems together suggest that the latter may be true.

(2) *The qualia-integration problem*: Computational accounts also face the problem of explaining how myriad qualia are integrated together to produce overall unified perceptions such as visual images. Detector neurons are buried in visual circuits and have only limited localized information. So, each detector neuron lacks the global perspective needed to create an overall, unified picture (Van der Velde and de Kamps, 2006). This integration could instead come from systematically connecting cells hierarchically via synapses, gap junctions, *et cetera*. For example, as already noted, some ventral-cortical detectors connect into many lower detectors to recognize particular objects, such as faces. Yet there are no top-level detectors to recognize all possible visual scenes. So, this circuitry has isolated information about different shapes but no unified, global perspective.



Traditional dualist field theories: Minds are emergent, nonphysical products or correlates of EM fields in brains. Examples: Libet, Popper, Lindahl & Arhem, and perhaps Kohler, John.

Reductionist field theories: Minds are reducible to certain spatiotemporal patterns in EM fields. Examples: Pockett, Fingelkurts, and perhaps Charman.

Computationalist field theories: Minds are nonphysical products or correlates of information carried by EM fields in brains. Examples: McFadden, John, Hales, Ward & Guevara, Keppler & Shani, and perhaps Bond.

Resonating-substance field theory: Minds are the underlying nature of resonating neural EM, which is a concrete substance (EM activity), not abstract information. Examples: Jones, Hunt & Schooler, and perhaps Bond.

FIGURE 1
Varieties of EM-field theories of consciousness the traditional dualist theories do not address how different qualia arise. So, they do not appear in the present paper.

Similarly, color and shape circuits do not synapse systematically, so their cells also lack global perspectives for integrating the circuits. Here the integration problem dovetails with the binding problem concerning what mechanism is uniting colors and shapes into an overall pictorial image. Neuroscience has yet to find any specific neural codes for this unified pictorial form.

(3) *The hard problem:* In addition to the two empirical problems above, computational accounts face a hard, metaphysical problem. Why are neural events accompanied by any qualia at all? That is, are the two related by identity, causality, third entities–or some other relation?

To start with, computationalist (information-processing) accounts of cognition treat minds as abstract computing systems that are realizable in multiple hardwares or substrates (Rescorla, 2015). Examples are Putnam's (1967) computational functionalism, Churchland's (1986) computational qualia spaces, and Tononi (2008) IIT (see Koch, 2019, p. 150).

The problem here is that images are qualities that we experience. In contrast, computations are mere abstract relations. They are abstract for two reasons. (a) Since computations are said to be multiply realizable in different hardwares, they are abstracted from any particular hardware. (b) Haugeland (1985) argued that the blind, mechanical activities of hardwares only become meaningful information once we impose high-level, abstract functions on them (facial recognition, language translation, etc.). So, information states are necessarily abstract, theoretical constructs in the minds of scientists.

So, computationalist claims that images are just neural computations face an important explanatory gap. There is no such gap when we explain (for example) how temperature is just kinetic energy. But images are so radically different from the abstract relations comprising computations that the latter fails to explain the former (e.g., Levine, 1993). So, while questions about what computations correlate with images involve "easy" empirical problems, questions about how images and computations are related involve a "hard" metaphysical problem (Chalmers, 1996). The radical differences between computations and images not only make it hard to treat them as identical, but also to posit any possible causal relation between them, so it is hard to see why qualia accompany neural computations. For example, the emergence of conscious images from organized brain activity that lacks consciousness seems like sheer magic. Relations of aspects, realization, grounding, etc. are obscure for much the same reason (Jones, 2016). Computationalists end up with three quite different entities–images, neurons, and computations–with obscure relations between all three.

Computationalist theories will appear again below. Ultimately, in §2.4–2.5, we will reconstrue "information" and "computations" in terms of concrete and measurable EM activity between neurons (versus abstractions). We will also try to attribute qualia to this concrete EM activity without any overt explanatory gaps, so as to avoid the problems just listed here.

2. Electromagnetic field theories of qualia

While standard neuroscience seems stymied in explaining how brains create our different qualia and unify them into phenomenal consciousness, EM field approaches to minds have offered new theories of qualia and consciousness, some of which are testable. These electromagnetic approaches seat consciousness primarily in the various complex EM fields generated by neurons, glia and the rest of the brain and body. They can be classified in the varieties listed at the end of this paper in Figure 1 (see Jones, 2013, for references and reviews). The classifications overlap at times. They differ in their definitions and (for example) whether the qualia they attribute primarily to EM field activity are global or localized in brains, whether field-brain causality is one-way or two-way, and whether qualia are more akin to substances or to information.

These EM field approaches are proliferating because they draw on considerable experimental evidence and withstand past criticisms from standard neuroscience. For example, they have explained the unity of consciousness in terms of the physical unity (by definition) of EM fields–in contrast to the discrete nature of neurons and their synaptic firing. In the last two decades, they have also offered explanations of how neural EM activity creates different qualia.

2.1. Qualia as global EM activity in brains

Pockett's (2000) theory of qualia is an important landmark in EM field theories of mind. It is rooted in extensive experimental evidence, makes testable predictions, and is strongly defended against critics. If Kohler, Libet, Eccles, and Popper helped establish the EM field approach to minds, Susan Pockett has arguably done more to develop it than anyone else–except for perhaps Johnjoe McFadden. In this section, we will start with Pockett, then end with McFadden. Both attribute qualia to EM field patterns, though they differ in their metaphysical views on how exactly these patterns are related to qualia. Pockett arguably tends more toward treating qualia as concrete patterns in field substances, while McFadden treats them as abstract field information.

2.1.1. Pockett's theory

Pockett's basic claim is that "consciousness is identical with certain spatiotemporal patterns in the electromagnetic field" (*ibid.*, pp. vi, 109, 136–7). Her evidence comes mainly from extensive EEG and MEG studies of neural electromagnetic fields. They show correlations between sensory qualia and field patterns. For example, EEG studies by Freeman (1991) show that various odors (e.g., from bananas or sawdust) correlate with specific spatial patterns distributed across mammalian olfactory areas. The patterns altered when animals were trained to associate the odors with rewards, showing that the correlations were with odor awareness, not just chemical stimuli. Given the problems with neuronal correlates with qualia above, these global EM patterns appeared as more promising physical correlates of qualia.

Similar correlations appear in Freeman's many studies of auditory and visual awareness. Also, EEG studies by Laurent et al. (1996) show that these sorts of spatial patterns evolve while odors are puffed onto locust antennae. So, Pockett thinks that fields create a specific spatiotemporal pattern for each kind of sensory quality. This can ultimately be tested by examining whether these trends persist through all sensory and emotional qualia. Pockett (2011) attributes these qualia even to possible electromagnetic fields created artificially outside brains.

Pockett's (2012) theory not only offers a testable EM theory of how different qualia arise, it also offers a way to distinguish nonconscious fields from conscious fields. Assuming that the latter reside in the cerebral cortex (which has a six-layered architecture), she suggests that "conscious fields will have a surface layer of negative charge above two deeper layers of positive charge, separated by a distinct neutral layer". The fields are boosted to these significant levels of electrical activity by synchronized feedback between cortical areas (*ibid*). Also, modes of consciousness and individual experiences will reside (respectively) in regional variations in cortical thicknesses and cortical modules (*ibid.*). She gives various kinds of evidence for all these points while acknowledging that they just provide necessary conditions for consciousness (*ibid.*, §5). Pockett's (2012) analyzes of these conscious patterns suggests that electromagnetic fields may be the only conscious fields.

Pockett stresses that experiences are distributed across the brain's global electromagnetic field. For example, our perception of a red spot is widely spread across this field—it is not in one place (e.g., Pockett, 2000, pp. 10–11, 65–7, 70, 108). The field binds the spot's color, shape, and motion into an overall experience (*ibid.*, pp. 107–8). Images reside in global fields in nonpictorial, coded forms.

Pockett's theory raises issues that appear in other theories of qualia as well as her own. To start with, she realizes the problem raised by traditional identifications of qualia with firing neurons–given their observable differences. Yet, intriguingly, she feels that this problem is lessened by instead identifying qualia with the brain's "everchanging, shimmering, invisible" electromagnetic field (*ibid.*, pp. 136–7). She seems closest here to the reductionism of psychoneural identity theory (Pockett, 2000, pp. 109, 135–6; but *cf.* pp. 105, 136).

Yet since qualia cannot be observed by investigating this everchanging electromagnetic field, their identity remains problematic. Here, Pockett faces the same explanatory gap between the mental and neural that bedevils all attempts to fully explain minds in terms of physics. But Pockett's thoughtful psychoneural identity theory might be a step in the right direction here. For qualia might be private because they are hidden from public view ("invisible") in the sense that they are the underlying nature of fields that we detect only *indirectly* via EEGs. Explaining in this way why color qualia are not observable in neural activity could arguably help deal with the explanatory gap between color qualia and neural activity, for both the colors and the EM fields are not directly observable in brains (see §2.5 below).

It should be noted that while Pockett (2000), pp. vi, 109, 136–7 espouses a reductionist "psychoneural identity theory" in which "consciousness is identical with certain spatiotemporal patterns in the electromagnetic field," this needs qualification. She also repeatedly mentions neural information processing, though its relation to consciousness is not made clear. So it is possible that she is reducing qualia to either the physical substance of EM field patterns or the information they carry. Nonetheless, information approaches are typically nonreductive. So, we will construe her identity theory as attributing qualia to EM field's physical substance instead of their information.

Another possible objection concerns Pockett's view that the experiences of qualia are widely distributed across the brain. While Freeman found that each olfactory stimulus creates widely distributed responses in the olfactory system, other studies show that such stimuli create strong, isolated (versus global) responses (e.g., Stewart et al., 1979; Jones, 2010). Actually, the strongest responses in Freeman's own studies are rather isolated too–arguably his weaker responses are largely from the proclivity of detectors to respond faintly to diverse stimuli.

There is evidence that only this strong kind of sensory activity is fully conscious, while the rest is weakly conscious or subliminal. For example, it is widely known that qualia intensity covaries with the number and rapidity of neurons firing in sensory pathways. Also, MEG studies show that electrical activity is far higher in fully conscious processing than in the subliminal processing of binocular rivalry (Edelman and Tononi, 2000).

Arguably, such evidence might support treating perceptions as localized events where an image–for example, a yellow spot–is not widely distributed. Instead, it appears when one type of wavelength detector is most strongly active at a spot in retinas and associated sensory maps. This fixes the spot's color, shape, and location in the image.

By contrast, Pockett's global field theory is unclear on how globally distributed yellow spots would get their actual locations in images. If the field's spatial patterns are used to specify which colors exist, then what is left to specify the colors' spatial locations in images? This is part of a larger problem in computational approaches to minds, namely, how can nonpictorial field patterns be identified with pictorial images?

So, Pockett has important ideas about how qualia are created, which fields are conscious, *et cetera*. Her defense of field theory is also sophisticated. Yet questions may arise about how experience is identical to fields and how fields unite colors and shapes into all their right locations in pictorial images. To be fair, these questions apply not just to Pockett, but to other theories too.

2.1.2. McFadden's theory

As promised, we will now turn to McFadden's theory with an eye toward comparing it to Pockett's theory. McFadden's theory is the leading EM-field theory of consciousness today. It says that information is conscious at all levels, which seems to entail a form of panpsychism (McFadden, 2002b). The "discrete" consciousness of elementary particles is limited and isolated. But as particles join into a field, they form a unified "field" consciousness. As these fields affect motor neurons, the brain's consciousness is no longer an epiphenomenon, for its volition can communicate with the world. This level of "access" consciousness serves as a global workspace where specialized processors compete for access to volition's global, conscious processes (McFadden, 2002a, 2006).

McFadden (2002a, 2006) cites evidence that fields affect nerves, as the last level stipulates. For example, transcranial magnetic stimulation (TMS) produces fields as strong as the brain's own native fields, and these TMS fields make nerves fire. Field–nerve interactions occur mainly when fields are strong due to synchronized firing in regularly aligned nerves, and when nerves are myelinated and bent relative to field isopotentials (McFadden, 2002b). This affects neurons poised near firing thresholds, which proliferate when we are undecided (McFadden, 2006).

As noted above, McFadden rejects popular views that minds are just ineffectual epiphenomena of brain activity. Instead, field–nerve interactions are the basis of free will. The conscious field is deterministic, yet it is free in that it affects behavior instead of being epiphenomenal (McFadden, 2002a,b). This treats determinism as compatible with free will construed as self-determination.

McFadden (2002b) concludes that "Digital information within neurons is pooled and integrated to form an electromagnetic information field. Consciousness is that component of the brain's electromagnetic information field that is downloaded to motor neurons and is thereby capable of communicating its state to the outside world." He calls this theory "The conscious electromagnetic information" (CEMI) field theory.

McFadden has not said as much about qualia as Pockett, for he feels that detailed accounts of qualia are not possible, given our current knowledge. Yet his 2002a paper has an entire section on qualia. Like Pockett's theory, this paper attributes different qualia to different field patterns, such as those discovered by Freeman (1991). But McFadden stresses that these qualia arise only when processing streams are well integrated in brains due to the neural EM field. Reiterating this overall view, McFadden (2020) says, "the qualia associated with hearing the musical note middle C is what an EM field perturbation in the brain that correlates with the sensory input of middle C feels like, from the inside." Yet unlike Pockett (2000), he does not feel that these patterns are close to being specified at this time.

Like Pockett, McFadden (2002a) addresses the hard problem of why such field patterns are accompanied by qualia. But he does not adopt her psychoneural identity theory, where qualia are outright identified with neural field patterns. Instead, he adopts a functionalist approach that ties qualia to the functional organization of neural activity. Here he mentions well-known arguments that if qualia come from functional or computational organizations, then the population of China could at certain times have qualia—or qualia would fade away if brain circuits were gradually replaced by silicon chips. Turning to his own CEMI, McFadden says here that if brain circuits were gradually replaced by silicon chips, this would not produce qualia unless the neural EM field was somehow preserved in this replacement process (Pockett expressed a similar view above).

So, McFadden ends up with a functionalist-computationalist metaphysics quite different from Pockett's psychoneural identity theory. McFadden says that phenomenology (the study of consciousness) describes information from the inside, where it is privately experienced, while physics describes information from the outside, where it is physically observed (McFadden, 2002a,b). This echoes Chalmers' neutral monism, where the basic stuff of the world is not mental or physical, but neutral. The mental is constructed from its inner, intrinsic nature. The physical is constructed from its outer, extrinsic relations (Chalmers, 1996, pp. 155, 305).

To summarize, McFadden's theory of qualia resembles Pockett's theory that qualia correspond to neural EM-field patterns, though he is less sure about specifying these patterns. Also, McFadden explains why these correspondences obtain in terms of a different metaphysics than Pockett's. He relies on abstract functional–computational links between qualia and field patterns, while she seems to rely more on an outright identity between qualia and field patterns–that is, between qualia and physical field patterns versus abstract field information. Her view is a monism in which qualia just are neural field patterns, while his is more of a dual-aspect view in which qualia and field patterns are different aspects of information. Both theories are sophisticated empirically and metaphysically. Yet, like all extant theories of qualia, they raise certain issues.

2.1.3. Field theory's three main qualia problems

The three kinds of qualia problems we found in standard (neuron-based, computation-based) neuroscience also apply to the first two EM-field theories of qualia we have just reviewed above.

(1) *The coding/correlation problem*: What different EM-field activities encode or correlate with the various qualia? Both field theories above face difficulties here. Pockett's psychoneural-identity theory is based on correlating qualia such as colors with the spatial patterns of fields. But, as already noted, this makes it hard to specify the colors' spatial locations in images. McFadden's computationalist field theory above (and other computationalist theories below) are less forthcoming than Pockett's theory when it comes to spelling out correlations between qualia and information-processing operations that would encode these qualia. Arguably, these field theories have a way to go here before they can be said to improve upon standard neuroscience.

(2) *The qualia-integration problem:* How do EM fields integrate myriad qualia to form (for example) unified pictorial images? Here field theories seem quite promising in their ability to improve upon standard neuroscience.

As already noted, one aspect of this integration problem is the binding problem. The latter arises because standard neuron-based neuroscience has not shown how qualia bind together to form unified images by synaptic connections or synchronized firing of neurons. In contrast, field-based theories can attribute binding to the field's substance, which is a continuous, unified conscious whole. This field can thus pool different qualia together in the same consciousness. This is, quite arguably, an important advance upon standard neuroscience.

Nonetheless, computationalist field theories still face another aspect of the integration problem. In EM fields, how does information about qualia integrate together to encode or construct unified pictorial images? Fields pervade visual circuitries, so it might seem that they can readily connect information about particular colors together to form a more complete colored image. But this pervasiveness arguably leaves fields unable to selectively connect colors together in systematic ways. In contrast, neurons could in theory use synapses to selectively connect color information together point by point across neural maps (though they evidently do not do so, as already noted). But an EM field arguably lacks these selective connections and instead just pools color information together as a whole into a single consciousness.

Pockett's theory is an example. Once again, it uses the overall spatial form of fields to specify the colors in images. So, what is left to specify the colors' spatial locations in images? What we are left with are field patterns that do not appear anything like our pictorial images—and do not seem to explain how myriad colors combine point by point to form pictorial images.

It may seem that there is no real problem in explaining how colors are integrated to form pictorial images Arguably, neuroscientists are already showing how brains encode and construct such images. They are using artificial intelligence to decode patterns in EEGs and partly reveal people's visual images of (e.g.) faces. Or so it may seem. In fact, these EM patterns just arise from the processing that recognizes faces in terms of their gender, familiarity, etc.–which is quite different from the processing that actually constitutes the image in the first place. (Even if these coded patterns helped constitute images instead of just recognizing images, the question arises of how brain mechanisms would go about decoding these complex codes to yield our actual images—this issue leads into the hard problem below.)

So, field theory still owes us an explanation of how integrated pictorial images arise. It has not yet shown how fields integrate colors together point by point to create images. Arguably, one remedy is to attribute the colored spots in images to highly localized fields in neural maps that are rooted in retinas. Here, specific colors would come from color detectors' EM activity in maps and the colors spatial position in images would come from the detectors' spatial positions in the maps.

This would offer a simple way of connecting colors together in a pictorial form (see §2.5 below). But it is unclear whether computationalists would accept this, for the pictorial form of images is no longer a coded space–it is the actual space of neural maps. Computationalists may choose instead to wait patiently for the discovery of purely coded spaces and images akin to those in the EEG studies just mentioned above.

So, field theories have quite arguably improved on standard neuroscience in explaining how qualia bind together into unified forms. But it is currently unclear which direction field theories will take in explaining how colors integrate to form pictorial images–and whether they can improve on standard theories here.

(3) *The hard problem*: Apart from the issues above concerning neural correlates of qualia and their integrations into images, field theories face a relatively hard metaphysical issue. Are fields metaphysically related to qualia by identity, causality, third entities–or some other relation? The two theories above arguably construe qualia in terms of patterns in concrete field substances–or in terms of abstract field information. So, they arguably face similar problems to those in many other theories concerning how qualia can be intelligibly related to concrete neural substances or abstract computations or by relations of identity, causality, aspects, realization, grounding, third entities, etc. (Jones, 2016). For example, information approaches end up with three radically different entities (information, qualia, and EM) with obscure relations between each. In the end, metaphysical theories associated with field theories and standard neuroscience seem to be in the same boat. So, field theories have not improved on the latter in this regard.

2.2. Qualia as localized EM field activity in brains

In contrast to Pockett's global qualia in specific kinds of EM fields, Ward and Guevara (2022) localize qualia in the fields generated by a particular part of the brain. Their intriguing thesis is that our consciousness and its qualia are based primarily on structures in thalamic EM fields which serve to model environmental and bodily information in ways relevant to controlling action.

Ward and Guevara argue that the physical substrate of consciousness is limited to strong neural EM fields where synchronously firing neurons reinforce each other's information (instead of randomly firing neurons canceling each other out). They qualify this by adding that epileptic seizures are nonconscious even though they involve strong, synchronous firing. They thus contend that more is required for consciousness, namely, that fields also be integrated and complex.

Ward and Guevara adapt other views from field theories of consciousness. For example, they say that these EM fields contain all the information carried by the fields' neuronal sources. Also, these fields are integrated at light speed while neurons' synaptic integrations are relatively slow. Finally, local, nonsynchronous fields can be canceled out in favor of a dominant field that synchronously and coherently represents all the information from our senses, memories, emotions, *et cetera*. For these reasons, Ward and Guevara believe that fields are better candidates than neurons and synaptic firing for the primary substrate of consciousness.

Much like John (2001), they attribute consciousness to a specific part of the brain's EM field. They stress that this contrasts with attributing consciousness to the brain's entire field (as in Pockett, 2000 and Hales, 2014, for example) or to a specific kind of brain activity involving fields (as in McFadden, 2002a,b; McFadden, 2020) or to a nested hierarchy of EM fields in the brain (as in Fingelkurts et al., 2010, 2013; Hunt and Schooler, 2019). In defending this view, Ward and Guevara argue that (in mammals) the field's conscious part is generated by the thalamus.

Following Ward (2011), they cite four reasons for ascribing consciousness to the thalamus. (1) We are not conscious of all sensory computations, just their end result, which involves the thalamic dynamic core. (2) Thalamic dysfunctions (but not necessarily cortical dysfunctions) are deeply involved in nonconsciousness conditions such as anesthesia, unresponsive wakefulness syndrome, and anoxia. (3) The thalamus is a prime source and controller of synchronization (in itself and in cortex), which is also associated with consciousness. (4) The thalamus (especially its DM nucleus) is ideally suited for the integrative role associated with consciousness, for cortical feedbacks seem to download cortical computations into thalamus. All this aligns with suggestions that thalamus serves as an attentional searchlight during perception (Crick, 1984) and as an active blackboard for offering best guesses while representing objects (Mumford, 1991)–but see below. These lines of evidence indicate that while cortex computes qualia, thalamus displays qualia. Ward and Guevara contrast this view with Fingelkurts et al. (2010, 2013), where the highest of various nested levels of consciousness contains the conscious features of the lower levels. Ward and Guevara say that this does not explain why only the end result of information processing (which results from cortical feedbacks into thalamus) is conscious.

Ward and Guevara then argue that sensory qualia are the EM field structures of the thalamic nuclei, which model the information structures of the environment and sensory systems. For example, the thalamic field contains information from the retina and higher-level retinotopic maps about color, motion, shape, and the overall topology of the visual field. Their idea here seems to be that visual colors differ from auditory pitches because their information structures differ in the thalamic EM field (this idea thus resembles McFadden's computationalism more than Pockett's identity theory above). This partly resembles IIT's large-dimensional qualia space in which qualia are represented by vectors. But Ward and Guevara do not spell out these qualia spaces as IIT does.

Ward and Guevara identify consciousness in general with this EM field of the thalamic dynamic core which reflects the environment in ways relevant to controlling action. They reiterate what it is about this field that is conscious. It is not just the field's strength and synchrony–for smaller animals such as birds lack this strength yet still seem conscious. Also important is the complexity and differentiation-integration of the field's information, as already noted. Finally, the field is "unitary and reinforcing" relative to isolated fields in other areas that cancel each other out.

Ward and Guevara ask why we should equate qualia with a neural EM field rather than with, for example, Edelman and Tononi's (2000) differentiated and integrated neuronal activity. Their answer builds on their argument above that fields are better candidates than neurons for the substrate of consciousness. They add here that integrated neuronal activity cannot account for how we create and differentiate our various qualia. This important argument starts with a reference to Muller (1835), who tried to explain different qualia by saying that different sensory neurons have different "specific nerve energy." But Adrian (1928) argued that all action potentials are the same–whether they are from visual, auditory, or other nerves. Adrian thought that what is important here is not which nerve fires but where the nerve projects to (e.g., visual or auditory cortex). However, this view was later questioned because, for example, visual cortex can support inputs from visual or auditory receptors. Here, it is the input, not the cortical receiving area, that determines qualia. This points away from neurons toward neural input from the environment.

So, this is why Ward and Guevara claim that different qualia cannot come from indistinguishable neurons but must come from different EM field structures that model the different information structures of the environment. However, more in tune with Muller above, Jones (2019) gives recent evidence that different qualia may come from different proteins in sensory detector neurons and (in the case of emotions) limbic neurons. He argues that colors may thus arise from various levels where these proteins are found–from retinas to the V4 cortical area (see below). Ward and Guevara do not address emotional qualia. This raises the issue of whether a purely thalamus-based account of qualia can account for all qualia. This is an interesting debate.

There is another interesting issue raised by Ward and Guevara's account of integrating qualia information via EM. In their thalamic fields, each bit of information seems to be pooled indiscriminately with others, so it is unclear how these fields selectively connect information about particular colors and shapes in systematic ways–which is the integration problem (*cf.* §2.5 below).

An issue also arises in connection to Ward and Guevera's attribution of sensory qualia to thalamic-nuclei EM fields. This attribution contrasts with the view of Neitz and Neitz (2014), who argue that retinal opponent cells actually disambiguate cone inputs and may thus be responsible for color percepts. So, retinas arguably create raw color qualia, while (as Crick and Mumford might say) thalamus arguably acts on these at higher levels that can involve attention and integration. In this way, various levels of sensory activity could be unified by coherent field activity across these circuits. Qualia–from raw to meaningful levels–would be a multi-level (nested) affair rather than being tied mostly to thalamus. This might explain why thalamic and cortical distortions do not appear in visual images, while retinal detachments and retinal blind spots do (Jones, 2019).

Ward and Guevara's thesis that our different qualia are different "information spaces" (in Chalmers, 1996) within thalamic EM fields seems to have a similar status to IIT's qualia theory above. A useful theory of how qualia arise needs to be testable, yet neither theory makes precise, testable predictions about how different qualia arise, which raises the coding/correlation problem above. Nor does either theory deal with the hard problem above. Like other EM-field theories of qualia, Ward and Guevara's faces the integration problem concerning, for example, how myriad qualia are integrated to form pictorial images. In all fairness to their provocative theory, it seems to be in much the same boat as most other EM-field theories in these various regards.

2.3. Qualia as fundamental EM activity

While Pockett attributes qualia to macro-level EM fields, other authors try to ground qualia in fundamental-level EM-field events. These authors include Keppler, Shani, and Bond.

2.3.1. Keppler and Shani

Keppler (2021) tries to develop a fundamental theory of consciousness that can fit qualia seamlessly with physical and psychological science and predict the phenomenal state of any system, given its physical state. He criticizes common claims (including those in many EM-field theories of mind) that conscious states emerge from physical complexity. For this creates troubles in explaining how consciousness can (seemingly) magically pop into existence from previously nonconscious states (Strawson, 2006), and in detailing which states this emergence occurs in.

Keppler tries to avoid this problem with a fundamental (versus emergent) theory of consciousness based on quantum theory. He notes that EM is the fundamental force shaping biological systems (*cf.* Hales and Ericson, 2022). Whereas EM dynamics are usually framed in physics as a matter of classical field physics, Keppler frames his theory of consciousness based on the quantum theory of EM fields (quantum electrodynamics or QED), which is a more fundamental physical theory than the classical approach. QED explains EM by treating the classical vacuum state as a vibrant ocean of energy, rich with structure, energy, and potentialities. Even more basic than QED is stochastic electrodynamics, which views the vacuum as an omnipresent EM background field with the lowest possible energy–the zero-point field (ZPF)–which mediates all EM events. Here, the potential energy in charged particles comes from them being embedded in the ZPF.

Keppler and Shani (2020) see the ZPF as a foundational component of the cosmos with two aspects. Its extrinsic appearance is physical, and its intrinsic manifestation is conscious. The entire palette of qualia is supposedly rooted in the ZPF's vibrational spectrum in a potential (versus actual) way. This ZPF is thus the carrier of primordial energy and consciousness. Intriguingly, it resembles the formless sea of consciousness in mystical Hindu thought (Shani and Keppler, 2018).

They further speculate that the brain generates actual concrete (versus potential) conscious states and qualia by coupling with specific ZPF modes in resonating, oscillating ways. Here, these modes operate like a keyboard for composing various conscious states. Interestingly, this view thus "shares commonalities with the General Resonance Theory (GRT) of Hunt and Schooler (2019), according to which resonance-induced phase transitions underlie the formation of macro-conscious entities" (Keppler, 2021). In this process, oscillating cell assemblies are orchestrated by synaptic input. Here changing neurotransmitter concentrations alter the resonance properties of the assemblies "by altering their coupling strengths to synaptic action fields."

Keppler concludes that familiar mechanisms for consciousness–such as the synchronous dynamic core of Edelman and Tononi (2000), the global neural workspace of Dehaene et al. (2006), or various EM-field views noted above–produce consciousness in mysterious emergent ways. By contrast, in his theory, a deeper, fundamental mechanism is at work in which neuronal assemblies couple in resonant ways to an omnipresent field of consciousness. This consciousness is fundamental, not emergent. This coupling process thus delineates conscious from nonconscious activities in this fundamental way. This mechanism is "the truly global workspace in which conscious processes unfold" (Keppler, 2021). The ZPF is thus a creative force behind the scenes with no equivalent in classical physics (Keppler, 2021). it is the key to this fundamental theory of consciousness.

Keppler's theory may yield predictions about neural correlates of qualia. Subjective reports of our different qualia experiences can be linked to different neurotransmitter levels and thus to phase-locked ZPF states. Qualia spaces would thus be systematically mapped onto ZPF information spaces (Shani and Keppler, 2018; Keppler, 2021).

Keppler (2016) argues that local consciousness in the ZPF increases with the degree of phase-locking in the local ZPF–and the integration of its information. The latter parallels IIT in some ways. The two theories parallel each other in other ways too. In the end, Keppler and Shani's approach to qualia, like IIT's, is theoretically impressive–yet also speculative and not yet backed up with actual evidence of specific correlates for qualia. Their interesting claim about resonance's role in creating qualia is quite credible, yet their claim that this role involves tapping the ZPF remains highly conjectural. For example, they do not detail the specific mechanisms for how this "tapping" would systematically unite shapes and colors point by point to make images.

Also, Keppler and Shani are unclear about how qualia and EM are metaphysically related. In their dual-aspect view, the ZPF's extrinsic manifestation is an abstract mathematical structure, while its intrinsic manifestation is conscious and qualitative. These extrinsic-intrinsic and dual-aspect relations are arguably among the murkiest ones in philosophy of mind today. For these various reasons, Keppler and Shani arguably face the coding/correlation problem and the hard problem. They also seem to face the integration problem concerning how myriad qualia are integrated to form images. In other words, they face many of the problems confronting field theories in general.

2.3.2. Bond

Another author who attributes qualia to fundamental EM activity is Bond (2023). This clear, succinct paper explains that quantum coherence involves the entanglement of quanta within energy fields, including the EM fields generated by neurons. Neural matter typically lacks this coherence because the haphazard orientation of quantum spins in the matter creates destructive interference and decoherence. Bond proposes the novel idea that firing neurons generate EM fields that can flow through nearby molecular structures and entangle with their atoms. This coherence produces our perceptions. The different subjective feelings of these perceptions come from different hybrids or mixtures of the fields' wavelengths as they vibrate or resonate.

On a larger scale, this coherence ties into the well-known phase-locking of corticothalamic feedback loops. Together, they produce the holism or unity of consciousness. This combination of coherent, phase-locked feedback loops and coherent, entangled wave-particles in EM fields is called by Bond a "coherence field." It is investigated by his Coherence Field Theory (CFT).

This CFT supplements McFadden's well-known CEMI theory. The latter stresses that phase locking in feedback loops produce a strong EM field. This pools and integrates information in neurons, part of which is conscious. CFT adds nanoscale quantum coherence to the macroscale phase locking to explain unified consciousness. It is unclear how testable CFT is at this time.

An issue that Bond may face (if we interpret him correctly) is whether unified consciousness might be better explained in CFT simply by EM in macrolevel phase-locked feedback loops–rather than in combination with nano-level entangled wave-particles. One question here concerns how entangled wave-particles–which are no longer separate individuals describable independently–can account for all the varieties and differences in sensory experience.

Be all that as it may, one of Bond's many exciting claims is that the complex, diverse qualia we feel could arise from enhancing the vibrations in nanoscale matter by means of the *vibrations in specially adapted macroscale neural structures*. Presumably, these structures could span all the way from specialized neuronal proteins up to cortical columns. This may have important implications for two views we sketch below–Hunt and Schooler's (2019) attribution of qualia to resonating EM fields and Jones (2019) attribution of qualia to electrically active proteins in sensory and limbic neurons that detect sensory stimuli and hormones. Bond's claim may point to a way of synthesizing these views (see below). Whether or not his binding by entanglement idea is right, his various views are important and will hopefully be further developed. One way his CFT stands out from other theories is its headway (as just described above) into the integration problem concerning how qualia become integrated into overall perceptions.

2.4. Qualia in Hunt and Schooler's general resonance theory

Another approach to the Qualia Problem is Hunt and Schooler's General Resonance Theory (GRT), which is grounded in a panpsychist framework (Hunt, 2011, 2014; Schooler et al., 2011; Goff, 2017; Hunt and Schooler, 2019). Hunt is a co-author of the present paper.

GRT assumes that all matter is associated with at least some capacity for phenomenal consciousness (this is called the "panpsychism axiom"), but that consciousness is extremely rudimentary in the vast majority of cases due to a lack of physical complexity mirrored by the lack of mental complexity. The EM fields associated with all baryonic matter (i.e., charged particles) are thought to be the primary seat of consciousness simply because EM fields are the primary force at the scale of life (strong and weak nuclear fields are operative at scales far smaller and gravity is operative mostly at scales far larger). Accordingly, GRT is applicable to all physical structures and as a theory is not limited only to neurobiological or even biological structures (Hunt and Schooler, 2019).

GRT suggests that resonance (similar but not synonymous with synchronization and coherence) of various types is the key mechanism by which the basic constituents of consciousness, when in sufficient proximity, combine into more complex types of consciousness. This is the case because shared resonance allows for phase transitions in the speed and bandwidth of information exchange to occur at various organizational levels, allowing previously disordered systems to self-organize and thus become coherent by freely sharing information and energy. The speed and bandwidth of information flows achieve a step change through such a phase transition, allowing for the unity of consciousness in each moment. This is GRT's suggested solution to the binding problem as well as the Qualia Problem.

In GRT, consciousness is a product of resonance chains[4] of various information/energy[5] pathways, and the spatial and temporal boundaries of any particular conscious entity is established by the slowest-frequency shared resonance within that conscious entity, for each particular information/energy pathway (Hunt, 2020b). Shared resonance and resulting resonance chains are the key mechanisms for self-organization and are constantly changing in most entities (Walleczek, 2000). Thus, the spatial and temporal boundaries of conscious entities will be constantly changing at least a little (Hunt calls this constantly changing EM field structure in human and mammalian brains "the blob" in Hunt (2020b), and this structure is the physical basis for the dominant consciousness in each moment).

Most combinations of consciousness, in which less complex entities combine into more complex entities in biological structures like mammal brains, will be comprised of a nested hierarchy of conscious entities, with one dominant conscious entity in each moment, and without extinction (elimination) of the nested entities' subsidiary consciousnesses. This notion is stated well by Whitehead et al. (1929): "The many become one and are increased by one." This lack of extinction of subsidiary entities distinguishes the present approach from IIT and other theories that assume the extinction of nested conscious entities, leaving only one macro-conscious entity left (this is, e.g., IIT's "exclusion principle").

Qualia, in GRT, are synonymous with consciousness, which is simply subjective experience. Nevertheless, qualia may act as a conceptual tool for distinguishing specific qualities or aspects of consciousness. As such, some degree of qualia are associated with all EM field activity but will be more complex in more complex physical structures such as evolved biological entities with advanced sensory abilities (such as humans and other animals). Any EM field shape, which can be represented visually with the traditional EEG frequency and amplitude sine wave diagram, represents a specific quale or experience–but only at a specific level of organization. Any complex quale or moment of human consciousness, for example, is an extended nested hierarchy of resonating fields starting perhaps with extremely fast terahertz-level frequencies in microtubules and other similar subcellular proteins, and then upwards through the chain of complexity to the global EM fields measured by normal EEG at the 2–60 Hz frequency bands conventionally labeled delta through gamma.

Each layer of this extended nested hierarchy forms part of the highest-level quale or moment of consciousness, with the specific types of resonance between each level determining what information is passed from the lower level to the higher level and vice versa. The atlas of patterns comprising specific quale in any particular milieu is termed the "resonome" in GRT. The details of what comprises specific resonomes in each species have not yet been fleshed out so this term is a placeholder for now.

Chalmers (2017) asks "how do microqualities combine to yield macroqualities?" He labels this "the quality combination problem." (We call this the integration problem.) He adds: "Here macroqualities are specific phenomenal qualities such as phenomenal redness (what it is like to see red), phenomenal greenness, and so on. It is natural to suppose that microexperience involves microqualities, which might be primitive analogs of macroqualities. How do these combine?"

GRT answers this question as follows: the oscillating/vibrating nature of all baryonic matter allows combination when achieving a shared resonance frequency between different constituents in proximity, with the speed of the specific energy/information flows that are present within each oscillation time period determining the size of the conscious entity in each moment. Biological structures have mastered the use of higher-speed information channels (nerves, electrical fields, etc.), through various types of resonance, allowing for much larger conscious entities (compared to non-biological structures) to form and to be sustained as semi-stable patterns over time. Their combination, as described above, includes the combination of their

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[4] Bandyopadhyay has developed a sophisticated approach to resonance chains in a broad theory of consciousness he calls the Fractal Integrated Information (FIT) theory of consciousness (Bandyopadhyay, 2019). Resonance in GRT is similar to its role in FIT, but GRT adopts a metaphysically foundational role for resonance through its general congruence with Whitehead's process philosophy and the "actual entities" that are the "final real things" that comprise the world (Whitehead et al., 1929; Hunt and Schooler, 2019).

[5] Information is generally defined as a subjective aspect of the physical world, whereas energy is an objective aspect; but in the context of GRT these terms are often used interchangeably because information is defined as "aspects of energy that we can measure." Accordingly, information is a concept that supervenes on the presence of matter. All physical dynamics consist of nothing more than energy flows, but those energy flows that we can measure may be labeled "information" and may be usefully quantified under established information theoretic concepts. Hunt (2020b) offers an information theoretic framework for quantifying the presence and complexity of consciousness in any physical structures.

experienced qualities into a macro-conscious subject. Just as a musical note or chord is the sum of its constituents, or a paint color mixed from other colors is the sum of its constituents, the qualities (qualia) of each macro-conscious entity are the sum of its constituents in each moment.

Hunt (2020b) fleshes out a quantitative framework for GRT and allows for the calculation of the complexity of consciousness, which may be characterized as qualia in specific entities in each moment. A single quale can be calculated in GRT, in terms of its capacity for phenomenal consciousness as a scalar value, following Equation 5 from Hunt (2020b), with Ω representing the capacity for phenomenal consciousness, Δ_t symbolizing any specific duration, such as 1 s, 1 min, etc., and f_{SSR} the frequency of the Slowest Shared Resonance:

$$\Omega\left(\Delta_t\right) = \Omega^* \; f_{SSR}{}^* \; \Delta_t$$

While GRT uses the tools of information theory to calculate the capacity for phenomenal consciousness and of specific qualia in each moment, it is not a computationalist account of consciousness because it does not reduce consciousness, in an ontological manner, to information or information processing. Rather, consciousness is a fundamental feature of the fields associated with baryonic matter (and, to be precise, of any matter or fields more generally, though it appears that baryonic matter EM fields are the "main game in town" in terms of being the most suited physical structures for complex consciousness).

Hunt et al., 2022 proposes a framework for testing GRT and related theories of consciousness by measuring various "measurable correlates of consciousness" (MCC), which include Neural Correlates of Consciousness (NCC), Behavioral Correlates of Consciousness (BCC), and Creative Correlates of Consciousness (CCC).

2.5. Qualia as EM substances

Jones (2017, 2019), a coauthor of the current paper, has developed an EM-field theory of qualia. Like other field theories, it attributes qualia and images to neural EM-field patterns (and probably the EM-charged matter emitting the fields). Yet these are not the coded images of computational field theories that are based on information processing. Instead, in his theory images actually reside in conscious, pictorial form within the EM fields of neural maps.[6]

Admittedly, machine learning and deep learning have decoded EEG and fMRI data to infer visual images of faces and other objects (e.g., Nemrodov et al., 2018–*cf.* Lin et al., 2022; Takagi and Nishimoto, 2022).[7] But these data appear to come from the fusiform gyrus whose processing does not (counter to some computationalists) really encode actual facial images. For the inferred faces only partly resemble the actual images.

Moreover, fusiform gyrus does not create images, it just recognizes faces as Aunt Bea, *et cetera*. Injury to this area can harm facial recognition but not the production of facial images. So, the EEG data do not encode conscious images, they encode related nonconscious processes that culminate in consciously recognizing Aunt Bea (lots of visual processing is subliminal like this).

Further, it is unclear what brain mechanism would decode the coded face (like the machine learning did to EEG patterns above). Also, how can actual images pop into existence from coded images that lack color and pictorial form? Strawson (2006) dismissed such emergence as magic. Computationalists end up with three quite different entities–abstract information, concrete EM patterns, and visual images–with unclear relations between each (Jones, 2016).

Nonetheless, field patterns might be eventually found in EEG or fMRI data from areas of the brain that create images instead of interpreting them. But Jones does not think these field patterns will have coded, nonpictorial form. In his view, images are not obscure, elusive *codes* that the brain must somehow decode. They are simply neural EM *substances* laid out in conscious pictorial form in the fields of neural maps (which are the only neural structures having pictorial arrays of color detectors).

Here, "substance" denotes the concrete, fundamental stuff comprising the universe (e.g., EM), whether it is seen as a thing or a process. Note that while Jones's theory treats images as substances, not as computations (i.e., coded information processing), it accepts that brains refine images' depth, constancy, etc. behind the scenes using computations (viewed simply as material interactions, not as abstract multiply realizable relations–§1.5).

This is a neuroelectrical, pure panpsychist theory of mind (NP). The "pure panpsychism" says that everything (not just EM) is comprised purely of consciousness. This partly resembles Strawson's (2016) well-known panpsychism. The "neuroelectrical" refers to how consciousness in molecules, cells, etc. is united to form overall minds by the strong, continuous EM fields localized in ion currents along neuronal circuits (these are not global fields pervading brains, distinguishing this approach form Hunt and Schooler's GRT). Again, images and their color qualia are EM substances laid out in neural maps. NP addresses the hard problem, qualia-integration problem, and qualia coding/correlation problem (see §1.5, §2.1.3) in the following ways.

(1) *The hard problem*: How are qualia metaphysically related to brains and computations? In NP, consciousness and its qualia are the hidden nature of observable matter and energy. We are directly aware of our inner conscious thoughts and feelings. Yet we are just indirectly aware of the observable, external world through reflected light, instruments, sense organs, *et cetera*. The world is thus hidden–its *real* nature is up for grabs. So, for all we know, consciousness may be the real, underlying nature of the external world, beyond how it appears to our senses. Here, consciousness is the world's real, underlying substance (its concrete, fundamental stuff). It occupies space, exerts forces, and is matter-energy's sole constituent. Physicists cannot rationally object to this view, for they describe all particles and fields solely by their observable effects–while NP refers to what particles and fields are in themselves, apart from their observable effects.

NP is arguably clearer than existing mind–body theories because it does not reduce consciousness to the observable events of physics. Also, it is simpler and clearer than computationalist and functionalist views, with their obscure relations between qualia, brains, and computations (which are abstract relations–§1.5). Only consciousness exists in NP, and it is the real, hidden nature of matter-energy. NP's monism also avoids traditional dualism's two different substances with their unclear causal relations. NP may also avoid various other mind–body issues (Jones, 2010, 2016).

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[6] This section represents the views of Jones only.

[7] Nemrodov et al. (2018) use EEG data while Lin et al. (2022) and Takagi and Nishimoto (2022) use fMRI data. But they all have very similar problems.

(2) *The qualia coding/correlation problem*: How do our various qualia arise? Field theories (including Pockett's) have not yet spelt this out. Yet there is now growing evidence that different qualia correlate with different electrically active substances in cellular membranes found in sensory and emotional circuits. These substances are the membranes' ion-channel proteins and associated G-protein-coupled receptors (GPCRs). They detect the presence of hormones and sensory stimuli, then directly or indirectly generate electrical impulses in limbic and sensory circuits. They are thus exceedingly active electrically–both as EM-charged proteins and the EM fields they generate.

For example, the different primary colors correlate with different OPN1 GPCRs,[8] different temperatures correlate with different TRP ion channels, and some different tastes correlate with different T1R and T2R GPCRs.[9] These proteins reside in membrane electrical activity at various levels of the sensory system. There is also evidence that oxytocin and vasopressin receptor proteins correlate with feelings of love (e.g., Busnelli and Chini, 2018).[10,11] Also, estrogen and testosterone receptors correlate with lust (Fisher, 1997), the endorphin receptor correlates with euphoria (e.g., Sprouse-Blum et al., 2010), and the adrenaline receptor correlates with vigilance (e.g., Bayerl and Bosch, 2019). Jones (2019) gives a much longer list of correlations between sensory qualia and proteins, with supporting arguments and citations.

Jones (2019) thus identifies qualia with these proteins. In his view, Figure 2 below is the only existing list of neural correlates for qualia.[12] He argues that neuroplasticity does not threaten this list.[13] His identification of qualia with specific proteins is partly testable, for it predicts that the qualia-protein correlations in Figure 2 are not flukes and will continue expanding to eventually include all qualia.

Returning to color qualia and visual images, they may reside in the resonating EM fields of opsin proteins (and in a fundamental way, not in a problematic emergent way).[14] These opsins may thus form the labeled lines for colors, while cross-line comparisons modulate which lines are most active. (For example, we see blue when long-wavelength lines are activated and when opponent cells inhibit the other two opsin lines–all in line with existing theories of perception.) In contrast, other field theories have not yet been able to specify field patterns that encode qualia.

(3) *The qualia-integration problem*: First, how do various qualia unify together into an overall whole? Second, how specifically do qualia join point by point to form pictorial images?

First, neuron-based theories have trouble explaining this *unity*, while field-based theories excel here. In NP's field theory, active circuits create a continuous EM field between neurons that pools their separate, atomized consciousness. This creates a unified conscious mind along brain circuits (with the mind itself residing in the field and perhaps in the charged matter creating the field). This unity is strongest around the diffuse ion currents that run along (and even between) neuronal circuits. It is very strong among well-aligned cortical cells that fire together coherently. Yet this field degrades exponentially with distance, which can explain why consciousness is not united between brains and why minds are private. Even within each brain, the field is at times too weak to fully unify consciousness, leaving much brain activity merely subliminal.

Evidence that unified cognition comes from EM takes three forms. (A), no other mechanisms seem to explain the mind's unity (§1.3). (B),

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[8] Cone cells contain OPN1 proteins that are GPCRs of the opsin class. Light-absorbing molecules attached to these different opsins have different spatial conformations that detect different light wavelengths. This starts cascades of reactions, mediated by transducin molecules, which (via inward currents) hyperpolarize the cells. Depolarization quickly follows. The opsins are flooded by these strong ion currents that they trigger. It is possible here that colors may be determined not only by opsins but also by adjacent active proteins that they strongly interact with (see Jones, 2019). But the details are unclear, so this paper sticks to what seems relatively clear at present–the color-opsin link.

[9] https://www.genecards.org/

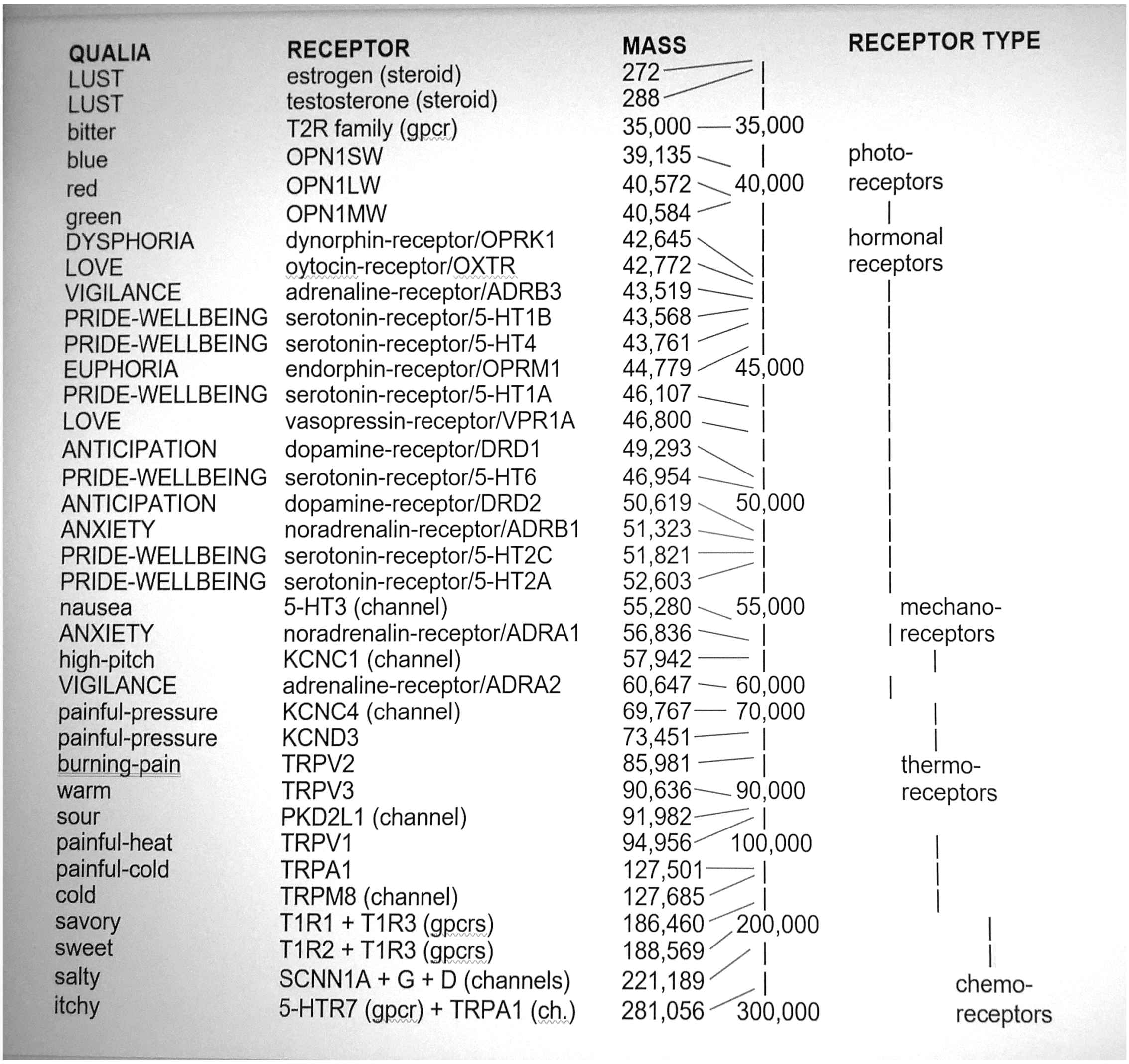
[10] The recent discovery that genetically altered prairie voles who lack oxytocin can still pair bond normally (Berendzen et al., 2023) shows that pair bonding does not require oxytocin. But this does not threaten Jones' claim that love requires oxytocin. Indeed, the authors argue that these altered voles may well have compensated for their lack of oxytocin by activating vasopression pathways to preserve the feeling of love and pair-bonding behavior.

[11] It may seem simplistic to attribute the vast complexities of love to the simple oxytocin molecule. But keep in mind that feelings of love are tinged with other emotions with different hormonal sources, such as joy, lust, jealousy, and anguish. Also, equating love and oxytocin is only meant to account for the innate emotional feeling (sheen) of love experiences, not the crucial conceptual components of love experiences, which are highly complex and learned.

[12] In this list, several proteins might conceivably be the same blue color. Yet one protein cannot be both blue and red. For the qualia correlations pertain only to primary qualia, which means a protein can be red or blue, but not a purple blend. Since a protein can thus only be a single quale, there's still genuine selectivity to qualia/protein correlations.

[13] It might be argued that neuroplasticity threatens this account of qualia. For example, if visual cortex is recruited for somatosensory processing by blind subjects, and these cortical detectors are stimulated, then subjects report somatic qualia (Ptito et al., 2008). This threatens Jones' claim that visual-detector proteins correlate with visual qualia. In reply, his view is not threatened if neurogenesis and plasticity yield not only new detector synapses, but also new detector GPCRs and channels. Many somatosensory GPCRs and channels already exist in occipital and parietal lobes (Su et al., 2004), so neurogenesis of more of them would hardly be surprising.

[14] What exactly is it about these opsins that gives them their different colors? (a) Arguably, it is their different molecular structures (electrical bonding structures). But this makes colors emergent. Blue would magically pop into existence from what lacked blue as trichromatic vision evolved at molecular levels (recall §2.3.1) So, these structures do not appear in Figure 2 below, which lists known correlates of qualia. (b) Opsins could instead get their colors from the different resonances of these proteins and their EM fields. These resonances might be construed as fundamental instead of emergent due to the fundamental energy levels they bear. But these resonances are presently unknown and thus do not appear in Figure 2 below. (c) What gives opsins their colors could also be these proteins' different masses (m)–and thus their rest energies (mc^2). In this case, the whole range of our qualia would reside like a rainbow in the range of these protein rest energies (in nature at large, this rainbow might repeat across many orders of magnitudes of rest energies in electrically bound masses, see Jones, 2019). These options all align with NP's view that qualia are fundamental substances (*cf.* Keppler and Shani above).



QUALIA	RECEPTOR	MASS		RECEPTOR TYPE
LUST	estrogen (steroid)	272		
LUST	testosterone (steroid)	288		
bitter	T2R family (gpcr)	35,000	35,000	
blue	OPN1SW	39,135		photo-
red	OPN1LW	40,572	40,000	receptors
green	OPN1MW	40,584		
DYSPHORIA	dynorphin-receptor/OPRK1	42,645		hormonal
LOVE	oytocin-receptor/OXTR	42,772		receptors
VIGILANCE	adrenaline-receptor/ADRB3	43,519		
PRIDE-WELLBEING	serotonin-receptor/5-HT1B	43,568		
PRIDE-WELLBEING	serotonin-receptor/5-HT4	43,761		
EUPHORIA	endorphin-receptor/OPRM1	44,779	45,000	
PRIDE-WELLBEING	serotonin-receptor/5-HT1A	46,107		
LOVE	vasopressin-receptor/VPR1A	46,800		
ANTICIPATION	dopamine-receptor/DRD1	49,293		
PRIDE-WELLBEING	serotonin-receptor/5-HT6	46,954		
ANTICIPATION	dopamine-receptor/DRD2	50,619	50,000	
ANXIETY	noradrenalin-receptor/ADRB1	51,323		
PRIDE-WELLBEING	serotonin-receptor/5-HT2C	51,821		
PRIDE-WELLBEING	serotonin-receptor/5-HT2A	52,603		
nausea	5-HT3 (channel)	55,280	55,000	mechano-
ANXIETY	noradrenalin-receptor/ADRA1	56,836		receptors
high-pitch	KCNC1 (channel)	57,942		
VIGILANCE	adrenaline-receptor/ADRA2	60,647	60,000	
painful-pressure	KCNC4 (channel)	69,767	70,000	
painful-pressure	KCND3	73,451		
burning-pain	TRPV2	85,981		thermo-
warm	TRPV3	90,636	90,000	receptors
sour	PKD2L1 (channel)	91,982		
painful-heat	TRPV1	94,956	100,000	
painful-cold	TRPA1	127,501		
cold	TRPM8 (channel)	127,685		
savory	T1R1 + T1R3 (gpcrs)	186,460	200,000	
sweet	T1R2 + T1R3 (gpcrs)	188,569		
salty	SCNN1A + G + D (channels)	221,189		chemo-
itchy	5-HTR7 (gpcr) + TRPA1 (ch.)	281,056	300,000	receptors

FIGURE 2
Protein Correlates of Sensory and Emotional Qualia: Molecular biology is finding growing evidence that neural proteins correlate with our qualia. Column 1 lists sensory and emotional qualia in lowercase and uppercase, respectively. Column 2 lists the correlating proteins–usually ion channels or GPCRS that detect sensory stimuli or act as hormone receptors–all in electrically active ways. Column 3 lists (at a more fundamental level) the proteins' masses (in Dalton units). This column 3 shows that each of these electrically bound proteins has a distinctive mass–and thus distinctive rest energy (which Jones, 2019 construes as the protein's fundamental substance). While some masses (m) are fairly close, their rest energies (mc^2) lie exponentially far apart. Finally, note that some qualia correlate with more than one mass (which is unsurprising because these qualia likely reside like repeating rainbows in the range of electrically bound masses in nature). Yet each mass correlates (crucially) with a different quality. This figure comes largely from papers and directories (e.g., genecards.org/) cited in Jones (2019). Evidence for the emotional qualia is sometimes less conclusive than with the sensory qualia.

Koch et al. (2016) argue that locally activated EEGs actually track conscious perceptions across brains better than other events, such as neuronal firing synchrony or P300 events. This EEG evidence links perceptions (i.e., unified sensory experiences) to local neuroelectrical fields. (C), EM fields–rather than just particles or synapses–propagate signals across slices in hippocampal tissue (Chiang et al., 2019; *cf.* Libet, 1993). This indicates that it is most likely the fields that unify this activity.

Second, neuron-based theories, as discussed above, also have trouble explaining how we see overall *pictorial images*. For we lack top-level detectors to encode all the possible scenes comprising our pictorial images. Some field-based theories have trouble here too. Their difficulty is in showing how EM fields (which lack the specificity of neuronal connections–except, as discussed above with respect to Hunt and Schooler's GRT–through selective resonance) can systematically attribute colors point by point all across images. As Pockett's account illustrates, it is difficult to distinguish color and spatial information in fields. Jones suggests that no EM-field patterns have yet been found that actually encode the creation of images (versus associated events such as facial recognition).[15] Nor is it clear how to get from these codes to the actual conscious images.

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[15] Hunt does not agree that EM field patterns do not encode images, due to a number of published studies illustrating how machine learning AI has successfully decoded various images and other qualia from EEG and fMRI signals (Nemrodov et al., 2018; Lin et al., 2022).

In NP, images are not obscure, complicated coded activities. Instead, they are simply arrays of electrically active detectors laid out in pictorial form across neural maps. All the intense electrical activity of these maps is fully conscious–from retinas to the thalamocortical areas that they tie into.[16] Their images are not separate, for their systematic electrical connections bind them point by point into a single unified conscious whole.[17]

Retinal opsins and cones feed into numerous V1 color processors (blobs), which in turn activate V4 color processors and flood their opsins with currents. This helps V1 to create detailed colors, V4 to create color constancy, and retinas to create images' pictorial form and overall elliptical shape at their peripheries. Damage to V4 blocks colors from accessing higher cortical levels that support the overall unified mind with its controlling subject. So, color blindness results.

NP might ultimately attribute pictorial images to the standing waves in retinas and other neural maps that connect to them (*cf.* Lehar, 2003). These waves are like the patterns of ripples across fluid surfaces in vibrating containers. They are standing in that they are created by stable map structures. The spatial layouts of retinal standing waves would come from arrays of cone activity. This would provide the pictorial layouts of images. Different colors would be different local field perturbations generated by the EM dynamics of each opsin folding and unfolding–and the intense, oscillating ion currents this unleashed.

In summary, computational field theories have not yet shown how to encode the colors and pictorial form of images, and they are unclear about how to get from any such codes to conscious images. NP treats images not as neural codes but as neural substances–the pictorial standing waves of neural maps, beyond how they appear to EEGs. This theory is partly testable.

So, NP ends up differing from many other EM-field theories of qualia. Everything is conscious in NP, not just EM fields. Also, minds are unified by local EM fields right around neural circuits, not by global fields pervading brains. Nor are qualia encoded in field patterns, instead they are laid out in pictorial form across EM fields. Finally, qualia are not emergent from, nor intrinsic to EM, but are the real nature of EM beyond how it appears EEGs. NP is perhaps closest to the GRT of Hunt and Schooler. above, especially when it comes to GRT's account of the multi-scale EM fields associated with brains as the primary seat of consciousness, with the brain as a relatively stable underlying neuroanatomical backbone supporting conscious EM fields. GRT supporters might not agree with NP's attempt to extend GRT's approach to qualia. In the end, NP arguably mixes neuronal and field approaches to qualia, for qualia and images reside in the neural EM field, and perhaps also in the charged neuronal matter that generates this field.

NP's drawbacks are its conflicts with other field theories. Jones thinks these differences are justified, but other field theorists often disagree. Especially contentious are NP's pure panpsychism, its local fields, its anti-computationalism, and its claim that all qualia correlate with neural proteins.

3. Conclusion

Consciousness is characterized mainly by its privately experienced qualities (qualia). Standard, computation-based and synapse-based neuroscience have serious difficulties explaining them. Key commonalities between consciousness and EM fields led us to review EM-field theories of qualia to see if they can improve upon standard neuroscience's approaches to three crucial issues. (1) What neural events encode or correlate with the various qualia? (2) How do neural events integrate qualia to form (for example) pictorial images? (3) Are neural events metaphysically related to qualia by identity, causality, third entities–or some other relation? We call these the qualia coding/correlation problem, the qualia-integration problem, and the hard problem, respectively.

(1) Field theories usually look for different field patterns that encode or correlate with different qualia. But they have not yet established that such patterns exist. Nor do they agree on whether to construe these patterns as *codes* (information processing) or as *substances* (physical stuff). One option is to continue looking for patterns that encode qualia. For example, Nemrodov et al. (2018) argue that EEG studies of face processing in brains show the "rich informational content of spatiotemporal EEG patterns." Another, less recognized option (suggested in Jones's work) is to look for correlations between qualia and certain EM substances, such as the vibrating fields (and charges) of certain proteins (e.g., colors seem to correlate with the EM activity of wavelength detectors–opsins). It is presently unclear whether these options will improve upon standard neuroscience.

(2) Field theories have arguably made real progress in explaining how fields integrate colors to form unified pictorial images. This unity comes not from field codes, but from the continuous extension of EM fields across space. This extension allows neurally-associated EM fields at various spatiotemporal scales to pool qualia together to create a single, unified consciousness. But field theories must make more progress in explaining how fields integrate qualia, such as colors, point by point across space to make (in this example) pictorial images. One option is to continue looking for how field patterns encode spatial arrays. Another is to look for pictorial standing EM waves (like those in the fluid surfaces of vibrating containers) in neural maps rooted in retinas. Here, images are the substances of EM activity in pictorially arranged visual detectors.

(3) Field theories are in the same situation as standard theories concerning the hard problem of whether neural events are metaphysically related to qualia by identity, causality, or some other relation. But field theories do employ fairly recent metaphysics (such as Whitehead's, Strawson's, Shani's, and McFadden's) that can protect

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[16] There is evidence that colors do not exist just at cortical levels. Mancuso et al. (2009) injected genes for long-wavelength cones into monkey retinas that had only short and medium-wavelength cones (and associated opsins). The retinas rapidly grew long-wavelength cones, enabling the monkeys to discern color trichromatically. The rapid growth indicates that no cortical rewiring was involved, the authors argue. Also, Neitz and Neitz (2014) argue that retinal opponent cells actually disambiguate cone inputs, thus giving retinas the ability to create accurate color percepts.

[17] In contrast to these sensory images, the pictorial form of mental images likely comes from the undistorted visual arrays of grid and place cells in the entorhinal cortex and hippocampus. They help in imagining and navigating scenes.

them from traditional mind–body problems. GRT and NP, for example, both suggest that an intrinsic property, or the true nature, of EM fields is qualia/conscious experience.

So, field theories have improved in key ways upon standard neuroscience in explaining qualia. But this progress is sometimes tentative–it awaits further evidence and development.[18]

Author contributions

MJ wrote the draft. TH provided numerous rounds of revisions and feedback. All authors contributed to the article and approved the submitted version.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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[18] EM approaches may also help explain higher cognition. For example, Hunt and Jones' "Where is consciousness" (under review) argues that higher cognition and consciousness rely on coherent EM field activities of various frequencies that perform various tasks. Additionally, Jones's "A simple, testable, mind–body theory" (under review) gives evidence that neuroelectrical activity generates qualia, binds them into the unified experiences, helps focus attention and guide cognitive activity and metacognition, and helps form the mind's subject (controlling center).

References

Aaronson, S. (2014). *Why I am not an integrated information theorist*. Available from: http://www.scottaaronson.com/blog/?p=1799 (Accessed December 1, 2014).

Adrian, E. D. (1928). *The basis of sensation*. New York: W.W. Norton & Co.

Bandyopadhyay, A. (2019). *Resonance chains and new models of the neuron*. Available at: https://medium.com/@aramis720/resonance-chains-and-new-models-of-the-neuron-7dd82a5a7c3a (Accessed June 15, 2019).

Bayerl, D., and Bosch, O. (2019). (2019) brain vasopressin signaling modulates aspects of maternal behavior in lactating rats. *Genes Brain Behav.* 18:e12517. doi: 10.1111/gbb.12517

Berendzen, K. M., Sharma, R., Mandujano, M. A., Wei, Y., Rogers, F. D., Simmons, T. C., et al. (2023). Oxytocin receptor is not required for social attachment in prairie voles. *Neuron* 111, 787–796.e4. doi: 10.1016/j.neuron.2022.12.011

Beshkar, M. (2020). The QBIT theory of consciousness. *Integr. Psychol. Behav. Sci.* 54, 752–770. doi: 10.1007/s12124-020-09528-1

Bond, E. (2023). The contribution of coherence field theory to a model of consciousness: electric currents, EM fields, and EM radiation in the brain. *Front. Hum. Neurosci.* 16:1020105. doi: 10.3389/fnhum.2022.1020105

Busnelli, M., and Chini, B. (2018). (2017) molecular basis of oxytocin receptor signalling in the brain: what we know and what we need to know. *Curr. Top. Behav. Neurosci.* 35, 3–29. doi: 10.1007/7854_2017_6

Chalmers, D. (1996). *The Conscious Mind*. Oxford: Oxford University Press.

Chalmers, D. J. (2017). "The combination problem in panpsychism" in *Panpsychism: Contemporary perspectives*. eds. G. Bruüntrup and L. Jaskolla (New York: Oxford University Press)

Chiang, C., Shivacharan, R., Wei, X., Gonzalez-Reyes, L., and Durand, D. (2019). Slow periodic activity in the longitudinal hippocampal slice can self–propagate non-synaptically by a mechanism consistent with ephaptic coupling. *J. Physiol.* 597, 249–269. doi: 10.1113/JP276904

Churchland, P. (1986). Some reductive strategies in cognitive neurobiology. *Mind* 95, 279–309. doi: 10.1093/mind/XCV.379.279

Churchland, P. (2014) *Touching a nerve*. Norton (New York, London).

Conway, B. (2009). Color vision, cones, and color-coding in the cortex. *Rev. Neurosci.* 15, 274–290. doi: 10.1177/1073858408331369

Crick, F. (1984). Function of the thalamic reticular complex: the searchlight hypothesis. *Proc. Natl. Acad. Sci.* 81, 4586–4590. doi: 10.1073/pnas.81.14.4586

Crick, F., and Koch, C. (1990). Towards a neurobiological theory of consciousness. *Semin. Neurosci.* 2, 263–275.

Da Rocha, F., Pereira, A., and Coutinho, B. (2001). N-methyl-D-aspartate channel and consciousness: from signal coincidence detection to quantum computing. *Prog. Neurobiol.* 64, 555–573. doi: 10.1016/S0301-0082(00)00069-1

Dehaene, S. (2014). *Consciousness and the brain: Deciphering how the brain codes our thoughts*. New York: Viking (The Penguin Group).

Dehaene, S., Changeux, J. P., Naccache, L., Sackur, J., and Sergent, C. (2006). Conscious, preconscious, and subliminal processing: a testable taxonomy. *Trends Cogn. Sci.* 10, 204–211. doi: 10.1016/j.tics.2006.03.007

Dehaene, S., and Naccache, L. (2001). Towards a cognitive neuroscience of consciousness: basic evidence and a workspace framework. *Cognition* 79, 1–37. doi: 10.1016/S0010-0277(00)00123-2

Dong, Y., Mihalas, S., Qiu, F., von der Heydt, R., and Niebur, E. (2008). Synchrony and the binding problem in macaque visual cortex. *J. Vision* 8, 1–16.

Edelman, G., and Tononi, G. (2000). *A universe of consciousness.* New York: Basic Books.

Fingelkurts, A. A., Fingelkurts, A. A., and Neves, C. (2010). Natural world physical, brain operational, and mind phenomenal space-time. *Phys Life Rev* 7, 195–249. doi: 10.1016/j.plrev.2010.04.001

Fingelkurts, A. A., Fingelkurts, A. A., and Neves, C. (2013). Consciousness as a phenomenon in the operational architectonics of brain organization: criticality and self-organization considerations. *Chaos, Solitons Fractals* 55, 13–31. doi: 10.1016/j.chaos.2013.02.007

Fisher, H. (1997). Lust, attraction, and attachment in mammalian reproduction. *Hum. Nat.* 9, 23–52. doi: 10.1007/s12110-998-1010-5

Freeman, W. (1991). The physiology of perception. *Sci. Am.* 264, 78–85. doi: 10.1038/scientificamerican0291-78

Georgiev, D., Papaioanou, S., and Glazebrook, J. (2007). Solitonic effects of the local electromagnetic field on neuronal microtubules. *NeuroQuantology* 5, 276–291. doi: 10.14704/nq.2007.5.3.137

Goff, P. (2017). *Consciousness and fundamental reality*. Oxford, UK: Oxford University Press.

Gray, C., König, P., Engel, A., and Singer, W. (1989). Oscillatory responses in cat visual cortex exhibit inter-columnar synchronization which reflects global stimulus properties. *Nature* 338, 334–337. doi: 10.1038/338334a0

Hagan, S., Hameroff, S., and Tuszyński, J. (2002). Quantum computation in brain microtubules: Decoherence and biological feasibility. *Phys. Rev.* 65:061901.

Hales, C. (2014). The origins of the brain's endogenous electromagnetic field and its relationship to provision of consciousness. *J. Integr. Neurosci.* 13, 313–361. doi: 10.1142/S0219635214400056

Hales, C., and Ericson, M. (2022). Electromagnetism's bridge across the explanatory gap: How a neuroscience/physics collaboration delivers explanation into all theories of consciousness. *Front. Hum. Neurosci.* 16:836046. doi: 10.3389/fnhum.2022.836046

Hameroff, S., and Penrose, R. (1996). Conscious events as orchestrated spacetime selections. *J. Conscious. Stud.* 3, 36–53.

Haugeland, J. (1985). *Artificial Intelligence: The Very Idea*. Cambridge: MIT Press.

Humphries, P. J. (2020). *The spike: Journey through the brain in a millionth of a second*. Princeton, NJ: Princeton University Press.

Hunt, T. (2011). Kicking the psychophysical Laws into gear a new approach to the combination problem. *J. Conscious. Stud.* 18, 11–12.

Hunt, T. (2014) *Eco, Ego, Eros: Essays on philosophy, spirituality and science*. Santa Barbara: Aramis Press.

Hunt, T. (2020a). *The feeling of life itself. Medium*. Available at: https://tamhunt.medium.com/the-feeling-of-life-itself-7747eed82944 (Accessed March 26, 2023).

Hunt, T. (2020b). Calculating the boundaries of consciousness in general resonance theory. *J. Conscious. Stud.* 27, 55–80.

Hunt, T., Ericson, M., and School, J. W. (2022). Where's my consciousness-Ometer? How to test for the presence and complexity of consciousness. *Perspect. Psychol. Sci.* doi: 10.1177/17456916211029942

Hunt, T., and Schooler, J. (2019). The "easy part" of the hard problem: a resonance theory of consciousness. *Authorea* 2019:7989. doi: 10.22541/au.154659223.37007989

John, E. R. (2001). A field theory of consciousness. *Conscious. Cogn.* 10, 184–213. doi: 10.1006/ccog.2001.0508

Jones, M. (2010). How to make mind–brain relations clear. *J. Conscious. Stud.* 17, 135–160.

Jones, M. (2013). Electromagnetic-field theories of mind. *J. Conscious. Stud.* 20, 124–149.

Jones, M. (2016). Avoiding perennial mind-body problems. *J. Conscious. Stud.* 23, 111–133.

Jones, M. (2017). Mounting evidence that minds are neural EM fields interacting with brains. *J. Conscious. Stud.* 24, 159–183.

Jones, M. (2019). Growing evidence that perceptual qualia are Neuroelectrical not computational. *J. Conscious. Stud.* 26, 89–116.

Jones, M., and LaRock, E. (2019). How subjects can emerge from neurons. *Process. Stud.* 48, 40–58. doi: 10.5406/processstudies.48.1.0040

Kawato, M. (1997). "Bi-directional theory approach to consciousness Bi-directional theory approach to consciousness," in *Cognition, Computation, and Consciousness*. eds. M. Ito, Y. Miyashita and E. Rolls (Oxford: Oxford University Press).

Keppler, J. (2016). On the universal mechanism underlying conscious systems and the foundations for a theory of consciousness open. *J. Philos.* 6, 346–367. doi: 10.4236/ojpp.2016.64034

Keppler, J. (2021). Building blocks for the development of a self-consistent electromagnetic field theory of consciousness. *Front. Hum. Neurosci.* 15:723415. doi: 10.3389/fnhum.2021.723415

Keppler, J., and Shani, I. (2020). Cosmopsychism and consciousness research: a fresh view on thecausal mechanisms underlying phenomenal states. *Front. Psychol.* 11:371. doi: 10.3389/fpsyg.2020.00371

Koch, C. (2019). *The feeling of life itself*. MIT Press, Cambridge, MA.

Koch, C., Massimini, M., Boly, M., and Tononi, G. (2016). Neural correlates of consciousness: progress and problems. *Nat. Rev. Neurosci.* 17, 307–321. doi: 10.1038/nrn.2016.22

Lamme, V. (2004). Separate neural definitions of visual consciousness and visual attention; a case for phenomenal awareness. *Neural Networks* 17, 861–872.

Lamme, V., and Roelfsema, P. (2000). The distinct modes of vision offered by feedforward and recurrent processing. *Trends Neurosci.* 23, 571–579. doi: 10.1016/S0166-2236(00)01657-X

Larkum, M. (2012). A cellular mechanism for cortical associations: an organizing principle for the cerebral cortex. *Trends in Neurosciences* 36, 141–151.

LaRock, E. (2006). Why neural synchrony fails to explain the Unity of visual consciousness. *Behav. Philos.* 34, 39–58.

LaRock, E. (2007). Disambiguation, binding, and the Unity of visual consciousness. *Theory Psychol.* 17, 747–777. doi: 10.1177/0959354307083492

Laurent, G., Wehr, M., and Davidowitz, H. (1996). Temporal representations of odors in an olfactory net- work. *J. Neurosci.* 16, 3837–3847. doi: 10.1523/JNEUROSCI.16-12-03837.1996

Le Chang, S., and Tsao, D. (2017). The code for facial identity in the primate brain. *Cells* 169, 1013–1028. doi: 10.1016/j.cell.2017.05.011

Lehar, S. (2003). *The world in your head: A mechanism of conscious experience*. Mahwah, NJ: Lawrence Erlbaum Associates.

Levine, J. (1993). "On leaving out what it is like" in *Consciousness*. ed. M. Davies (Oxford: Blackwell)

Lewtas, P. (2017). Building minds: solving the combination problem. *Inquiry* 60, 742–781. doi: 10.1080/0020174X.2016.1216464

Libet, B. (1993). *Neurophysiology of consciousness*. Boston, MA: Birkhauser.

Lin, S., Sprague, T., and Singh, A. (2022). Mind reader: reconstructing complex images from brain activities. *Adv. Neural Inf. Proces. Syst.* 9:1769

Lovheim, H. (2012). A new three-dimensional model for emotions and monoamine neurotransmitters. *Med. Hypotheses* 78, 341–348. doi: 10.1016/j.mehy.2011.11.016

Mancuso, K., Hauswirth, W. W., Li, Q., Connor, T. B., Kuchenbecker, J. A., Mauck, M. C., et al. (2009). Gene therapy for red–green colour blindness in adult primates. *Nature* 461, 784–787. doi: 10.1038/nature08401

McFadden, J. (2002a). Synchronous firing and its influence of the brain's electromagnetic field. *J. Conscious. Stud.* 9, 23–50.

McFadden, J. (2002b). The conscious electromagnetic information field theory. *J. Conscious. Stud.* 9, 45–60.

McFadden, J. (2006). "The CEMI field theory" in *The Emerging Physics of Consciousness*. ed. J. Tuszynski (Berlin: Springer)

McFadden, J. (2020). Integrating information in the brain's EM field: the cemi field theory of consciousness. *Neurosci. Conscious.* 2020:niaa016. doi: 10.1093/nc/niaa016

Muller, J. (1835). *Handbuch der Physiologie des Menschen für Vorlesungen*, *2nd Edn*. Coblenz: Hölscher

Mumford, D. (1991). On the computational architecture of the neocortex. *Biol. Cybern.* 65, 135–145. doi: 10.1007/BF00202389

Nagel, T. (1974). What is it like to be a bat? *Philos. Rev.* 83, 435–456. doi: 10.2307/2183914

Neitz, M., and Neitz, J. (2014). Curing color blindness–mice and nonhuman Primates. *Cold Spring Harb. Perspect. Med.* 4:a017418. doi: 10.1101/cshperspect.a017418

Nemrodov, D., Niemeier, M., Patel, A., and Nestor, A. (2018). The neural dynamics of facial identity processing: insights from EEG-based pattern analysis and image reconstruction. *eNeuro* 5:e0358. doi: 10.1523/ENEURO.0358-17.2018

Parker, D. (2019). Color perception. SAGE publications. Young, T. (1802). II. The Bakerian lecture. On the theory of light and colors. *Philos. Trans. R. Soc. Lond.* 92, 12–48.

Pockett, S. (2000) *The nature of consciousness: A hypothesis*. New York: Writers Club Press.

Pockett, S. (2011). Initiation of intentional actions and the electrowmagnetic field theory of consciousness. *Humanamente* 15, 150–175.

Pockett, S. (2012). The electromagnetic field theory of consciousness: a testable hypothesis about the characteristics of conscious as opposed to nonconscious fields. *J. Conscious. Stud.* 19, 191–223.

Ptito, M., Schneider, F., Paulson, O., and Kupers, R. (2008). Alterations of the visual pathways in congenital blindness. *Exp. Brain Res.* 187, 41–4910. doi: 10.1007/s00221-008-1273-4

Purves, D., Augustine, G. J., Fitzpatrick, D., Katz, L. C., LaMantia, A. S., McNamara, J. O., et al. (2001). *Neural coding in the taste system, in neuroscience. 2nd Edn*. Sunderland, MA: Sinauer Associates.

Putnam, H. (1967). "The nature of mental states" in *Art, Mind, And Religion*. eds. W. Capitan and D. Merrill (Pittsburgh: University of Pittsburgh Press)

Rescorla, M. (2015). The computational theory of mind. *The Stanford encyclopedia of philosophy*. Available at: http://plato.stanford.edu/archives/win2015/entries/computational-mind/.

Roelfsema, P., Engel, A., Konig, P., and Singer, W. (1997). Visuomotor integration is associated with zero time-lag synchronization among cortical areas. *Nature* 385, 157–161. doi: 10.1038/385157a0

Rosenthal, D. M. (2005). *Consciousness and mind*. New York: Oxford University Press.

Schooler, J. W., Hunt, T., and Schooler, J. N. (2011). "Reconsidering the metaphysics of science from the inside out," in *Neuroscience, consciousness and spirituality*. eds. H. Walach, S. Schmidt and W. B. Jonas (Springer), 157–194.

Shani, I., and Keppler, J. (2018). Beyond combination: how cosmic consciousness grounds ordinary experience. *J. Am. Philos. Assoc.* 4, 390–410. doi: 10.1017/apa.2018.30

Solomon, S., and Lennie, P. (2007). The machinery of colour vision. *Nat. Rev. Neurosci.* 8, 276–286. doi: 10.1038/nrn2094

Sprouse-Blum, A., Smith, G., Sugai, D., and Parsa, D. (2010). Understanding endorphins and their importance in pain management. *Hawaii Med. J.* 69, 70–71.

Stewart, W., Kauer, J. S., and Shepherd, G. M. (1979). Functional organization of rat olfactory bulb analysed by the 2-deoxyglucose method. *J. Comp. Neurol.* 185, 715–734. doi: 10.1002/cne.901850407

Strawson, G. (2006). Realistic monism. *J. Conscious. Stud.* 13, 3–31.

Strawson, G. (2016). "Mind and being: the primacy of panpsychism" in *Panpsychism: Philosophical essays*. eds. G. Bruntrup and L. Jaskolla (Oxford: Oxford University Press)

Su, A., Wiltshire, T., Batalov, S., Lapp, H., Ching, K. A., Block, D., et al. (2004). A gene atlas of the mouse and human protein-encoding transcriptomes. *Proc. Natl. Acad. Sci. U. S. A.* 101, 6062–6067. doi: 10.1073/pnas.0400782101

Takagi, Y., and Nishimoto, S. (2022). High-resolution image reconstruction with latent diffusion models from human brain activity. *bioRxiv* 2022:517004. doi: 10.1101/2022.11.18.517004

Thiele, A., and Stoner, G. (2003). Neuronal synchrony does not correlate with motion coherence in cortical area MT. *Nature* 421, 366–370.

Tomkins, S. S. (1981). The role of facial response in the experience of emotion: a reply to Tourangeau and Ellsworth. *J. Pers. Soc. Psychol.* 40, 355–357. doi: 10.1037/0022-3514.40.2.355

Tononi, G. (2008). Consciousness as integrated information: a provisional manifesto. *Biol. Bull.* 215, 216–242. doi: 10.2307/25470707

Treisman, A. (1998). Feature binding, attention and object perception. *Philos. Trans. R. Soc. f London B Biol. Sci.* 353, 1295–1306. doi: 10.1098/rstb.1998.0284

Turausky, K. (n.d.). *Picturing panpsychism: new approaches to the combination problem.* (Unpublished manuscript).

Van der Velde, F., and de Kamps, M. (2006). Neural blackboard architectures of combinatorial structures in cognition. *Behav. Brain Sci.* 29, 37–70. doi: 10.1017/S0140525X06009022

Walleczek, J. (2000). *Self-organized biological dynamics and nonlinear control toward understanding complexity, chaos, and emergent function in living systems*. Cambridge: Cambridge University Press.

Ward, L., and Guevara, R. (2022). Qualia and phenomenal consciousness Arise from the information structure of an electromagnetic field in the brain. *Front. Hum. Neurosci.* 16:874241. doi: 10.3389/fnhum.2022.874241

Ward, W. (2011). The thalamic dynamic core theory of conscious experience. *Conscious. Cogn.* 20, 464–486.

Whitehead, A. N., Griffin, D. R., and Sherburne, D. W. (1929). *Process and reality: An essay in cosmology*. New York: Free Press.

Zeki, S. (2003). The disunity of consciousness. *Trends Cogn. Sci.* 7, 214–218. doi: 10.1016/S1364-6613(03)00081-0

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Consciousness and its hard problems: separating the ontological from the evolutionary

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Few of the many theories devised to account for consciousness are explicit about the role they ascribe to evolution, and a significant fraction, by their silence on the subject, treat evolutionary processes as being, in effect, irrelevant. This is a problem for biological realists trying to assess the applicability of competing theories of consciousness to taxa other than our own, and across evolutionary time. Here, as an aid to investigating such questions, a consciousness "machine" is employed as conceptual device for thinking about the different ways ontology and evolution contribute to the emergence of a consciousness composed of distinguishable contents. A key issue is the nature of the evolutionary innovations required for any kind of consciousness to exist, specifically whether this is due to the underappreciated properties of electromagnetic (EM) field effects, as in neurophysical theories, or, for theories where there is no such requirement, including computational and some higher-order theories (here, as a class, algorithmic theories), neural connectivity and the pattern of information flow that connectivity encodes are considered a sufficient explanation for consciousness. In addition, for consciousness to evolve in a non-random way, there must be a link between emerging consciousness and behavior. For the neurophysical case, an EM field-based scenario shows that distinct contents can be produced in the absence of an ability to consciously control action, i.e., without agency. This begs the question of how agency is acquired, which from this analysis would appear to be less of an evolutionary question than a developmental one. Recasting the problem in developmental terms highlights the importance of real-time feedback mechanisms for transferring agency from evolution to the individual, the implication being, for a significant subset of theories, that agency requires a learning process repeated once in each generation. For that subset of theories the question of how an evolved consciousness can exist will then have two components, of accounting for conscious experience as a phenomenon on the one hand, and agency on the other. This reduces one large problem to two, simplifying the task of investigation and providing what may prove an easier route toward their solution.

KEYWORDS

EM fields, theories of consciousness, the self, agency, mental causation, order from fluctuations

1. Introduction

There is no shortage of theories as to the nature and origin of consciousness (Atkinson et al., 2000; Van Gulick, 2018; Seth and Bayne, 2022). Few, however, whether philosophical, psychological or computational in their focus and assumptions, explore the role played by evolution in a thorough and systematic way. Yet evolution is an essential component of explaining biological innovations of any kind, in that, as expressed by Dobzhansky (1973), "nothing makes sense in biology except in light of evolution." Perhaps consciousness will prove to be unique in this respect, and ultimately explainable without reference to evolutionary processes (Rosenthal, 2008), but there is good reason, based on past experience, to doubt this until it can be convincingly demonstrated. This is certainly the case for anyone adopting biological realism as a stance (Revonsuo, 2018), because any comprehensive theory must address the problem of how consciousness will have changed over time. This makes a consideration of evolution unavoidable, especially so for those interested in the distribution of consciousness in taxa other than our own, a topic currently attracting increasing attention (Fabbro et al., 2015; Irwin, 2020).

It would be easier to assess the claims of competing theories of consciousness, as to what they do and do not require of evolution and evolutionary processes, if we had a conceptual framework that could be applied across theories. To this end, and to provide a point of reference for the analysis that follows, I introduce here a consciousness machine that can be reconfigured to accommodate different categories of theory. I begin by considering its applicability to what I will refer to as neurophysical theories, defined here as those where innovation at the neurocircuitry level has enabled neurons to manipulate some aspect of physical reality so as to produce conscious sensations. This is equivalent to neuroscientific stance (Winters, 2021) and dependence on some aspect of "the physical" (Godfrey-Smith, 2019), generally attributed to the action of electromagnetic (EM) fields and the like (Kitchener and Hales, 2022). There are various arguments to be made as to why, in principle, EM field theory should be central to any explanation of consciousness (e.g., see Hales and Ericson, 2022), but my intent in this paper is a more limited one, of illustrating the utility of a neurophysical stance when it comes to thinking about the evolutionary origins of consciousness. The alternative, of adopting a non-neurophysical stance, means attributing consciousness to the connectivity of neural circuits in and of itself, irrespective of any physical consequences of activating those circuits beyond the processes their connectivity sets in motion. This would include computational theories of diverse kinds (Sun and Franklin, 2007; Stinson, 2018) along with those classed as process-based, substrate-independent or functionalist (Atkinson et al., 2000; Levin, 2023), including higher-order and other representational theories (Gennaro, 2018; Lycan, 2019). However, since the source of phenomenal experience is not always specified in higher-order theories, proponents of the same theory can differ on whether or not neurophysical inputs are required at the phenomenal level (e.g., see Gennaro, 2018 on representational theories). This complicates the task of assessing those theories from an evolutionary perspective, where accounting for the emergence of subjective experience of any kind is a central concern (Feinberg, 2023), meaning any manifestation of what philosophers would call a first-person perspective, or in other contexts sentience, subjectivity, or phenomenal (or P-) consciousness. Questions relating to the neurophysical basis of higher order functions such as binding (Revonsuo and Newman, 1999; Feldman, 2012), or for solving the combination problem (Hunt and Schooler, 2019), are separate concerns and beyond the scope of this account.

In contrast with the neurophysical stance, theories or variants of theory that either reject neurophysical explanations for phenomenal experience or are agnostic on the issue will be grouped together as algorithmic theories. This necessarily means lumping together theories that are otherwise quite different, and to be clear, the term algorithmic is applied here in its most general sense, to refer to any sequence of events that achieves an end through actions that follow a predetermined set of rules or constraints. Patterns of synaptic connectivity are, by this measure, sufficient constraints, so they function in an algorithmic way irrespective of the formal similarities they may or may not share with computer programs and mathematical procedures. Further, wherever dynamic features such as synaptic plasticity are required, this can be accommodated by having a suitably constructed set of rules. To paraphrase Kitchener and Hales (2022), algorithmic theories in their purest form (here, fully algorithmic theories) rest on the proposition the connectome provides a sufficient explanation for consciousness in all its aspects where, for a neurobiological system, we are freed from the limitations of treating the connectome as a rigidly engineered structure incapable of real-time change.

Algorithmic processes as broadly defined are of course widespread in non-conscious neural events as well as conscious ones. The reason for choosing the term in this instance is specifically to emphasize an evolutionary point: that from an evolutionary perspective, the crucial difference between theories of consciousness has less do to with different ways they explain the higher-order functions of a fully evolved consciousness like our own, than their position on the nature of the neurocircuitry innovations that produced the simplest of phenomenal contents in the first instance. Here there are only two possibilities: that these innovations depend on neurons evolving novel ways to manipulate physical reality at the EM field level, i.e., the neurophysical option, or not. If not, then by default the contribution those innovations make to emerging consciousness can only be explained in terms of what algorithmic processes are capable of accomplishing in and of themselves.

An issue that emerges as especially important in the analysis that follows is that of agency, meaning, for the individual, the ability to consciously initiate and control behaviors. If we think of this in terms of the top-down control of voluntary action, then it is indeed a complex issue (Morsella, 2005; Morsella et al., 2020). An evolutionary approach is simpler in focusing attention first and foremost on explaining, from a scientific standpoint, how subjective experiences can be more than just byproducts of neural activity, epiphenomena in other words, that exert no controlling effect over behavior. This question is explored at some length, and leads to a consideration of the concept of a "self" endowed, among other attributes, with agency. The self concept is widely discussed in the literature (e.g., Panksepp, 1998; Damasio, 1999; Feinberg, 2011; Marchetti, 2012; Merker, 2013; Peacocke, 2015), and has proven a useful device, both to account for agency and other higher-order functions. Examining agency from an evolutionary perspective, and specifically how it originates, then leads me to a reconsideration of the hard problems as seen from that perspective.

2. A neurophysical consciousness machine

My consciousness machine (Figure 1) has a large wheel, much like an old-fashioned coffee grinder, which when turned through successive cycles, grinds out contents. The casing enclosing the machine separates the workings within, of biology and evolution,

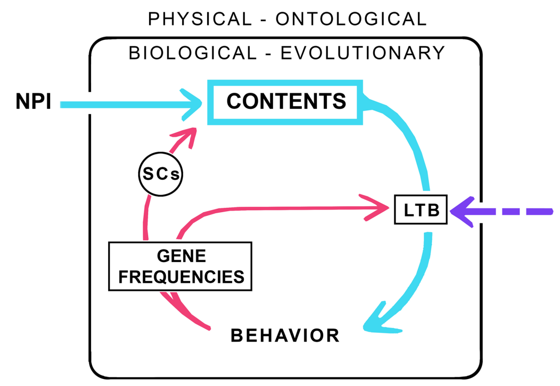

FIGURE 1
A consciousness machine configured, in this example, as the minimum required for consciousness to evolve given a neurophysical input (NPI). The internal workings of the machine, comprising the evolving neural structures and circuitry that make consciousness possible, are separated from the ontological realm, of physical rules and constraints on which life depends, where the input in question is that subcomponent of physical influences specifically required for consciousness to emerge from an otherwise non-conscious brain. How the emerging contents of consciousness are then elaborated and refined depends on natural selection, with each cycle (each turn of the "wheel") moving the system, meaning the breeding population as a whole, through one generation. The descending half of the cycle (arrows on the right, in blue for conscious neural pathways) represents the effects of emerging contents on behavior, while the ascending half of the cycle (red arrows on the left) represents the effects on brain structure and circuitry in the next generation due to the differential effect of emerging consciousness on survival and reproductive success. To complete the cycle, it is essential that there be a link between emerging consciousness and behavior (the arrow labeled LTB, the link to behavior), but the nature of this link, whether simple or complex, or endowed with agency or not, is not specified. The LTB may itself depend on an external input from the ontological realm as indicated by the dashed purple arrow, or it may not. If the latter, meaning that the LTB is entirely algorithmic in nature, the dashed arrow would vanish. Specific neurocircuitry features are not shown except for the selector circuits (SCs). SCs are the subset of neural correlates of consciousness (NCCs) responsible for selecting a given category of experience rather than some other, meaning they exert a direct causal influence on the nature of the experience that is evoked by a given stimulus. And, since the machine itself is an evolving system, its internal mechanisms will change over time, as will the contents which, if simple to begin with, will become increasingly complex.

from the external ontological realm and the physical laws governing the universe as a whole. Biology of course depends on those laws, and on the material world more generally, but the intent here is to single out the specific inputs required to support consciousness in individual brains beyond what is required of the physical realm by those same brains to function without consciousness. And, because the machine is intended to model evolution, it operates at a population level. Hence the box labeled CONTENTS represents the mean and variance of the contents of consciousness measured across the population, and likewise for the other components of the machine. Each turn of the wheel then marks the transition from one generation to the next, with the descending pathway on the right representing effects of emerging and evolving contents on behavior, which then, via effects on survival and reproduction, alter gene frequencies in the next generation, brain circuitry, and the conscious contents those brains produce. The figure is schematic and agnostic about the nature of the neurocircuits involved, whether localized or spread diffusely across larger cortical networks, nor should it be taken to imply that functions shown as formally separate need necessarily be carried out by separate groups of neurons rather than a single group, or even a single neuron. One category of circuits is singled out: the selector circuits (SCs, see Lacalli, 2021), equivalent to the differences makers of consciousness (DMCs) of Klein et al. (2020). These are the subset of neural correlates of consciousness (NCCs) responsible for selecting a particular kind of subjective experience rather than some other, and so, in one form or another, are an essential feature of any explanation for consciousness that depends on neurocircuitry.

I begin by considering a machine configured as a neurophysical device. I do this not because of a preference for neurophysical theories over the alternatives, but because the constraints imposed by physics on neurophysical theories limits the range of competing models and ideas that need to be considered in comparison with theories for which there are no such constraints. Neurophysical theories then have a significant advantage in terms of their practical utility for exercises of this kind. What distinguishes the neurophysical machine from all others is that there will be an input from the physical/ontological realm (NPI in the figure) where, as above, the input is whatever is specifically required to support conscious brain functions over and above the physical requirements for brains to function without consciousness. What this input might be is a matter of conjecture, but most proponents of neurophysical theories assume it involves as yet inadequately understood electromagnetic field effects (McFadden, 2020; Hales and Ericson, 2022; Kitchener and Hales, 2022), though something more exotic, perhaps at the quantum level, could also play a role (Tegmark, 2015). However, since nothing specific is known about how consciousness is to be accounted for using a field-based explanation, adopting a neurophysical stance means asking more of physics than it is currently able to deliver. As Block (2009) has framed the argument, such an explanation would require a conceptual leap beyond what is currently known, which collectively puts us in the position of someone trying to explain lightning in the thirteenth century. Equating this to a hard problem means that "hard" in this usage is not a claim that the problem is uniquely intractable, only that the nature of the solution is not evident at this point in time.

For an evolving consciousness, the contents of consciousness (CONTENTS in the figure) will change over time, and where this involves an increase in complexity, the expectation is that the internal working of the machine, i.e., the neural circuitry on which these changes depend, will become correspondingly more complex. However, for any of this to happen, there must be link between the emerging contents of consciousness and behavior (LTB in the figure, the link to behavior), as there is otherwise no route by which those contents can be changed in a non-random way in consequence of natural selection. As to how this link arises, there are two possibilities. First, it may be of neurophysical origin so that, as with NPI, it ultimately depends on an external input (the dashed purple arrow). Or, it may be entirely algorithmic, meaning no such input is required (the dashed arrow would vanish). Hence, even if we defer to physics on the question of ultimate origins and the nature of the NPI, there remains the problem of accounting for the link to behavior. Much of the remainder of this account is designed to address this issue.

3. Evolutionary process: emergence and bootstrapping

So, where does the LTB come from? Consider first the question of how anything novel arises in evolution. The answer is that it emerges by the selective amplification of random variations at the genetic level. But selective amplification can occur during development as well, allowing neural structures and their connectivity to be reordered by real time kinetic processes as the brain develops. The Turing mechanism used to explain pattern formation during embryogenesis provides a model for how this might occur, and though there have been specific proposals for how the mechanism might apply to networks of interacting neurons (e.g., Schmitt et al., 2022), my interest here is in the more general principle involved, of the extraction of order from fluctuations across timescales (Lacalli, 2020, 2022a). The reference to timescales here is a recognition that ordering in evolving biological systems can occur both during development, in real time, and across generations due to genomic innovations encoded at the molecular level. Investigating phenomena that combine development and evolution together thus introduces an unavoidable complication, of having to deal simultaneously with two incompatible timescales, an issue discussed more fully below. But here, as a first step, I want to illustrate the utility of the order-from-fluctuations principle as a conceptual device for understanding emergence both in general terms and as it relates to consciousness.

Order, in this context, can be thought of as arising though selective amplification of random fluctuations inherent in the constituent structures and dynamics of a less ordered starting point. Consider first a situation where this involves a real-time process of synaptic reordering that occurs during brain development as a consequence of Turing-type competition. Other mechanisms could clearly be involved, as there are a multitude of other ways to produce spatial and structural order during development. But of all these options, Turing's is arguably the most useful from a heuristic standpoint in having analytical solutions, so the underlying principles on which it depends can be understood in mathematical terms. The other point to emphasize is that, though Turing's model can generate order (i.e., pattern) from a disordered (unpatterned) starting point, its more useful feature in broader developmental terms, and for brain development in particular, is its ability to drive processes already producing an ordered outcome toward a specified subset of all possible ordered states. In other words, the resulting pattern, whether of digits on a limb or synaptic arrays on a set of dendrites, will be ordered in a particular way rather than any other. What is then required to produce a circuit capable of a rudimentary form of consciousness by this means is for the starting point to involve a category of neural circuits sufficiently close to having the capability of producing some form of subjective experience, that random variants in that circuitry can produce a rudiment of that experience of a size suitable for further amplification. In that sense, the system must already be "on the cusp" of evolving consciousness. For a neurophysical theory this would mean that a category of circuits is present that already have at least some of the capabilities required for subjective experience to be extracted from the neurophysical source on which that experience depends. Such circuits need not necessarily be complex, but greater complexity has the advantage providing more raw material for evolution than would be present in simpler brains. For algorithmic theories, in contrast, we require the presence of circuits specifying an algorithmic process that is in some sense on the cusp of producing a conscious state. This could, for example, involve an emergent self as discussed below, but the important point is that the order-from-fluctuations principle can be applied across theories. Hence, irrespective of the theory one adopts, the answer to the question "where did it come from?" applied to consciousness, is that it was already there in a rudimentary form, hidden in the fluctuations, meaning circuitry variants that randomly arise from a genomic or developmental source. But then, because a starting point is required that is already on the cusp of making the transition to consciousness, the real puzzle is moved back a step to the preconditions necessary for the system to be on that particular cusp.

The same conceptual framework can also be applied to the link to behavior, whether this has a neurophysical source or is entirely of algorithmic origin. But there is a further problem, that without a link to behavior evolution has no way of selectively amplifying anything. In my previous analysis of emergence using Turing's model (Lacalli, 2020), I chose to assume the link was present, and with that as a precondition, circuits capable of generating conscious contents could in principle emerge from the preconscious condition. What was missing was a consideration of how it is possible for conscious experience to be amplified from fluctuations when the link to behavior is itself just emerging by selective amplification of fluctuations in circuitry capable of producing that link. In other words, for the first conscious contents and the link to behavior to emerge together they must each, in effect, bootstrap the other at every step along the way. Precisely how this might occur is less important than whether in principle it can, which would require that the system be on two cusps at once, of producing both an emergent conscious experience and a link to behavior. The question of which came first does not arise because, much like the chicken and egg conundrum, the evolutionary answer is entirely straightforward: that neither can come first when both are equally essential at every step.

This account would not be complete without a further remark on innovation at the genomic level. Changes in the genome alter the developmental program and the way it is implemented, producing highly ordered structures in many cases without the intervention of global, dynamic patterning mechanisms like Turing's. I have referred to this non-global, more case-specific mode of control over developmental events as programmatic assembly (Lacalli, 2022a), but it shares with the Turing mechanism a dependence on energy dissipation and irreversible thermodynamics. And in both cases order arises through amplification of random variation inherent to the system, but in different timescales. This is because a dynamic mechanism like Turing's can reorder developmental outcomes in real time, whereas the ability of programmatic assembly to achieve a deterministic error-free result in real time depends on the way the genome has been reordered in the past, i.e., in evolutionary time, from generation to generation. This would apply as well to other rules-based patterning mechanisms, including cellular automata, where specific rules are applied in an iterative way (for examples see Berto and Tagliabue, 2022). It is premature to judge whether this latter mechanism, Turing's, or any other dominates in the assembly of the neural circuits responsible for consciousness, but for my purposes this does not matter when it is the underlying principle, of order from fluctuations, that is the primary concern.

4. Evolving a minimal behavioral link: a neurophysical scenario

This section examines a scenario devised to account for how a link to behavior might first have evolved, not to argue the case, but to clarify some key issues. Theoretical stance matters, and since neurophysical theories are better constrained by physical principles than the alternatives, I will cast the argument in terms of EM field effects. The premise then is that the brain in question contains neurons able to generate a suitably configured EM field capable of being consciously perceived where, for the latter function, we require a subset of neurons that are differentially responsive in order to ensure the response is specific to that subset of neurons, as opposed to being subsumed in the background of electromagnetic field effects to which all neurons respond. Figure 2 shows one way of satisfying those conditions. The starting point is a pair of sensorimotor pathways, one of which (pathway 2) is modulated by inputs from an integrative center (C2) responsive to a particular subset of EM effects generated by the central integrative center (C1) where this subset of effects have the potential to be consciously perceived. A further assumption is that the outputs from the two pathways are identical in the absence of such input, which means pathways 1 and 2 will differ in their output only when EM effects of a specified kind, i.e., those capable of being consciously perceived, are present. Should the situation then arise where the "conscious" pathway, i.e., pathway 2, is more adaptive, that pathway will be strengthened over a series of generations at the expense of pathway 1, which will be suppressed or lost. The proximate reason for this outcome might be any number of things, say, that modulation via consciously perceived EM field effects produces a slight delay in activating a motor response in the presence of a particular olfactory stimulus, or sped up that same response, in either case to the benefit of the individual. The result either way is to produce a neural pathway modulated by signals capable of generating a conscious experience.

Because Figure 2 is highly schematic, some further remarks required to avoid misunderstandings, chiefly as to how EM effects act across distance in nervous tissue. The broadcast signal is shown in the figure as a wave propagated from C1 across empty space, but the intervening space would in fact be packed with neurons and nerve fibers, each capable of generating local field potentials in its own right. It is then the resulting coupling between neurons (ephaptic coupling, Weiss and Faber, 2010; Anastassiou and Koch, 2015; see also Supplement A to Hales and Ericson,

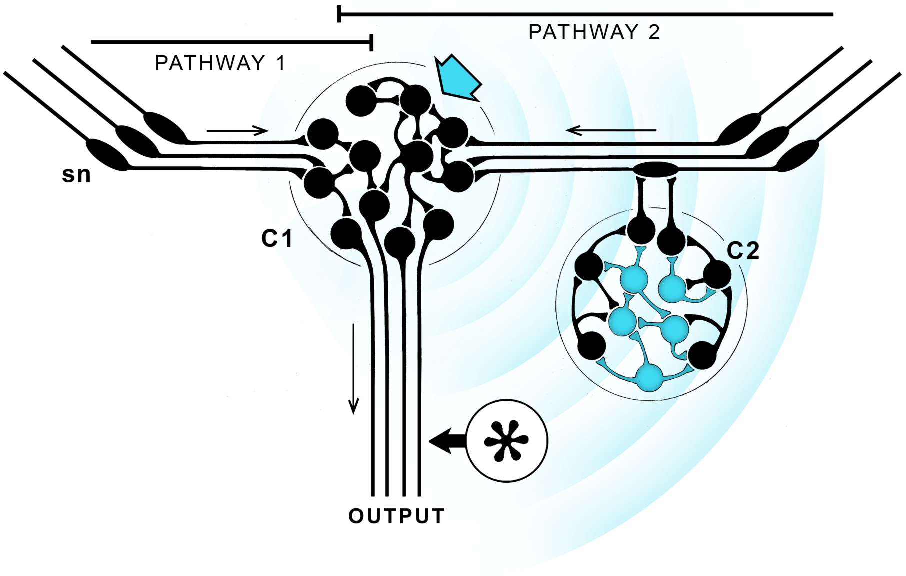

FIGURE 2
Avoiding the epiphenomenal trap: how a link to behavior might evolve given neurophysical assumptions, that consciousness depends on a EM field effects that can propagate across 3D space. Since the fields are supposed here to play a role in both generating contents and affecting behavior, this example would correspond to the workings of a consciousness machine, as in Figure 1, with external inputs to both emerging contents and the LTB. The starting point for this thought experiment is an integrative center (C1) with redundant sensory input (sensory neurons, sn, are shown with projecting cilia, and the direction of transmission by arrows) via two pathways that are assumed, in the absence of any effects ascribed to consciousness, to be functionally equivalent. Pathway 2 then differs from pathway 1 in incorporating a cluster of neurons (blue arrow) able to produce EM field effects capable of being consciously perceived that propagate (concentric blue arrow) and preferentially affect a separate subset of neurons (in blue) belonging to a second integrative center, C2. In fact the functions ascribed to C1 and C2 could be combined in a single center so the distances involved would be much reduced, but for purposes of illustration it is easier to separate them. C2 could then in principle act upstream of C1, as shown, or downstream (at the asterisk), without altering the argument. Suppose then that sensory inputs to pathway 2 can, under suitable conditions, generate a field effect that modulates C2 input, thereby altering the combined output of both pathways by changing the balance between them. If pathway 2, operating in conscious mode, produced a more adaptive outcome than pathway 1 acting alone, the optimal balance between the two would be one favoring pathway 2, which would then be strengthened generation by generation. This could involve adjustments to the character of the signal, making its dominant components an optimally selected subset of all possible EM field effects. A conscious experience of a specific kind will then have evolved, but the decisions made in consequence of this process will have been made by evolution acting over a series of generations, not by the individual in real time. The result, which applies to all such schemes so far as I can determine, is a form of consciousness without agency, where the individual lacks the ability to consciously control its own behavior in real time.

2022) that would propagate the signal, which also means the character of the signal can change with distance in ways that would not be possible for waves propagated in a passive medium. The point that then needs addressing is what an emergent experience would be like in such a situation and how it would evolve. Consider first that the signal at any point in the space can be thought of as being composed of different waveforms that each differ in their effect on the neurons responding to the signal. Assuming some waveforms activate the circuit in a more optimal way than others, the neuronal structures and configurations that generate those waveforms will be selected and enhanced over structures and configurations that generate less optimal waveforms. This will change the character of the signal which, as the broadcast center (C1) evolves, will be refined and optimized, while the response capabilities of neurons in C2 are likewise optimized. The waveform and the conscious sensation it generates will change accordingly, but the consequences of this at a behavioral level are due solely to the changing balance in output between the conscious and non-conscious pathways across generations. The key point here is that all of this happens without reference to the way the resulting sensation is actually experienced by the individual, the reason being that Figure 2 provides no route by which the character of an experience can be monitored by that individual. Nor is there a way to alter behavior in real time, because the balance between pathways, and hence behavior, only changes on an evolutionary timescale, across generations. In consequence the individual lacks agency, meaning the ability to initiate and terminate actions consciously under its own volition in real time. The sensations generated by activating pathway 2 then need not correspond to any of those experienced by animals with agency, such as ourselves, because the subjective character of the experience is irrelevant.

Figure 2 includes a second option, where C2 is moved (to the asterisk) so it directly modulates the output pathway. The field effects would then act on an integrative center able to influence motor output directly. But the result is the same, that in both cases what is happening is that evolution is adjusting the balance between the purely reflexive component of the circuit and its conscious counterpart so as to optimize that balance. Again, because it is evolution making the adjustment, across generations, rather than the individual acting in real time, the individual lacks agency even for behaviors that are variable, because it is evolution that determines the range of variation and the set point around which that variation occurs. And finally, though C1 and C2 are portrayed as separate, this is chiefly for ease of explanation, there being no reason that both functions could not be combined in a single a single center if, say, the spatial range of the signal was highly constrained. According to our current understanding of EM field theory this may well be the case (cf. Pockett, 2012, 2013), which tends to support the idea of multiple functions combined in a single center rather than multiple centers separated by a significant distance.

Consider now, with reference to Figure 2, what evolution has achieved by selecting pathway 2 over pathway 1. The result is a simple form of emerging consciousness that, in addition, is more than just an epiphenomenon. This is because it is now an essential component of a neural circuit that acts, when active, to alter behavioral outcomes. But neither the content of the experience nor its qualitative character play a causal role. Instead we have a behavioral switch where the "decision" as to which pathway dominates has been made by evolution. Why then, if this process bypasses the individual, involve consciousness at all? This is essentially the question posed by Velmans (2012), of why consciousness should exist if all its functions could as effectively be achieved by non-conscious circuits, with the brain operating "in the dark." The answer is that having parallel pathways that differ enlarges the behavioral repertoire, and if a pathway that incorporates conscious experience has evolved from this starting point, then it must have provided an adaptive advantage at some point in the past, and in circumstances where the preconditions in terms of neurocircuit complexity, whatever those are, were also present. This is not a circular argument, but rather a simple restatement of the nature of evolutionary change. But, being an argument in principle, it will not satisfy those wanting a more specific, function-based explanation as to the proximate reason that consciousness first evolved.

The very fact that consciousness without agency is possible deserves some further comment. First, there are theories of consciousness that deny agency in any case, supposing it to be an illusion (Wegner, 2002; Halligan and Oakley, 2021). Experimental evidence for this view has come from work on the timing of conscious motor responses, principally by Libet (1985), though current interpretations of those results cast some doubt on his conclusions (Morsella et al., 2020; Neafsey, 2021). But the difficulty with this stance, however one interprets Libet's data, is that consciousness and the character of its contents must then be accounted for without reference to adaptive optimization or evolutionary processes, leaving, for the biological realist, nothing of explanatory value. Hence, not surprisingly, this stance finds limited support among neuroscientists and evolutionary biologists. The second point relates to the body of behavioral studies summarized by Cabanac et al. (2009), and interpreted by them as implying an origin for vertebrate consciousness among the reptiles. If, in fact, the real obstacle to evolving consciousness such as our own is to incorporate agency, then these and similar results could be seen in a different light: that the transition across vertebrate taxa, from an apparent lack of consciousness to its presence, might instead be a transition from consciousness without agency to consciousness with agency. In consequence, there could be anamniote vertebrates swimming and crawling about today that remain at an ancestral and less evolved state, of being conscious without agency, representing in effect a stage in the evolution of consciousness frozen in time.

A final point concerning agency relates to the problem of accounting for the qualitative character of particular sensations. Cabanac (1992) has argued that a consciously perceived pleasure/displeasure axis is the key to understanding the benefits conferred by consciousness, with pleasure as the main motivator. This is a useful starting point for my argument, though with pain as my example, and specifically sharp pain, as from a pinprick. Consider why evolution would have chosen this particular sensation to motivate avoidance/withdrawal behavior, or, more to the point, why is sharp pain "painful"? The answer has two parts. First, one can ask whether there is something intrinsic to the stimulus of sharp pain that guarantees that it will necessarily be experienced in one particular way. If so, evolving a consciousness where pain is experienced as we do would be a predictable outcome. Conversely, it might be that the sensation of pain as we experience it induces an avoidance response only because evolution has ensured that it will do so, while the sensation itself has no intrinsic motivating power beyond that which evolution has assigned to it. There would then be no constraints on what sensation evolution assigns to an experience like sharp pain or any sensory experience, and what is painful could just as easily have evolved to be felt as we feel pleasure and vice versa. I raise this issue primarily to pose the question, not to answer it in a definitive way. But, as part 2 of this digression, a partial answer may be that for a restricted subset of sensory modalities the nature of the stimulus biases the choice of sensation. Consider again sharp pain, of the kind a newborn or newly hatched animal might receive by accident from contacts with sharp objects or in encounters with potential predators, and contrast this with the tactile stimulus from gentle stroking and soothing vocalizations by a parent comforting its offspring. For tactile experience as with sound, there is a frequency-dependent aspect of short vs. long wavelength components (von Békésy, 1959, 1960), where harm in this case correlates more with stimuli that are spatially more narrowly focused and hence higher pitched in the way they are experienced. This could explain the contrast in how sharp vs. soothing tactile stimuli are experienced where the bias toward higher pitch is with the former. Similarly, the association of anxiety and fear with physiological responses where time is a factor, e.g., of increased heart rate and rapid breathing, would bias any evolving sensation designed to signal those emotional states. Generalizing the argument to other sensory modalities is difficult, in part because these do not always have polar opposites requiring a binary choice. For example, for light there is an opposite condition, the absence of light, but no positive sensation signifying this absence. Likewise, though odors can be pleasant or noxious, both arise by chemical interactions of a qualitatively similar kind, implying their hedonic valence is assigned by other means. For these examples, one could suppose that the choice of a particular sensation, or quale, rather than some other, has been biased less by the nature of the stimulus than the availability of previously established conscious pathways that other modalities can draw on after the fact. So, for example, an odor signaling withdrawal would become associated in consciousness with experiences already associated with withdrawal, making valence in this case entirely independent of the intrinsic properties of the odor in question.

5. Behavioral links with agency

The analysis above shows that, for a subset of theories, there are plausible scenarios in which consciousness could evolve without agency. How then to add agency? One approach is to think in terms of the concept of a "self." A self is a component of numerous theories, variously conceived of as a witness and viewpoint (Merker, 2013; Williford et al., 2018), an experiencer (Cleeremans, 2011), experiencing subject (Marchetti, 2022), sentient entity (Reddy et al., 2019), or epistemic agent (Levin, 2019), but in sum, in most formulations, an entity endowed with some kind of monitoring ability, whether this is a form of awareness or something else, combined with agency. Here my concern is specifically with the self as agent (David et al., 2008) with the consciousness machine reconfigured accordingly (Figure 3). Figure 3A shows the neurophysical machine from Figure 1 with its minimal link to behavior replaced by a self with agency, while Figures 3B,C show two of many possible ways such a self-like entity might be incorporated into the machine, which could then, like Figure 3A, be neurophysical or, as in Figures 3B,C, fully algorithmic.

The first point to make about the selves in Figure 3 is that, because they are algorithmic constructs, we have no way *a priori* to place limits on what their capabilities may be supposed to be. So, for example, an emergent self could from the start be capable of converting non-conscious reflex pathways of considerable complexity directly into conscious contents. This might include somatosensory and visual maps, which would then become conscious without going through a sequence of steps where simple sensations were assembled into contents of progressively increasing complexity. However, we would still be faced with the question of how evolution assigns a particular sensation to the emergent contents, which ultimately depends on selector circuits (SCs) where the ability of each SC to evoke a particular sensation can only be systematically accounted for, regardless of theoretical stance, as a refinement achieved through an extended process of selection over multiple generations. The position SCs would likely occupy in relation to the selves in Figure 3 is: unchanged from Figure 1 in Figure 3A, as a component of the self in Figure 3B, and as part of the pathway activated by the interaction between sensory processing and the self in Figure 3C.

Now consider agency in its own right, and how it originates. To answer this in general terms we can apply the same logic used above to explore the origin of consciousness and the link to behavior for the neurophysical case. However, rather than circuits on the cusp of generating conscious experience, we must now postulate algorithmic processes on the cusp of selfness with agency. Regardless of what that entails in terms of neurocircuitry, the emerging self would then be acting simultaneously as an agent (and hence as the beginnings of a link of behavior) and as a modulator of phenomenal experience (hence its component of SCs), so the bootstrapping argument made above will again apply: that both can emerge together. There is a conceptual problem relating to the timescales involved, but I will defer this to the next section, leaving only the following difficulty: that however agency is embodied, I see no route beyond speculation to begin to answer the evolutionary question "how did it evolve?" This is because, having tried, I can state with some confidence that no amount of tinkering with scenarios like that in Figure 2 will generate a link to behavior conferring agency on the individual because, in effect, agency resides and remains throughout with evolution. Hence, in framing the question of how agency acting at the level of the individual first evolved, it is in my view more meaningful to do so, not in terms of a *de novo* origin of agency from unknown beginnings, but as a transfer of agency from evolution to the individual. This makes explicit the deeper ties that link the process as a whole, of the evolution of consciousness, with the dual nature of the timescales involved. If we then look at the recipient of agency, the individual, we are back in the realm of real-time events, and it is investigating these that is likely to prove most fruitful. The operative question is then not "how did it (agency) evolve?" but "how does it develop?" A promising approach would appear to be the one proposed by Cleeremans (2011), see also Cleeremans et al. (2020), to frame the question in terms of learning: that the brain must learn to be conscious, or in the same vein, that selfness must be learned and achieved (Marchetti, 2022). I will be more restrictive than Cleeremans, as he is concerned with higher order forms of consciousness, whereas I care only about the simplest contents, i.e., phenomenal ones. Further, my perspective is bottom-up in being concerned only with how the individual acquires agency, which prompts me to make the following conjecture: that transferring agency from evolution to the individual can only happen through the action of feedback processes operating in something other than evolutionary time, which by default means real time. Where this depends on a learning process, then memory will also be involved, so that information on the experiential result of particular actions can be stored and recalled. Establishing agency would then be inescapably an algorithmic process that operates in real time.

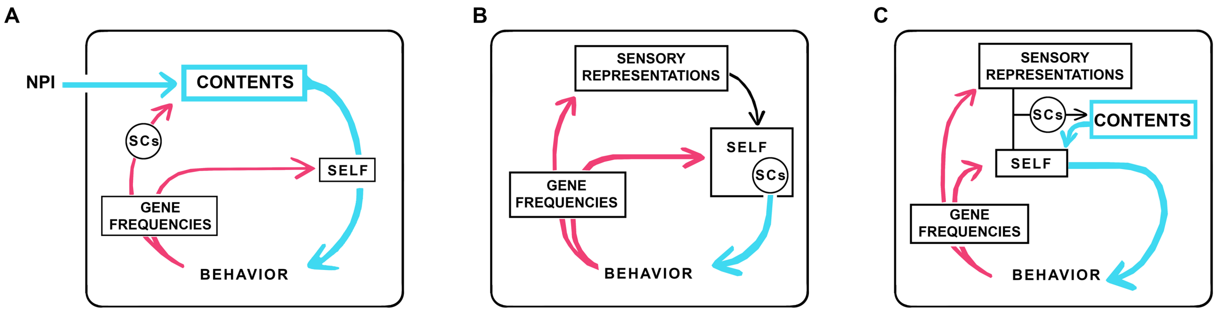

FIGURE 3
Three examples of how the consciousness machine might be reconfigured to accommodate an algorithmic self endowed with agency. **(A)** is configured for a neurophysical theory, so there is an external input as in Figure 1, but the LTB is now replaced by an algorithmic SELF. **(B)** is configured as a fully algorithmic theory with no external inputs, so the ultimate source of consciousness is algorithmic and internal to the machine. **(C)** is a more complicated version of **(B)** whose SELF is modeled on a proposal by Marchetti (2022) among others, where the self first interacts with representations of sensory processing to produce contents and, by being aware of those contents, initiates actions. There are many other ways the internal workings of the machine could be configured, the point of the figure being simply to show the formal equivalence between selves with agency across theories, regardless of whether the ultimate source of consciousness is neurophysical or algorithmic. As an aside, there is a second distinction to be made among all theories where a learning process is required for the self to acquire agency. If learning in such cases depends on a physical interaction with something external to the individual, there is in effect a physical input to the machine directed at the box labeled SELF. This is different in character from the field-dependent inputs shown in the figures, but there is a formal equivalence that begs the question of whether the learning process required for a self with agency could be accomplished in the absence of any such interaction, implying a virtual learning process where interactions with the external world were modeled using algorithms. I will defer judgment on this point, seeing no reason why evolution should opt for a virtual mechanisms given the easy access a developing brain has to sensory inputs from the real world, but it remains a question worth consideration.

How broadly the above conjecture can be applied across the theoretical landscape is difficult to assess given the diversity of theories of consciousness and how little the majority of them have to say about the role of evolutionary processes. However, for theories to which the conjecture does apply, a prediction one can make is that the necessary feedback processes will occur during a phase of development when the individual is able to actively test the consequences of real-time motor activities, implicating the period from late embryogenesis through the immediate post-hatching and/or post-natal period (Delafield-Butt and Gangopadhyay, 2013; Ciaunica et al., 2021). And, if such actions are indeed obligatory for species with conscious agency, the behaviors of animals during such periods could provide an empirical test for distinguishing between species that have consciousness with agency from those that have either a simpler form of consciousness, without agency, or none at all.

6. Timescale-related issues: synaptic plasticity, feedback, and behavioral flexibility

Within the framework developed above, there is an important distinction to be drawn between the neurocircuitry involved in producing sensations of particular kinds, i.e., phenomenal experience, and those involved in generating agency. Logically it would appear that the former must be in place so their output can guide the learning process by which agency is established, so the period of synaptogenesis and synaptic plasticity required for the correct assembly of the circuits responsible for phenomenal experience, including SCs, would have to be over or nearly so before the learning process could begin. If restricted to embryogenesis, there would also then be no way to subsequently correct errors that occur during the assembly process for SCs without a specific mechanism in place that operates after birth or hatching in order to do so. Such postnatal mechanisms clearly operate to shape and refine complex contents, the conscious display of the visual field being a well studied example (Hensch, 2004; Levett and Hübener, 2012). For the simplest of phenomenal contents, however, meaning the qualia of experience, this appears not to be the case. In consequence, the sensations experienced by individual brains for these would be fixed at the completion of brain development however distant those sensations were from the population standard. As shown in Figure 4, this manifests as an asymmetry in the relation between phenomenal experience (PE) and agency (Ag) whereby Ag depends on PE, as indicated by the arrow between them, but not the reverse. In addition, since the only way to remove discrepancies between PEs in individual brains and the population standard is through natural selection acting over evolutionary time, feedback on the PE side of the diagram is exclusively via an evolutionary route (indicated by the red arrow on the lower left). Agency, in contrast, is like vision as a total experience in depending on feedback occurring in real time, as this is required as part of the process by which each individual adjusts its actions as it learns. Hence the feedback loop shown for agency (F in the figure) operates in real time, but has no counterpart on the PE side of the diagram. There is then an apparent contradiction with the bootstrapping argument made in previous sections, that Figure 4 incorporates the assumption that PEs develop independently of and before the learning process for Ag can begin, while bootstrapping requires PEs and Ag to mutually assist each other, implying simultaneity. The reason this is not in fact contradictory is that when the emergence of PEs, Ag and hence consciousness is being dealt with in an evolutionary context, all of development is effectively a single point in time so long as the adaptive utility of the outcome is tested only after development is complete. Hence, developmental events can be simultaneous in evolutionary time when, in real time, they are not.

Having two separate timescales is noteworthy for other reasons. First, to continue with the point made in the previous paragraph, it segregates the feedback processes required, which occur in real time for emerging agency, but in evolutionary time for the progressive diversification and

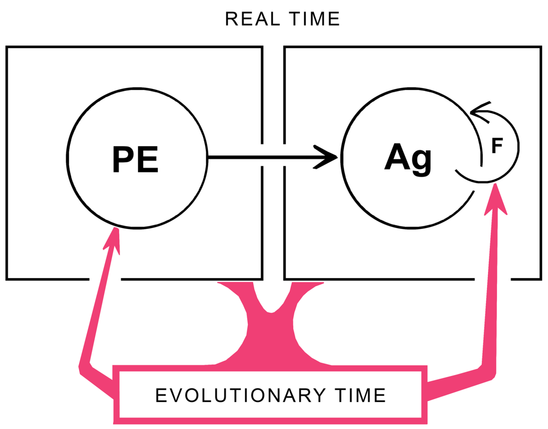

FIGURE 4
A schematic representation of how development and evolution work together to generate consciousness. Both real time (i.e., developmental) and evolutionary timescales must be included, and these are separable as shown. For the former, a key issue is that the developing brain must be capable of some form of real-time phenomenal experience (PE) in advance of the actions by which agency (Ag) can be "learned" through the real-time feedback mechanisms (F) on which that learning process depends. There are two asymmetries here that operate in real time, during brain development, that (1) Ag depends on PE but not the reverse, so the arrow connecting these is unidirectional, and (2) that Ag is adjusted and refined by real-time feedback while the subset of PEs on which this process depends operate as fixed reference points that can be altered and refined only in evolutionary time. Any conscious contents subject to alteration by late embryonic or post-natal feedback processes would then be precluded from being PEs, which would, by definition, be limited to consciously perceived sensations (i.e., qualia) that, once the neurocircuitry mechanisms required to evoke them are in place, remain subsequently unchanged by the real-time experiences of the individual. The evolutionary side of the story (in red) indicates the role genomic change plays, generation by generation, in changing both the character of PEs and the feedback mechanisms required for agency to develop. A complication is that, in evolutionary time, emergent phenomenal experience and emergent agency are co-dependent, because neither can evolve without the other. But this does not contradict the real-time asymmetry in the dependence of Ag on PEs, because for evolution, all of development is a single point in time (see text for further discussion). The key point then is that having two timescales allows phenomenal experiences and agency to evolve together while being, in effect, insulated from one another. This is an important insight in reductionist terms, justifying the separation of one large problem, of investigating consciousness as a whole, into two, of investigating phenomenal experience on the one hand and agency on the other.

refinement of phenomenal contents. For agency this is a change from the preconscious condition, and is consequential, which is why the transferral of agency from evolution to the individual has been given the emphasis it has in this account. The reason for doing so is ultimately a reductionist one, best illustrated by considering blanket statements of the form "consciousness must be learned": that even if is correct to say that agency at the level of the individual must be learned, so that consciousness with agency also requires learning in order to exist (i.e., to evolve), there is nevertheless a good deal about phenomenal experience that can be usefully investigated without concerning oneself with learning. This is because the timescale difference insulates processes relating to the elaboration and refinement of phenomenal experience, including much of what is considered under the umbrella of the hard problem, from the mechanisms involved in generating agency. The problem of explaining consciousness is consequently reduced to two separable problems, of explaining phenomenal experience on the one hand and agency on the other, both of which can then be more easily investigated separately than they could be together. A caveat is that, because the arguments I have used here to justify this reductive step are evolutionary, it is not clear if the same result would obtain for all theories of consciousness, and specifically for theories or variants of theory that are silent on the role played by evolution. Absent an answer from my analysis, I address that question to proponents of those other theories.

A final point relating to timescales concerns the function of consciousness, where the reference here is to function in general terms rather than the specific functions consciousness may first have evolved to perform. I have addressed this previously in my analysis of selector circuits and experience space, the conclusion being that consciousness allows evolving populations to gain access to regions of both selector-circuit space and experience space that would otherwise not be available to them (Lacalli, 2021). Simply put, a greater range of behaviors is possible with consciousness than without. This is then a precise statement about function, but it should ideally be more specific about the benefits of transferring agency from evolution to the individual. Amended, a more *complete* statement is that the function of consciousness is to (1) increase the behavioral repertoire by expanding access to otherwise inaccessible regions of behavior space, and (2) reduce by orders of magnitude the time required for behavioral changes to occur in response to changing circumstance. The second point relates to what might generally be referred to as behavioral flexibility, but in an evolutionary context this term acquires a more specific meaning: of the ability of the individual to alter its behavior in real time where, absent consciousness, that same alteration could only have been achieved by natural selection operating over generational time, and hence many orders of magnitude more slowly.

7. Conclusions: consciousness and its hard problems

A certain amount of lumping and splitting occurs in the early stages of the development of most scientific ideas, of determining which of the various phenomena under study should be treated together in analytical terms and which should be dealt with separately. For consciousness, considered from a philosophical, psychological or neurological perspective, a considerable amount of lumping and splitting has already been accomplished, and a degree of consensus has emerged as to the issues at stake and the range of perspectives one can adopt, including the nature of the hard problems and explanatory gaps that bedevil the subject (Levine, 1983, 2009; Chalmers, 1995). Though these issues are seldom considered from an explicitly evolutionary perspective, there is an implicit evolutionary component to the analysis by Majeed (2016), who recasts what is generally considered the least tractable of the hard problems as two questions, namely (1) how subjective experience of any kind can exist in the first place, and (2) how a consciousness consisting of diverse distinguishable contents is to be accounted for. This separates the issue of origins from that of elaboration and refinement, and for theories that deal with contents as separable and individually subject to selection, elaboration and refinement are inescapably matters to be dealt with in an evolutionary context. Previous papers in this series (Lacalli, 2020, 2021, 2022b) were in fact designed to do exactly this, adding, in the current installment, an investigation of how a link to behavior that embodies agency might first have evolved. Regardless of how difficult resolving such questions proves to be, they all belong to a category that Chalmers (1995, 1996) treats as "easy" problems, as they fall within the bounds of established neuroscience and are soluble in principle using established or emerging methodologies given sufficient time (Kostić, 2017; Kitchener and Hales, 2022). In contrast, a truly hard problem would be one that tests the bounds of what science is capable of explaining, in this case how subjective experience can exist, but more precisely, how it is that something with no material existence can have definable properties of a particular type, or indeed any properties at all.

An evolutionary view recasts the issue of hard problems in several ways. First, it reinforces the supposition that the easy and hard problems referred to above should be dealt with separately. This is because, so long as the evolutionary sequence is from simple contents to more complex ones, solving Chalmers' ultimate hard problem for a subjective experience of any kind solves it fully. Subsequent innovations in conscious experience are then a matter of elaborating neural processing in ways that conventional neuroscience should, in principle, be able to explain. Accepting that the elaboration and refinement of conscious contents is an evolutionary process also resolves the second issue raised by Majeed (his point 2, above), that if consciousness is composed of separable subcomponents, as would likely be the case for any EM field-based theory, then evolution is simply the means by which that separation is effected. But explaining consciousness as it is today in evolutionary terms raises an additional set of potentially hard problems relating, not to the limits of scientific explanation, but the fragmentary nature of the evidence available to us on unique events lodged in the distant past. Absent a relevant fossil record, we are reliant on inference to answer such questions, e.g., as to the proximate reason for which consciousness first evolved, or the sensory modality involved, and there is currently little one can say beyond speculation. The situation may improve, and would, should the relevant neurocircuitry prove to contain some form of consciousness "signature" that could be traced across taxa. But however difficult a problem this proves to be in practice, it is currently simply a matter of insufficient data, not a test of the limits of scientific explanation.

What does test those limits is the problem Chalmers identifies, now generally accepted as fundamental (Searle, 1998; Robinson, 2015), of how it is possible for any kind of subjective experience to exist. Different categories of theory will parcel out the burden of explanation in different ways. The distinction I've made throughout this paper is between theories that attribute the ultimate source of subjective experience to either a neurophysical cause on the one hand, or algorithmic processes on the other. To begin with the former, for neurophysical theories the burden of explanation is divided between physics, neuroscience and evolutionary biology. If we suppose that subjective experience can be conceived of as depending on EM fields composed of separable harmonic components, emergence results from the selective amplification of some of these at the expense of others. How this is done is a matter of understanding events occurring at a neurocircuitry level. Hence it belongs to the category of easy problems, and yields answers that are at best examples of weak emergence (*sensu* Bedau, 1997). The deeper problem is why the signal thus generated over a background of noise should manifest itself to the individual in a particular way, or in any way at all. This can be dealt conceptually with by assuming that subjective experience is simply a particular sum of waveforms that solve the relevant field equations, selected from many possible such sums. But knowing the waveforms does not explain why some solutions but not others should have the property of being perceived as an apparently real experience of a particular kind by a suitably configured assemblage of neurons. This is at root an ontological issue, as it concerns existence and the nature of reality. Hence it belongs in physics, even if the answer does not fit within the existing explanatory structures of physics as it is today. In this sense the very existence of subjective experience performs a useful function in alerting physicists to a significant part of reality they cannot yet fully explain. That attempts to do so have so far reached only the stage of arguments by analogy, to relational aspects of quantum behavior as an example (Smolin, 2020), shows how early we are in terms of seriously exploring the subject in scientific terms.

Fully algorithmic theories yield a problem of somewhat different kind, because subjective experience must then be conjured up out of a set of procedures carried out by a network of interacting elements where the content of that process, meaning the task it is designed to perform, generates subjective experience in and of itself. Hence physics, except perhaps physics of a radically new kind, would seem to provide little by way of assistance. Instead, we must devise *ab initio* explanations as to how a process, essentially computational in character, can give rise to something that is immaterial yet real, and exists only due to the execution of that process. This is a speculative enterprise in the extreme at this point in time, and is especially problematic for the subset of algorithmic theories that suppose the answer resides in the as yet poorly understood realm of ideas concerning the capabilities of network-based information processing. First is the problem of requiring information to be more than an epistemic convenience, in other words a way of describing reality rather than a component of that reality, is inadequate in principle as an explanation (Manson, 2010; Manzotti, 2012; Pockett, 2014; see also Kitchener and Hales, 2022 on the grounding problem). On the other hand, at a more practical level, there is the problem that the methodologies available for dealing analytically with information processing are specifically designed to be agnostic on the content of what is being processed (Wood, 2019). This is of particular concern where content is important, e.g., when considering whether a given network process has at yet achieved selfhood, or awareness, or not. My conclusion in consequence is that the supposition, that algorithmic processes in and of themselves generate conscious experiences, must be one of two things: it is either a hard problem of a very profound kind, or it is a strong argument that any fully algorithmic theory lacking a neurophysical component must be false.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

TL is solely responsible for the preparation and content of this article.

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Conflict of interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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References

Anastassiou, C. A., and Koch, C. (2015). Ephaptic coupling to endogenous electric field activity: why bother? *Curr. Opin. Neurobiol.* 31, 95–103. doi: 10.1016/j.conb.2014.09.002

Atkinson, A. P., Thomas, M. S. C., and Cleeremans, A. (2000). Consciousness: mapping the theoretical landscape. *Trends Cogn. Sci.* 4, 372–382. doi: 10.1016/S1364-6613(00)01533-3

Bedau, M. A. (1997). "Weak emergence" in *Philosophical perspectives: Mind, causation, and world*. ed. J. Tomberlin, vol. *11* (Malden, MA: Blackwell), 375–399.

Berto, F., and Tagliabue, J. (2022). "Cellular automata" in *The Stanford encyclopedia of philosophy*. ed. E. N. Zalta (Stanford, CA: Metaphysics Research Lab, Stanford University) Available at: https://plato.stanford.edu/archives/spr2022/entries/cellular-automata/

Block, N. (2009). "Comparing the major theories of consciousness" in *The cognitive neurosciences*. ed. M. S. Gazzaniga. *4th* ed (Cambridge, MA: MIT Press), 1111–1122.

Cabanac, M. (1992). Pleasure: the common currency. *J. Theor. Biol.* 155, 173–200. doi: 10.1016/S0022-5193(05)80594-6

Cabanac, M., Cabanac, J., and Parent, A. (2009). The emergence of consciousness in phylogeny. *Behav. Brain Res.* 198, 267–272. doi: 10.1016/j.bbr.2008.11.028

Chalmers, D. J. (1995). Facing up to the problem of consciousness. *J. Cons. Stud.* 2, 200–219. doi: 10.1093/acprof:oso/9780195311105.003.0001

Chalmers, D. J. (1996). *The conscious mind: In search of a fundamental theory*. New York: Oxford University Press.

Ciaunica, A., Safron, A., and Delafield-Butt, J. (2021). Back to square one: the bodily roots of conscious experience in early life. *Neurosci. Conscious.* 2021:niab037. doi: 10.31234/osf.io/zspm2

Cleeremans, A. (2011). The radical plasticity thesis: how the brain learns to be conscious. *Front. Psychol.* 2:86. doi: 10.3389/fpsyg.2011.00086

Cleeremans, A., Achoui, D., Beauny, A., Keuninckx, L., Martin, J. R., Muñoz-Moldes, S., et al. (2020). Learning to be conscious. *Trends Cogn. Sci.* 24, 112–123. doi: 10.1016/j.tics.2019.11.011

Damasio, A. (1999). *The feeling of what happens: Body and emotion in the making of Consciousness*. New York, NY: Harcourt Brace.

David, N., Newen, A., and Vogeley, K. (2008). The "sense of agency" and its underlying cognitive and neural mechanisms. *Cons. Cogn.* 17, 523–534. doi: 10.1016/j.concog.2008.03.004

Delafield-Butt, J. T., and Gangopadhyay, N. (2013). Sensorimotor intentionality: the origins of intentionality in prospective agent action. *Dev. Rev.* 33, 399–425. doi: 10.1016/j.dr.2013.09.001

Dobzhansky, T. (1973). Nothing in biology makes sense except in the light of evolution. *Am. Biol. Teach.* 35, 125–129. doi: 10.2307/4444260

Fabbro, F., Aglioti, S. M., Bergamasco, M., Clarici, A., and Panksepp, J. (2015). Evolutionary aspects of self- and world consciousness in vertebrates. *Front. Hum. Neurosci.* 9:157. doi: 10.3389/fnhum.22015.00157

Feinberg, T. E. (2011). The nested neural hierarchy and the self. *Cons. Cogn.* 20, 4–15. doi: 10.1016/j.concog.2010.09.016

Feinberg, T. E. (2023). *From sensing to sentience: How feeling emerges from the brain*. Cambridge, MA: MIT Press. (in press)

Feldman, J. (2012). The neural binding problem(s). *Cogn. Neurodyn.* 7, 1–11. doi: 10.1007/s11571-012-9219-8

Gennaro, R. J. (2018). "Representational theories of consciousness" in *The Routledge handbook of consciousness* (London: Taylor & Francis), 107–121.

Godfrey-Smith, P. (2019). Evolving across the explanatory gap. *Philos. Theor. Pract. Biol.* 11:1. doi: 10.3998/ptpbio.16039257.0011.001

Hales, C. G., and Ericson, M. (2022). Electromagnetism's bridge across the explanatory gap: how a neuroscience/physics collaboration delivers explanation into all theories of consciousness. *Front. Hum. Neurosci.* 16:836046. doi: 10.3389/fnhum.2022.836046

Halligan, P. W., and Oakley, D. A. (2021). Giving up on consciousness as the ghost in the machine. *Front. Psychol.* 12:571460. doi: 10.3389/fpsyg.2021.571460

Hensch, T. K. (2004). Critical period regulation. *Ann. Rev. Neurosci.* 27, 549–579. doi: 10.1146/annurev.neuro.27.070203.144327

Hunt, T., and Schooler, J. W. (2019). The easy part of the hard problem: a resonance theory of consciousness. *Front. Hum. Neurosci.* 13:378. doi: 10.3389/fnhum.2019.00378

Irwin, L. N. (2020). Renewed perspectives on the deep roots and broad distribution of animal consciousness. *Front. Syst. Neurosci.* 14:57. doi: 10.1389/fnsys.2020.00057

Kitchener, P. D., and Hales, C. G. (2022). What neuroscientists think, and don't think, about consciousness. *Front. Hum. Neurosci.* 16:767612. doi: 10.3389/fnhum.2022.767612

Klein, C., Hohwy, J., and Bayne, T. (2020). Explanation in the science of consciousness: from neural correlates of consciousness (NCCs) to difference makers of consciousness (DMCs). *Philos. Mind Sci.* 1:4. doi: 10.33735/phimisci.2020.II.60

Kostić, D. (2017). Explanatory perspectivalism: limiting the scope of the hard problem of consciousness. *Topoi* 36, 119–125. doi: 10.1007/s11245-0149262-7

Lacalli, T. C. (2020). Evolving consciousness: insights from Turing, and the shaping of experience. *Front. Behav. Neurosci.* 14:598561. doi: 10.3389/fnbeh.2020.59856

Lacalli, T. C. (2021). Consciousness as a product of evolution: contents, selector circuits, and trajectories in experience space. *Front. Syst. Neurosci.* 15:697129. doi: 10.3389/fnsys.2021.697129

Lacalli, T. C. (2022a). Patterning, from conifers to consciousness: Turing's theory and order from fluctuations. *Front. Cell Dev. Biol.* 10:871950. doi: 10.3389/fcell.2022.871950

Lacalli, T. C. (2022b). On the origins and evolution of qualia: an experience-space perspective. *Front. Syst. Neurosci.* 16:945722. doi: 10.3389/fnsys.2022.945722

Levett, C. N., and Hübener, M. (2012). Critical-period plasticity in the visual cortex. *Ann. Rev. Neurosci.* 35, 309–330. doi: 10.1146/annurev-neuro-061010-113813

Levin, M. (2019). The computational boundary of a "self": developmental bioelectricity drives multicellularity and scale-free cognition. *Front. Psych.* 10:2688. doi: 10.3389/fpsyg.2019.02688

Levin, J. (2023). "Functionalism" in *The Stanford encyclopedia of philosophy*. ed. E. N. Zalta (Stanford, CA: Metaphysics Research Lab, Stanford University) Available at: https://plato.stanford.edu/archives/sum2023/entries/functionalism/

Levine, J. (1983). Materialism and qualia: the explanatory gap. *Pac. Philos. Q.* 64, 354–361. doi: 10.1111/j.1468-0014.1983.tb00201.x

Levine, J. (2009). "The explanatory gap" in *The Oxford handbook of philosophy of mind*. eds. A. Beckerman, B. P. McLaughlin and S. Walter (Oxford: Oxford University Press), 281–291.

Libet, B. (1985). Unconscious cerebral initiative and the role of conscious will in voluntary action. *Behav. Brain Sci.* 8, 529–539. doi: 10.1017/S0140525X00044903

Lycan, W. (2019). "Representational theories of consciousness" in *The Stanford encyclopedia of philosophy*. ed. E. N. Zalta https://plato.stanford.edu/archives/fall2019/entries/consciousness-representational/.

Majeed, R. (2016). The hard problem and its explanatory targets. *Ratio* 29, 298–311. doi: 10.1111/rati.12103

Manson, N. C. (2010). What does language tell us about consciousness? First person mental discourses and higher-order thought theories of consciousness. *Philos. Psychol.* 15, 221–238. doi: 10.1080/0951508021000006076

Manzotti, R. (2012). The computational stance is unfit for consciousness. *Int. J. Mach. Cons.* 04, 401–420. doi: 10.1142/S1793843012400239

Marchetti, G. (2012). "How consciousness builds the subject through relating" in *Philosophy of mind*. eds. R. J. Jenkins and W. E. Sullivan (Hauppauge, NY: Nova Science Publishers), 27–64.

Marchetti, G. (2022). The why of the phenomenal aspect of consciousness: its main functions and the mechanisms underpinning it. *Front. Psychol.* 13:913309. doi: 10.3389/fpsyg.2022.913309

McFadden, J. (2020). Integrating information in the brain's EM field: the cemi field theory of consciousness. *Neurosci. Cons.* 2020:16. doi: 10.1093/nc/niaa016

Merker, B. (2013). The efference cascade, consciousness, and its self: naturalizing the first person pivot of action control. *Front. Psych.* 4:501. doi: 10.3389/fpsyg.2013.00501

Morsella, E. (2005). The function of phenomenal states: supramodular interaction theory. *Psy. Rev.* 112, 1000–1021. doi: 10.1037/0033-295X.112.4.1000

Morsella, E., Velasquez, A. G., Yankulova, J. K., Li, Y., Wong, C. Y., and Lambert, D. (2020). Motor cognition: the role of sentience in perception and action. *Kines. Rev.* 9, 261–274. doi: 10.1123/kr.2020-0017

Neafsey, E. J. (2021). Conscious intention and human action: review of the rise and fall of the readiness potential and Libet's clock. *Cons. Cogn.* 94:103171. doi: 10.1016/j.concog.2021.103171

Panksepp, J. (1998). The preconscious substrates of consciousness: affective states and the evolutionary origins of self. *J. Cons. Stud.* 5, 566–582.

Peacocke, C. (2015). "Perception and the first person" in *The Oxford handbook of philosophy of perception*. ed. M. Matthen (Oxford, UK: Oxford University Press), 168–180.

Pockett, S. (2012). The electromagnetic field theory of consciousness. *J. Cons. Stud.* 19, 191–223. Available at: https://philpapers.org/rec/POCTEF

Pockett, S. (2013). Field theories of consciousness. *Scholarpedia* 8:4951. doi: 10.4249/scholarpedia.4951

Pockett, S. (2014). Problems with theories that equate consciousness with information or information processing. *Front. Syst. Neurosci.* 8:225. doi: 10.3389/fnsys.2014.00225

Reddy, J. S. K., Roy, S., de Souza, L. E., and Pereira, A. (2019). The "self" aspects: the sense of the existence, identification, and location. *Integr. Psychol. Behav. Sci.* 53, 463–483. doi: 10.1007/s12124-019-9476-8

Revonsuo, A. (2018). "Biological naturalism and biological realism" in *The Routledge handbook of consciousness*. ed. R. J. Gennaro (London: Taylor & Francis), 188–201.

Revonsuo, A., and Newman, J. (1999). Binding and consciousness. *Cons. Cogn.* 8, 123–127. doi: 10.1006/ccog.1999.0393

Robinson, H. (2015). "Phenomenal qualities: what they must be, and what they cannot be" in *Phenomenal qualities: Sense, perception, and consciousness*. eds. P. Coates and S. Coleman (Oxford: Oxford University Press), 103–120.

Rosenthal, D. M. (2008). Consciousness and its function. *Neuropsychologia* 46, 829–840. doi: 10.1016/j.neuropsychologia.2007.11.012

Schmitt, O., Nitzsche, C., Eipert, P., Prathapan, V., Hütt, M. T., and Hilgetag, C. C. (2022). Reaction-diffusion models in weighted and directed connectomes. *PLoS Comput. Biol.* 18:e1010507. doi: 10.1371/journal.pcbi.1010507

Searle, J. R. (1998). How to study consciousness scientifically. *Philos. Trans. R. Soc. Lond* 353, 1935–1942. doi: 10.1098/rstb.1998.0346

Seth, A. K., and Bayne, T. (2022). Theories of consciousness. *Nat. Rev. Neurosci.* 23, 439–452. doi: 10.1038/s41583-022-00587-4

Smolin, L. (2020). The place of qualia in a relational universe. *PhilPapers, SMOTP0-3* Available at: https://philpapers.org/rec/SMOTPO-3

Stinson, C. (2018). "Explanation and connectionist models" in *The Routledge handbook of the computational mind*. eds. M. Sprevak and M. Colombo (London: Taylor & Francis), 120–133.

Sun, R., and Franklin, S. (2007). "Computational models of consciousness: a taxonomy and some examples" in *The Cambridge handbook of consciousness*. eds. P. D. Zelazo, M. Moscovitch and E. Thompson (Cambridge: Cambridge University Press), 151–174.

Tegmark, M. (2015). Consciousness as a state of matter. *Chaos Sol. Frac.* 76, 238–270. doi: 10.1016/j.chaos.2015.03.014

Van Gulick, R. (2018). "Consciousness" in *The Stanford encyclopedia of philosophy*. ed. E. N. Zalta (Stanford, CA: Metaphysics Research Lab, Stanford University) Available at: https://plato.stanford.edu/archives/spr2018/entries/consciousness/

Velmans, M. (2012). The evolution of consciousness. *Contemp. Soc. Sci.* 7, 117–138. doi: 10.1080/21582041.2012.692099

von Békésy, G. (1959). Similarities between hearing and skin sensations. *Psych. Rev.* 66, 1–22. doi: 10.1037/h0046967

von Békésy, G. (1960). *Experiments in hearing*. New York: McGraw-Hill.

Wegner, D. M. (2002). *The illusion of conscious will*. Cambridge, MA: MIT Press.

Weiss, S. A., and Faber, D. S. (2010). Field effects in the CNS play functional roles. *Front. Neural Circuits* 4:15. doi: 10.3389/fncir.2010.00015

Williford, K., Bennequin, D., Friston, K., and Radrauf, D. (2018). The projective consciousness model and phenomenal selfhood. *Front. Psychol.* 9:2571. doi: 10.3389/fpsyg.2018.0271

Winters, J. J. (2021). The temporally-integrated causality landscape: reconciling neuroscientific theories with the phenomenology of consciousness. *Front. Hum. Neurosci.* 15:768459. doi: 10.3389/fnhum.2021.768459

Wood, C. C. (2019). The computational stance in biology. *Philos. Trans. R. Soc. Lond* 374:20180380. doi: 10.1098/rstb.2018.0380

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Fields or firings? Comparing the spike code and the electromagnetic field hypothesis

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Where is consciousness? Neurobiological theories of consciousness look primarily to synaptic firing and “spike codes” as the physical substrate of consciousness, although the specific mechanisms of consciousness remain unknown. Synaptic firing results from electrochemical processes in neuron axons and dendrites. All neurons also produce electromagnetic (EM) fields due to various mechanisms, including the electric potential created by transmembrane ion flows, known as “local field potentials,” but there are also more meso-scale and macro-scale EM fields present in the brain. The functional role of these EM fields has long been a source of debate. We suggest that these fields, in both their local and global forms, may be the primary seat of consciousness, working as a gestalt with synaptic firing and other aspects of neuroanatomy to produce the marvelous complexity of minds. We call this assertion the “electromagnetic field hypothesis.” The neuroanatomy of the brain produces the local and global EM fields but these fields are not identical with the anatomy of the brain. These fields are produced by, but not identical with, the brain, in the same manner that twigs and leaves are produced by a tree’s branches and trunk but are not the same as the branches and trunk. As such, the EM fields represent the more granular, both spatially and temporally, aspects of the brain’s structure and functioning than the neuroanatomy of the brain. The brain’s various EM fields seem to be more sensitive to small changes than the neuroanatomy of the brain. We discuss issues with the spike code approach as well as the various lines of evidence supporting our argument that the brain’s EM fields may be the primary seat of consciousness. This evidence (which occupies most of the paper) suggests that oscillating neural EM fields may make firing in neural circuits oscillate, and these oscillating circuits may help unify and guide conscious cognition.

KEYWORDS

EM-field theories of consciousness, consciousness, spike codes, general resonance theory, ephaptic coupling, cross-frequency coupling (CFC)

1. Introduction

The conventional view in neuroscience today is that neuronal and synaptic activity are the key dynamics supporting consciousness. In other words, if we peer into the body and brain in search of the “neural correlates of consciousness” what we’ll find is that electrochemical synapse activities of various types, perhaps in particular areas of the brain, are the specific neural correlates of consciousness. These synaptic activities are, in this view, necessary and sufficient for consciousness (e.g., Crick and Koch, 1990; Li and Tsien, 2017; Humphries, 2020). We will call this “the spike code approach” or “spike code view” from now on.

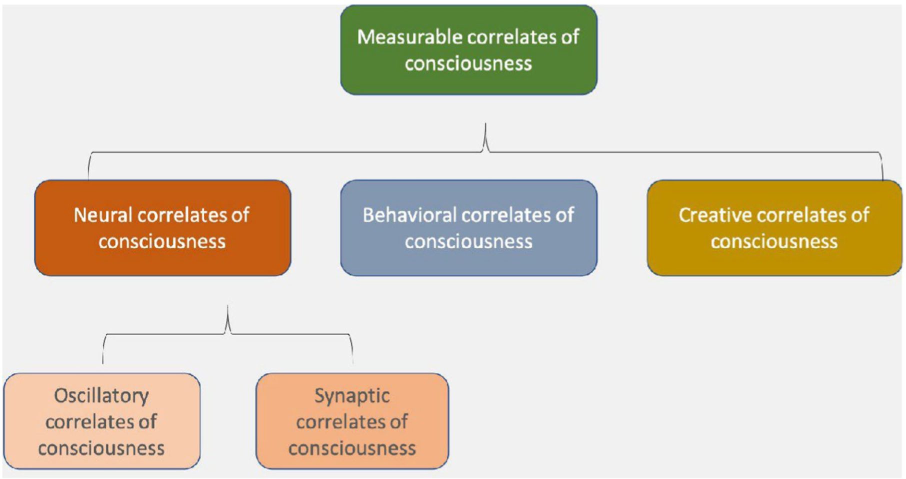

FIGURE 1
Neural correlates of consciousness include oscillatory and synaptic correlates, which are both types of electromagnetic field phenomena, at different spatial and temporal scales (Hunt et al., 2022).

But what if the spike code approach overlooks key features of the brain and consciousness? What if various spatiotemporal scales of electromagnetic (EM) fields generated by, but not identical with the anatomy of the brain, are in fact the primary seat of consciousness? In this alternative view, neurons and synaptic transmission of information are necessary for consciousness, but they are not sufficient for consciousness, at least not the complex kind that humans and other mammals (and probably other animals too) enjoy.

Hales coined the term "electromagnetic correlates of consciousness" (EMCC) in a 2014 paper on how the brain's endogenous (internally versus externally generated) EM fields produce consciousness (Hales, 2014). Figure 1 shows this simple taxonomy of various correlates of consciousness and suggests that the well-known "neural correlates of consciousness" should be divided into synaptic correlates and, as a new category, oscillatory or electromagnetic correlates of consciousness (Hunt et al., 2022).

If Hales and his co-thinkers like us are right, the spatially and temporally more fine-grained dynamics of local and global EM fields may be the primary seat of consciousness. Under this view, rather than looking solely for neural correlates, and their "spike codes," we would look for specific EMCC (see Figure 1), or what we have begun calling "the resonome," or the "oscillome," which we define as the set of oscillating fields that create various shades of consciousness in each moment. Oscillating EM fields and synaptic dynamics, in this view, jointly comprise the neural correlates of consciousness.

This debate is highlighted in NIH researcher Douglas Fields' 2020 book *Electric Brain* and he generally supports the view that EM fields are functionally relevant and causally potent in the brain.

We'll examine now the various arguments in favor of each of these two approaches: (1) the spike code approach in which regional and global EM fields are largely epiphenomenal (not causally relevant to brain activity or consciousness); (2) the EM field hypothesis of consciousness, in which EM fields at all scales are not only causally relevant, but may be the primary seat of consciousness. To be clear, this EM field approach also accepts the importance of spike code dynamics in the workings of the brain and consciousness, but suggests also that there are additional EM field phenomena, working at a broader range of spatiotemporal granularity, necessary to explain the workings of consciousness.

A final prefatory note is important: the brain is *fundamentally* comprised of (almost) nothing more than EM fields (Hales, 2014; Hales and Ericson, 2022). This bears repeating: there is nothing in the brain that is not comprised fundamentally of EM fields (except, arguably, for the nucleons at the heart of each atom, comprised of strong and weak nuclear fields but which have no bearing otherwise in the physics of life).[1] EM field dynamics simply are the physics of life and consciousness and, as such, apply to all biological structures. Accordingly, this paper is focused on the role of regional and global EM fields over and above the more localized EM fields that are, uncontroversially, the basis for neuronal and synaptic dynamics.

Our approach in this paper is to not create a new and false dichotomy between the brain, on one hand, and its EM fields on the other hand—as just explained, it's all simply a set of nested fields. Rather, we aim to expand understanding of the EM field dynamics, which are the dynamics of both the brain and consciousness, to comprise the full range of spatiotemporal scales (local, regional and global) instead of just the highly localized dynamics of synapses.

2. Are the brain's EM fields causal or epiphenomenal?

We'll now look at representatives of these two opposing views about the role of the various EM fields in brains. We'll also offer our own preliminary remarks about both.

Like the proverbial train whistle on a steam-powered locomotive, some scholars view the EM fields produced by the brain as perhaps only noise (epiphenomena) with no significant causal

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[1] A possible exception may be found in Jones (2019), who attributes different qualia to different masses (and rest energies) of membrane proteins.

role. In this view, they do not affect the underlying function of the brain or play much role, if any, in consciousness. In response to a question about this possible causal potency of EM fields on brain functions and consciousness, a 2020 interview with Christof Koch, with one of the authors of the current paper (Hunt), is worth quoting at length because of its relevance and because Koch's views may be seen as representative of the prevailing view among most neuroscientists.

> While at this early stage of the exploration of the brain it would be foolish to categorically rule out any physical process, as an electrophysiologist I'm less enthused about ascribing specific functions to specific [EM field] frequency bands, let alone experience [Koch's term for consciousness] for two reasons.
>
> Firstly, by and large, the causal actors between neurons that act at the time scale relevant for consciousness (5–500 msec) are action potentials that cause, in turn, synaptic release of packets of neurotransmitters. Most neurons fire highly irregular spike trains, more compatible with a random Poisson process than with a highly synchronized, clocked process of the sort we are familiar with from electronic circuits. Yes, in a deeply asleep cortex, neuronal on–off states occur with a high degree of regularity every couple of 100 msec, leading to theta band oscillations.
>
> Furthermore, given the widespread feedback nature of excitatory pyramid cells and inhibitory interneurons, certain frequencies—such as in a broadly defined gamma band extending from 30 to perhaps 100 or more Hz—can be commonly found in the awake cortex. So, yes, the EEG that is recorded from the scalp outside the skull and its sibling, the local field potential (LFP) that is recorded with thin electrodes inserted into cortex proper (through the skull), all show peaks at particular frequencies. Yet these are broad and are superimposed onto a 1/f^n type of power-law decay characteristic of many natural systems (see Figure 2 as provided by Koch).
>
> Secondly, the extent to which oscillations in the LFP or the EEG have causal influence on firing pattern of neurons remains an open question. Consider the sounds the beating heart makes. These can be picked up by a stethoscope and can be used to diagnose cardiac conditions.
>
> However, there is no evidence that the body exploits these sounds for any function.
>
> My own group has provided some electrophysiological in vitro evidence that oscillations in the extracellular field at particular frequencies may be able to entrain spikes in a cell-type dependent manner (Anastassiou et al., 2011). At this point, we do not know what role such so-called ephaptic coupling (to distinguish them from the more conventional synaptic coupling) play in the human brain.

To summarize, Koch states that he is open to new evidence but he also makes it clear that he does not construe the evidence as supportive of the notion that EM fields (measured, for example, as LFPs or EEG readings) affect neuronal operations in ways sufficient to be important for consciousness, let alone being the primary seat of consciousness. Rather, Koch supports the spike code approach.

Further support for the spike code view comes from Humphries (2020). He provides a book-length overview of the science of "the spike code." Humphries acknowledges, however, that spike activity and its relationship to consciousness remains largely unknown: "what we can predict are the new directions we want to explore. And what we want to explore is everything that is missing entirely from this book because we know nothing about them: spikes that underlie disorders of the brain, and spikes that underlie human thought processes." He adds: "The most obvious chasm in our understanding is in all the things we did not meet on our journey from your eye to your hand. All the things of the mind I've not been able to tell you about, because we know so little of what spikes do to make them."

Humphries is refreshingly humble about how little light the spike code approach currently sheds on human consciousness or consciousness more generally. It is our view that the common

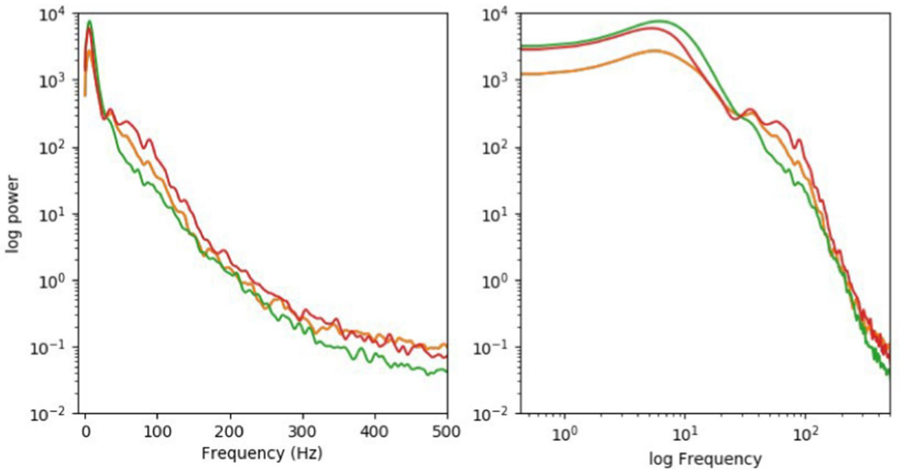

FIGURE 2
Logarithmic (right) coordinates. Typically, the EEG, picked up by large electrodes on the external scalp, will show a related spectrum. No single frequency dominates. The LFP in a human brain looks very similar.

assumption that spike codes can explain consciousness is largely not based on data at this time. It is more of a promissory note, based on the previous success of explaining certain motor and other brain functions through the spike code.

In sketching an alternative view, that EM fields at various scales are functionally relevant and may be the primary seat of consciousness, we offer first two preliminary arguments for considering EM fields to be causally potent and possibly even the primary seat of consciousness:

(1) If the brain's endogenous EM fields were only epiphenomenal, manipulating endogenous EM fields with exogenous EM fields (TMS, tACS, TDCS, etc.) would probably not lead to changes in consciousness. The epiphenomenal view of endogenous EM fields allows only a one-way causal path: neuroanatomy producing LFPs (ECoG) and global EM fields (EEG/MEG) and no causal impact resulting from these fields back on the neuroanatomy that produced them. Just as manipulating the sound of a train's whistle by changing its flowing steam dynamics would have no impact on the function of the locomotive that produces the steam that blows the whistle, so manipulating the brain's EM fields with exogenous EM fields would, in this view, have no impact on consciousness. Yet we know from abundant data that there is a direct impact of various transcranial brain stimulation (TBS) techniques, as well as Deep Brain Stimulation techniques that operate from devices embedded in the brain (DBS), on consciousness. Since these tools, which include TMS, tACS, tDCS, and others, use exogenous EM fields of distinct types to achieve their effects, it would not be possible to have an impact on consciousness without the brain's endogenous EM fields being causally potent in some manner.

(2) Similarly, in physics there is a strong presumption of two-way causality. For example, in discussions about the existence and nature of the ether, in the latter part of the 19th century and early 20th century, some versions of the ether were proposed that were not causally impacted by ponderous matter, but the ether itself did exert influence on ponderous matter. Einstein, among others, critiqued this notion of the ether as "unnatural" because all other things in nature seemed to display a two-way causality (see Kostro, 2000). Einstein's space–time, which has replaced notions of a physical ether, exhibits two-way causality. The notion of EM fields as epiphenomenal is a similarly "unnatural" view of the physics of the brain and consciousness.

These considerations are by no means dispositive of the question at issue: what role do EM fields play in consciousness? They are offered, rather as broad considerations in helping explain consciousness.

Another consideration which suggests that EM fields are conscious is the failure of purely neuronal accounts of standard neuroscience to explain how separate processing circuits bind to form our unified experience such as the unified sensory and emotional experience of seeing an old friend.

For example, some ventral-cortical detectors integrate many lower detectors to recognize particular objects, such as faces, as unified wholes. Yet there are no top-level detectors to recognize all possible visual scenes. Indeed, we can never have a top-level detector for each possible visual scene. So, while standard neuroscience has explained our vision with respect to some shapes and objects, it has not yet explained our perception of the overall unified shapes and layouts in visual images.

Another example of this binding problem is that visual processing uses separate, parallel circuits for color and shape, and it's unclear how they combine to form complete images. Ascending color and shape circuits have few if any synapses for linking their neurons to create colored shapes. Nor do they converge on any central visual area (Zeki, 1993, p. 296; 2003, p. 216). Zeki may have overlooked feedbacks from higher cortex into lower level maps (e.g., see Kawato, 1997; Lamme, 2004; Larkum, 2013). Arguably, these feedbacks might indirectly bind color and shape. But to encode detailed images, feedbacks would have to systematically connect shape and color elements point by point all across neural maps, which even the most detailed maps fail to do (Nor is there any evidence of a central cortical area which higher cognitive functions connect into so as to account for the mind's overall unity (*ibid.*).).

Nor does the firing of color and shape circuits in synchronized lockstep wholly encode their binding (Jones, 2017). For example, Thiele and Stoner (2003), Dong et al. (2008), and others found that neural firing synchrony does not always correlate with color and shape binding. Also, Koch et al. (2016) point out that neural firing synchrony occurs without consciousness during anesthesia and seizures. Here hypersynchrony seems to disintegrate binding. So, there is little support for binding by neural-firing synchrony. This is a different kind of synchrony than the binding by EM-field synchrony which this paper addresses, and our tentative view put forth in this paper is that it is various scales of EM field synchrony that is responsible for binding.

EM field theories of consciousness may explain binding in terms of EM fields, rather than neural-firing synchrony, without the problems above (Jones, 2017; Jones and Hunt, 2023, in progress). For example, while the brain lacks a single, central circuitry to bind colors and shapes together, its separate circuits still generate a single, continuous, unified EM field that can reach across neurons as a continuous wave, thus pooling consciousness in myriad neurons and circuits into a single, unified consciousness (This unified experience dissolves back into isolated, subliminal levels as the EM field steadily weakens). Even where circuits do not connect synaptically, they can still unite if the localized EM fields associated with their diffuse ion currents make contact, as color and shape circuits do in cortical maps.

EM fields are strongest—and most capable of unifying experiences—where they are synchronized (i.e., where their peaks and troughs reinforce rather than cancel each other out). Again, this field synchrony differs from neural-firing synchrony, although they are of course related phenomena and can affect each other. The former has the virtue of being more flexible than the latter. For this field synchrony allows different frequencies (gamma, theta, etc.) to align in phase by nesting within each other (see Section 5.1 below). This flexibility makes field synchrony more capable of explaining the binding which underlies unified, conscious cognition.

Evidence that unified cognition comes from these EM fields takes four forms. First, as already argued, neuronal connections and neural-firing synchrony seem to fail to explain the mind's unity. Second, Koch et al. (2016) argue that locally activated EEGs actually track conscious perceptions across brains better than other events, such as neural-firing synchrony or P300 events. This EEG evidence correlates unified perceptions with EM fields in sensory areas. Third, EM fields alone—in the absence of particles or synapses—evidently propagate signals across slices in hippocampal tissue (Chiang et al., 2019). This indicates that it very likely the continuous fields that unify this activity. Fourth, as noted below, there's growing evidence that oscillating fields help our conscious attention to control aspects of cognition. This indicates that subjects may exert forces in the form of EM fields. This is arguably a crucial facet in the unifying of conscious cognition.

Again, fields theories do not deny the crucial role of neuronal networks in contributing to consciousness. For example, the processing of binocular rivalry, color constancy, and object recognition, etc. are all vital to producing visual images. Field theories only argue that this neuronalprocessing operates behind the scenes. What is conscious in visual networks is just the EM field they generate, according to field theories.

To summarize, we have considered some or the arguments against EM fields being causally potent and we have found that these arguments do not rule out the EM field hypothesis.

3. EM field theories of consciousness

Of the dozens of EM-field theories of consciousness, the one that is most relevant to our account of oscillating fields in conscious cognition is the General Resonance Theory (GRT) of consciousness (Hunt, 2011, 2014, 2020; Schooler et al., 2011; Hunt and Schooler, 2019; Young et al., 2022; Hunt et al., 2022). GRT attempts to characterize the nature of consciousness and offers a quantitative framework for measuring the capacity for consciousness in any given organism or physical system.

GRT assumes that all matter is associated with at least some capacity for phenomenal consciousness, but that consciousness is extremely rudimentary in the vast majority of cases, due to a lack of physical complexity that is mirrored by a lack of mental complexity. EM fields that are associated with all baryonic matter (i.e., charged particles) are thought to be the primary seat of consciousness in GRT. The resonance (similar but not synonymous with synchronization and coherence) between various nested EM fields and the information processing afforded by EM fields are considered necessary and sufficient for consciousness. This EM field-based theory is applicable to all physical structures (of normal matter) and is not limited only to neurobiological or even biological structures (Hunt and Schooler, 2019).

Resonance is the key mechanism by which the basic constituents of consciousness combine into more complex types of consciousness. As the matter becomes more complex and integrated, the capacity for phenomenal consciousness increases. This is the case because shared resonance allows for phase transitions in the speed and bandwidth of information exchange to occur at various organizational levels, allowing previously disordered systems to self-organize and thus become coherent at multiple scales. The speed and bandwidth of information flows achieve a step change through such a phase transition, allowing for the unity of consciousness in each moment.

The spatial and temporal boundaries of any particular conscious entity are established by the slowest-frequency shared resonance within that conscious entity, for each particular information/energy pathway (Hunt, 2020; Young et al., 2022). Shared resonance and resulting resonance chains are the key mechanisms for self-organization and are constantly changing in most entities (Walleczek, 2000). Thus, the spatial and temporal boundaries of conscious entities will be constantly changing at least a little (Hunt calls this constantly changing EM field structure in human and mammalian brains "the blob" in Hunt, 2020).

Most combinations of consciousness, in which less complex entities combine into more complex entities in biological structures like mammal brains, will be comprised of a nested hierarchy of conscious entities, with one dominant conscious entity in each moment, without extinction (elimination) of the nested entities. This notion is stated well by Whitehead (1929): "The many become one and are increased by one." This lack of extinction of subsidiary entities distinguishes GRT from IIT and other theories that assume the extinction of nested conscious entities, leaving only one macro-conscious entity left (this is a consequence of, e.g., IIT's "exclusion principle").

It should be noted that GRT compares in interesting ways with the Integrated World Modeling Theory (IWMT) in Safron (2020). The latter is an intriguing attempt to reconcile integrated information theory and global neuronal workspace theory within a unified systems theory. Here consciousness is "what it is like to be processes capable of generating integrated models of systems and worlds with spatial, temporal, and causal coherence" (p. 1). This involves "synchronized couplings [that] take the form of hierarchically organized modules." These further involve "connectome harmonics" and "communication through coherence" (p. 14).

IWMT and GRT thus both seem to align at the most abstract level in that both rely on communications *via* coherent resonances between parts to produce coherent wholes. But GRT has a narrower view of which hardwares embody these mental systems. For reasons given above in Section 2 (and below at the start of Sections 4, 5), GRT attributes unified, conscious cognition to EM fields associated with neuronal circuits rather than the neuronal circuits themselves (their connections or synchronies) or to information transfers in general.

An implication of this EM approach is that it attributes minds not only to the EM fields in organic brains, but also to artificial brains that may eventually replicate these organic fields. This partly aligns GRT with Safron's abstract account of minds based on various possible kinds of hardware.

We will focus now on the physical mechanisms by which EM fields may form the physical basis for consciousness.

4. Regional and global EM fields interact with neural circuits

The remainder of our paper will build on the arguments above for the EM-field hypothesis. The outline of the overall argument is as follows. (1) Conscious cognition is unified by synchronized EM fields, not only by the underlying circuits generating them (from Section 2 above). (2) These oscillating EM fields also help to make the firing of the circuits oscillate coherently (see Section 4 below). (3) Oscillating circuits guide conscious cognition (Section 5). (4) So, EM fields help guide and unify conscious cognition, which means that they aren't epiphenomenal, and may in fact be the primary seat of consciousness (Section 6). In accordance with this outline, the present section will explain (2) above by reviewing evidence which suggests that the brain's extra-synaptic EM fields (local, regional and global) help make neuronal circuits oscillate through increased and more synchronized synaptic spikes.

It is, again, important to note the physical fact that all parts of the brain are comprised of nothing more than EM fields, fundamentally, so what we are focused on in this section is the role of regional and global EM fields over and above the highly localized EM fields that (uncontroversially) comprise the totality of neuronal and synaptic dynamics (Hales, 2014; Hales and Ericson, 2022). These local, regional and global EM fields are produced by, but not identical with, the brain, in the same manner that twigs and leaves are produced by a tree's branches and trunk but are not the same as the branches and trunk. As such, the EM fields represent the more granular, both spatially and temporally, aspects of the brain's structure and functioning than the more obvious neuroanatomy of the brain. The brain's regional and global EM fields seem to be more sensitive to small changes than the neuroanatomy of the brain, and thus may be capable of far higher rates of information processing and accompanying phenomenal consciousness. These fleeting, flexible fields may help explain how kaleidoscopic experiences emerge from relatively fixed neuronal structures much like intricate music arises from a fixed orchestra (*cf.* Fingelkurts et al., 2010). We flesh out these statements below.

4.1. How do neurons communicate?

Neurons and other excitable cells communicate via action potentials, i.e., rapid sequences of changes in the voltage across the cells' membranes that propagate signals along the membranes. At least four structures or activities contribute to changes in neurons' electrical potentials that may culminate in action potentials: (1) Synapses are specialized structures that release neurotransmitters between cells; (2) gap junctions are tiny channels that bridge adjacent cells, thus allowing charged particles (ions) to flow directly between the cells; (3) diffusion can move particles across the fluid extracellular space between cells without synapses or gap junctions; and, finally, (4) ephaptic coupling is "proposed to involve cell-to-cell transfer of electrical activation via electric fields, or ion transients" (Chiang et al., 2019; Gourdie, 2019). EEGs detect these ion currents and their fields some distance from their origins. While this involves some diffusion, the prime mover is electrical.

While communicating, neurons' activities naturally oscillate between firing and nonfiring states, and these oscillations can sometimes align so that they fire together. This can occur due to rhythmic external stimuli such as flickering visual inputs to retinas. It can also occur due to synaptic interactions between neurons. Entrainment is this process of rhythmic stimulation (endogenous or exogenous) causing neurons to synchronize their firing.

The prevailing view has long been that EM fields are so weak in brains that they are virtually negligible in terms of any effects on brains or consciousness. But this view has changed in recent years. Looking at the evolutionary origins of EM field oscillations, Buzsaki (2004) states: "These [electromagnetic field brain] oscillations are phylogenetically preserved, suggesting that they are functionally relevant. Recent findings indicate that network oscillations bias input selection, temporally link neurons into assemblies, and facilitate synaptic plasticity, mechanisms that cooperatively support temporal representation and long-term consolidation of information."

A series of experiments—including Frohlich and McCormick (2010), Anastassiou et al. (2011), and Anastassiou and Koch (2015)—the last was mentioned in the interview with Koch quoted above—showed that even weak exogenous (externally caused) fields can be applied to entrain spikes within slices of neural tissue. Furthermore, computer models (such as Hales, 2014) indicate that extracellular fields can synchronize network activity and alter signaling in neural networks. This growing body of data suggests that endogenous (internally caused) fields can affect rhythms in brains.

Skeptics reply that these effects of exogenous fields on neural tissue still do not show that the brain's own endogenous fields influence neural operations. They also argue that it would be hard to show that these endogenous fields and ion currents influence neurons because this effect could be due instead to ion currents in gap junctions.

But recent experiments have countered such skepticism with evidence that ephaptic effects do occur in various tissues. This data will be detailed in the rest of this section. The studies most important to our aims are examined in some detail, while the others are only sketched.

Gourdie (2019) took aim at the long-held view that gap junctions propagate action potentials (electrical impulses) in heart cells to produce heartbeats. He contended that mounting evidence has made this unlikely. For example, genetically altered mice without gap junctions retain heart function intact. Also, bird hearts have too few gap junctions to support reliable propagations.

Gourdie drew on computational and experimental work in the last decade to argue that propagation of action potentials in the heart probably involves both gap junctions and adjacent sodium-gated channels. These channels are close enough in neighboring cells (<30 nm) to enable ephaptic (electric-field) transmission of action potentials between the cells.

Zhang et al. (2019) presented evidence of ephaptic modulation of sensory circuits at the most peripheral level. They started by noting that, in general, olfactory receptor neurons (ORNs) housed in the same sensory hair in fruit flies often inhibit each other in ways that affect perceptions and behavior. Previous studies showed that, despite the lack of direct synaptic connections, activation of one ORN suppresses the activity of its neighbor (e.g., Su et al., 2012). These inhibitions appear to help in discriminating which odors are present.

For example, in the Drosophila (fruit fly) antenna, different subtypes of olfactory receptor neurons (ORNs) reside in the same sensory hair, and these inhibit each other non-synaptically. Zhang et al.'s recordings from pairs of sensory hairs impaled by the same tungsten electrode showed that direct electrical interactions (ephaptic coupling) on their own can produce lateral inhibition between ORNs. In contrast, there were no synaptic or gap-junction connections between the receptor cells to create the inhibitions. The researchers concluded that the inhibitions are mediated ephaptically. They argued that this ephaptic activity allows more rapid peripheral processing of odor-mixtures and more elaborately patterned neural coding at higher levels.

Zhang et al. explain additionally that ephaptic interactions involve uninsulated neurons packed together. This allows their electric currents to contact each other. These types of neuronal groupings commonly occur in bundles of unmyelinated axons, such as found in mammalian retinas, olfactory nerves, and interoceptive nerves. These neuronal groupings also commonly occur in the cerebellum, which serves motor movements—thus implicating ephaptic influences in motor control. These groupings also exist in hippocampus, which serves memory consolidation (see directly below). This involves transferring fleeting short-term electrochemical memory traces into more long-term chemical storage via protein synthesis. In all these cases just listed, electrical activity alters chemical activity in neurons.

Martinez-Banaclocha (2020) went further than Zhang and her team. Citing Frohlich and McCormick (2010) and Anastassiou et al. (2011), he said that ephaptic coupling "seems higher in oriented cortical structures like neocortex and hippocampus, where pyramidal cells organize in minicolumns with well-developed layers… These particular arrangements of neurons in the cerebral cortex and hippocampus allow a parallel and radial alignment (orthogonal) of the interstitial space that has relatively low impedance to the extracellular ionic currents."

The strongest evidence for ephaptic coupling, however, has come from Dominique Durand's team at Case Western Reserve University. For example, Chiang et al. (2019) studied slow periodic hippocampal oscillations (<1 Hz) in mice likely related to memory consolidation during sleep. They showed that these waves synchronized the propagation in ways best explained by ephaptic coupling (They characterized this coupling as a group of neurons generating an electric field capable of activating neighboring neurons, even though such fields were thought to be too weak to do so). This surprising result was triple checked at the request of the *Journal of Physiology*.

These researchers showed that the propagation speed (0.1 m/s) across longitudinal slices of hippocampal tissue taken from mice brains was unaffected by blocking synaptic activity. To start with, they eliminated all means of transmission except ephaptic coupling by cutting entirely through a hippocampal slice, severing it into two parts. The slow wave still propagated at the same speed as in the intact hippocampus until the gap reached 400 microns. Gap junctions (which directly connect cells) and synapses cannot account for how the wave activated tissue on the far side of the cut. Transmission by ion diffusion was also precluded because it's far too slow to account for the wave's 0.1-m/s transmission speed. In contrast, the slow wave was blocked by an anti-electric field, thus "strongly supporting the hypothesis that these waves propagate by ephaptic coupling."

These results indicate that the slow hippocampal waves aren't propagated by synapses, gap junctions, or ion diffusions. Instead, the propagation is explicable ephaptically by neurons generating electric fields to activate neighboring neurons, thus generating a self-propagating wave (which even regenerates itself across gaps). The authors conclude that "a wave can propagate by endogenous electric fields, instead of synaptic transmission, by activating neighboring neurons through ephaptic coupling."

Further experiments by Durand's laboratory (Shivacharan et al., 2019) also studied slow periodic wave activity in longitudinal slices of rodent hippocampus. They studied epileptiform waves (induced by 4-AP, a potassium-channel blocker) quite similar to the slow waves directly above. They used similar methods and reached similar conclusions.

The authors cited various studies that show this spontaneous activity propagates at a speed (0.1 m/s) that differs from those in synaptic propagation, axonal conduction, or ion diffusion. By contrast, this speed is compatible with ephaptic coupling. So they investigated whether this slow periodic propagation could be fully accounted for in ephaptic terms.

The hippocampal slice was cut with a scalpel, and the two halves were separated to verify the cut. They found that as they increased the distance between the halves slightly, activity arriving at one side of the cut still propagated across the cut to activate neurons at the other side. This showed that "propagation goes through a cut, strongly suggesting that the mechanism of propagation involves ephaptic or electrical field coupling."

Furthermore, consistent with purely ephaptic transmission, this propagation of the wave across the slice wasn't precluded by pharmacological blockers, including a pharmacological blockade of electrical transmission *via* gap junctions. Importantly, applying a voltage clamp completely blocked propagation of the neuronal activity by canceling the incoming field at the cut and preventing any ephaptic effects. So the ephaptic effect was shown to be necessary for propagation across the slice.

The self-propagating nature of the wave was evident from neurons on one side of the cut recruiting neurons on the other side. Also, in a separate experiment, stimulating this hippocampus slice (with a field of the same strength as its endogenous field) produced a self-propagating wave through the intact slice.

In summary, Shivacharan et al. showed that synchronized, self-propagating slow-wave activity in rodent hippocampus tissue can jump across cuts in the tissue, strongly suggesting the propagating synchrony involves the wave's EM field. These waves propagate at similar speeds to theta waves and may serve similar functions as a timing signal for neural plasticity without disturbing synaptic weights.

The authors warn that their findings about hippocampal slow waves do not necessarily apply to the dynamics of cortical slow waves. While their hippocampus slices had a dense laminar organization, cortical organization is more heterogeneous. Propagation in the latter is more likely synaptic, especially for long ranges to other brain regions (But compare contrary passages from Shivacharan et al., 2021 below and Zhang et al., 2019 above).

More recent experiments in Durand's lab have shown that (a) ephaptic effects occur *in vivo* in anesthetized rats, not just in tissue taken from rat brains (Subramanian et al., 2022), and (b) ephaptic effects occur in cortical tissue, not just hippocampus tissue, suggesting that the effect is robust in brain tissue (Shivacharan et al., 2021).

Han et al. (2020) showed that ephaptic coupling occurs in the cerebellar cortex of mice, which fine tunes purposeful motor activity *via* sensory feedback. They note that climbing fibers from the inferior olive enter into this cortex, where they wrap around and synapse with the highly branching dendrites of Purkinje cells. The climbing fibers have powerful action potentials, and the Purkinje cells are tightly packed together with dendrites that are parallel to each other and very large. These two factors make this network well-suited to ephaptic coupling.

They used *in vivo* and *in vitro* (inside and outside the mice) recording techniques with sub-millisecond resolution to identify the joint activity of climbing fiber and Purkinje cells. They found that a climbing fiber's powerful action potential generates large ion currents that spill over into intercellular space and exert a huge negative electric field strong enough to ephaptically affect the excitability of cells nearly 60 microns away. This hyperpolarized nearby Purkinje cells and reduced their firing.

A single climbing fiber could thereby ephaptically and synchronously pause the firing of over a hundred Purkinje cells for several milliseconds. This yields rapid, precisely timed spiking in downstream neurons far faster than any synaptic transmission. It enables climbing fibers to play central roles in controlling cerebellar activity and learning.

They discounted any role for gap junctions in the coordinated Purkinje cell activity, for there's no real evidence of gap junctions in these cells, and gap-junction blockers do not affect the Purkinje-cell activity (Han et al., 2018). They also discounted disynaptic influences (where cells synapse via an intermediate cell) because they have longer time spans than the observed ones.

The authors described contrasting kinds of ephaptic coupling. One contrast concerns how close in space the ephaptic effects occur to synapses. The authors said that most ephaptic couplings described previously involve currents between neurons near where they synapse. But some ephaptic coupling also involves currents between neurons distant from their synapses (as when currents from one Purkinje cell's sodium channels opens sodium channels in a neighboring Purkinje cell, distant from synapses—see Han et al., 2018).

Another contrast in ephaptic coupling concerns the number of cells involved. Often many neurons can ephaptically interact to correlate their firing (Anastassiou et al., 2011). At other times, voltage-gated channels in single cells can generate substantial currents that ephaptically influence the excitability of neighboring neurons (Han et al., 2018).

How does the ephaptic coupling focused on by the authors align with these contrasts? Firstly, in terms of closeness to synapses, the powerful climbing-fiber currents they studied came from ion channels near synapses. Secondly, in terms of the numbers of neurons involved, these powerful currents from single climbing fibers influenced many nearby Purkinje cells.[2,3]

In summary, a number of recent published experiments have provided increasingly strong evidence of ephaptic field effects, which by definition do not rely on synaptic connections. At the least, this evidence supports a multi-modal gestalt of information and energy flows in the brain, resulting in our conscious experience in each moment of waking consciousness.

4.2. Is the evidence for ephaptic coupling on firm ground?

Despite the evidence above, skepticism about ephaptic coupling persists. For example, in the same interview mentioned above (Hunt, 2020), Koch replied to claims of ephaptic field effects presented in Chiang et al. (2019) above as follows:

> As an experimentalist, I am skeptical of these claims, in particular given their statistical validity and effect size. Of course, at this point, no neuronal mechanisms, can be definitely ruled out (including exotic macroscopic quantum effects), as long as they don't violate the laws of physics.

Chiang's results might conceivably reflect statistical flukes, as Koch suggests, but the proliferating variety and number of ephaptic-coupling studies argue against Chiang et al.'s findings being flukes. In this interview (as already noted), Koch adds to his critique above by arguing that it's unclear what role (if any) ephaptic coupling plays in brains.

We may respond to this criticism by reiterating the recent evidence above that ephaptic effects occur in uninsulated neurons packed together with parallel alignments in sensory circuits, hippocampus, cerebellar cortex, and neocortex. These sites are involved in perception, memory, motor control, and higher cognition.

Buzsaki et al. (2013) directly addresses Koch's concerns about the averaging effect, and a 1/f^n distribution of EEG oscillations, noting that while there is a 1/f^n distribution over long temporal scales there are marked departures from that distribution during various function-related measurements, and is worth quoting at length (emphasis added):

> Integrated over a long temporal scale, the power distribution of the various frequencies has the appearance of 1/f^n "noise", partly reflecting the fact that slow oscillations generate large, synchronous membrane-potential fluctuations in many neurons in brain-wide networks, whereas faster oscillations are associated with smaller changes in membrane potential in a limited number of cells, that are synchronized only within a restricted neural volume. **Nonetheless, when the brain engages in specific functions such as processing sensory stimuli, directing attention to particular features, orienting in space, engaging working memory, or preparing movements, the dynamics of the involved structures changes and particular oscillation frequencies become dominant**. In these cases the frequency-power relationship deviates from the 1/f statistics, and a peak (bump) appears in the respective frequency band.

Moreover, given the remarkable results found by the Chiang team, the journal (*The Journal of Physiology*) required them to replicate their results before publishing their paper, which they did. Durand, the primary investigator on the Chiang et al. paper, was as surprised as everyone else about their results, as he told a science reporter in 2020[4]: "It was a jaw-dropping moment, for us and for every scientist we told about this so far."

5. Oscillating circuits help guide cognition and consciousness

This section presents further evidence supporting our thesis that EM fields may help guide cognition and consciousness.

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[2] Ephaptic effects may even exist in glial cells, including astroglial cells and oligodendrocytes that produce myelin sheathes around axons. Schmidt et al. (2021) calculate that in myelinated axonal fibers "only ephaptic coupling can explain the reduction of [sensory] stimulus latencies with increased stimulus intensities, as observed in many psychological experiments." Additionally, Martinez-Banaclocha (2020) argues that the biomagnetic field effects of astroglial cells can ephaptically affect cortical communications.

[3] Ephaptic effects may also exist in muscular activity. Roth (1994) suggests that such effects may feed back onto motor neuron axons, creating reverberating loops that help in repetitive firing. Also, ephaptic coupling may play a role in neuropathic pain *via* crosstalk between damaged nerves and adjacent fibers. Cohen and Mao (2014) note here that secondary hyperalgesia "is seen in adjacent undamaged tissue owing to sensitization within the CNS... In part, this may be caused by ephaptic transmission or the expansion of receptive fields of injured nerves (or both)."

[4] Online at https://www.sciencealert.com/neuroscientists-think-they-ve-found-an-entirely-new-form-of-neural-communication.

We have reviewed evidence above that oscillating neural EM fields make neural circuits oscillate coherently. Now, in accordance with our overall outline, we will review evidence that these oscillating circuits help guide conscious cognition (again, the more important studies will be discussed in more detail). These two lines of evidence will lead ultimately to our conclusion (in Section 6) that EM fields aren't epiphenomenal, and may in fact be the primary seat of consciousness.

But it must be acknowledged from the start that the studies below which show that oscillating circuits help guide conscious cognition do not typically claim that EM fields are involved in this conscious cognition, as our overall argument contends. Our reply is to refer back to the key evidence above that it is EM fields that help to make circuits oscillate coherently—and that it is these fields that also unify conscious cognition, while circuits alone do not create this unity (Section 2). This is why our overall argument is that it is EM fields that help unify and guide conscious cognition and that these fields may be the primary seat of consciousness itself.

We first take note that neuronal oscillations consist of rhythmic patterns in membrane potentials and action potentials that may be detectable by EEGs, and other tools; (these other tools are important due to the poor spatial resolution of EEGs, as noted below) and are created by neuronal interactions. The various frequencies of the oscillations are associated with various cognitive functions.

For example, delta waves (0.1–3 Hz) are associated with dreamless, slow-wave sleep and memory formation (Huber et al., 2004). Theta waves (4–7 Hz) associate with relaxed daydreaming and are likely involved in spatial learning and navigation (Buzsaki, 2005). These waves associate with gamma activity during memory tasks (Nyhus and Curran, 2010). Alpha waves (8–12 Hz) also associate with relaxed reflective states (Roohi-Azizi et al., 2017). They may inhibit cortical areas that aren't in use, and they may play active roles in network coordination (Palva and Palva, 2007). They also help modulate conscious perception (Gallotto et al., 2017). They may work in a top-down fashion along with beta waves to control gamma-wave activities (Fries, 2005).

At higher frequencies and more active cognitive states, Beta waves (12–38 Hz) associate with active concentration (Baumeister et al., 2008), learned rules and abstract categorization (Wutz et al., 2018), and inhibition of unneeded cortical activity (Lundvist et al., 2016). Gamma waves (38–100 Hz) associate with bottom-up roles in memory, attention, working memory, and perceptual grouping, often along with top-down theta (Buzsaki, 2006) and alpha/beta control.

5.1. The role of cross-frequency coupling (CFC) in cognition and consciousness

There are three main features of any EEG sine wave signal: frequency, amplitude, and an additional phase term defining the specific phase at origin. Phase synchrony, also known as phase–phase coupling, is one type of CFC that is functionally relevant for the workings of the brain and thus for consciousness (Siebenhuhner et al., 2020: "Phase synchronization of neuronal oscillations in specific frequency bands coordinates anatomically distributed neuronal processing and communication.") Numerous theories highlight the role of synchrony, coupling, coherence, or resonance (all similar albeit not synonymous terms), as a key mechanism for brain function and thus consciousness.

For example, Crick and Koch featured this concept in their neurobiological theory of consciousness (Crick and Koch, 1990; Koch, 2004). John (2001) makes "zero phase lag synchronization" central to his electromagnetic field theory of consciousness. Varela and colleagues suggested that the most plausible candidate for large-scale integration of consciousness is the "formation of dynamic links mediated by synchrony" (Varela et al., 2001). Fries (2005, 2015) has made the concept of "communication through coherence" (neural synchrony/resonance) even more widely known. Nunez and Srinivasan (2010) have developed a "binding by resonance" approach in various works; Dehaene, 2014 highlights the role of long-range synchrony between cortical areas as a key "signature of consciousness," (as does Koch, 2004). Hahn et al. (2014) have developed a "communication through resonance" theory of neuronal network dynamics. Grossberg (2017) has developed an Adaptive Resonance Theory (ART) of consciousness over the last two decades and argues that "all conscious states are resonant states," but that not all resonant states are conscious states. Bandyopadhyay (2019) has made the concept of resonance and resonance chains central to his Fractal Information Theory of consciousness.

A limitation of phase synchrony in neuronal firing is that gamma-frequency waves, for example, do not always correlate with conscious cognition, as noted in our discussion of binding above. However, phase synchrony in EM fields, more generally, tends to avoid this problem, for it's more flexible. It allows different frequencies (gamma, theta, etc.) to fire in phase by nesting within each other. It is thus more capable of explaining the binding which underlies unified, conscious cognition, as a mechanism for selective resonance across different parts of the brain and body.

Note that while the studies below typically use neuronal synchrony to help explain conscious cognition, we nonetheless construe these studies as evidence that it is actually field synchrony, rather than only neural firing synchrony, that helps explain conscious cognition. This is plausible because neuronal synchrony helps produce more large-scale EM field synchrony. The upshot of all this is that while neuronal synchrony by itself does not seem to explain conscious cognition, it still contributes to the creation and sustaining of field synchrony, which can better explain conscious cognition as a gestalt of various spatiotemporal scales of EM fields.

We'll now examine more specific examples of CFC in the workings of the brain and consciousness.

5.2. Perception and neuronal oscillations

There's significant evidence that neuronal oscillations play roles in sensory circuits by reflecting or fostering rhythmic changes in membrane excitability that weight sensory inputs and modulate sensory detection. For example, Spaak et al. (2014) presented human subjects with rhythmic visual stimuli and found through magnetoencephalography that this entrained visual cortical activity. These alpha oscillations led to better performance in visual detection tasks, supporting claims that alpha oscillations cause temporal organization of visual perception. Similarly, Helfrich et al. (2014) found that stimulating parieto-occipital cortex with 10 Hz tACS (transcranial alternating-current stimulation) entrained activity in this cortex and modulated visual detection performance, again highlighting the role of alpha oscillation in visual perception.

Neuling et al. (2012) showed that human auditory detection thresholds depended on the phase of the brain activity (the alignment of its oscillations' crests and troughs) that was entrained by alpha frequency transcranial direct current stimulation (tDCS). Manipulation of the brain activity's phase led to different detection thresholds, showing that auditory perception can be modulated by oscillatory processes. Gundlach et al. (2016) found that tACS applied over human occipital areas at the alpha frequency intrinsic to that area entrained alpha oscillations and modulated perception of weak somatosensory stimuli. Samaha et al. (2020) pointed out that spontaneous neural oscillations have emerged as key predictors of variations in perceptual decisions concerning, for example, the detection and discrimination of sensory stimuli (while the fidelity of stimuli remains unchanged). They claimed in particular that the amplitude of ongoing alpha oscillations "bias sensory responses and change conscious perception."

From studies like those above, Gallotto et al. (2017) concluded that "alpha-band (7–13 Hz) may index [indicate], or even causally support, conscious perception." One factor that helped establish the genuinely causal over the merely indexical was the technique of showing that only rhythmic—not arhythmic—stimulation supports conscious perception (see below).

Other rhythms, in addition to alpha ones, may affect conscious perception. For example, Helfrich et al. (2017) discovered evidence that frontal top-down activity involving delta oscillations helps control posterior bottom-up alpha activity, thus selectively facilitating visual perception. Participants were asked to detect a near-threshold target after a train of stimuli was presented either at an alpha frequency or arhythmically. They found that the bottom-up alpha rhythm entrained posterior cortical activity and modulated stimuli detection. Importantly, the arhythmic activity did not do so. A top-down delta rhythm from prefrontal areas modulated this alpha activity to selectively facilitate visual perception.

Vernet et al. (2019) found evidence that beta rhythms also affect conscious perception. This is important because beta waves are tied to more active, concentrated thought than alpha waves. They noted that previous evidence from numerous sources showed that the ability to consciously acknowledge the presence of a visual target is associated with beta oscillations in cortical areas, including the frontal eye field. They investigated whether this previous evidence points to a genuine causal role in visual cognition for the beta oscillations (which are coordinated by theta oscillations linked to focal attention).

These researchers recorded EEG signals on humans performing a visual detection task (reporting whether and where a visual target appeared) while receiving transcranial magnetic stimulation (TMS) to the frontal eye field. These stimulations were either arhythmic or at rhythms natural for this cortical area. They found that the rhythmic stimulation caused frontal eye field oscillations with greater phase alignment and amplitudes than the arhythmic stimulation caused. These entrained beta oscillations correlated with increased sensory consciousness (estimated by visual detection sensitivity). This finding that the magnitude of high-beta entrainment correlates with increases in visual performance "provides evidence in favor of a causal link between high-beta oscillatory activity in the frontal eye field and visual detection." But these results should be viewed with some caution due to the study's heavy reliance on EEGs, which can record activity from different sources and in distorted ways.

Somer et al. (2020) showed that theta oscillations in human visual cortex can modulate visual perception. Various studies indicate that perception can be modulated by the phase of neural oscillations, especially in the theta and alpha ranges (e.g., Busch and VanRullen, 2010). This oscillatory activity can be entrained in visual cortex either by transcranial alternating current stimulation (tACS) across the visual cortex—or by periodic visual stimulation (flicker). What Somer et al. investigated was whether visual perception is modulated when this tACS and flicker are synchronized.

They found that performance on a visual matching task (where subjects picked which figures looked most similar) was significantly improved when theta frequency tACS over the visual cortex were in phase with simultaneous visual stimulus flicker, but not when the two were out of phase. So, extending previous studies on visual and auditory perception, their results support a causal role for synchronized oscillations in perception.

5.3. Attention and neuronal oscillations

Turning from perception to attention, there's considerable evidence to support the argument that neuronal oscillations influence attentive processes. Fiebelkorn et al. (2018) are especially helpful here because their review paper spells out in detail how theta rhythms help organize attention processes. They draw on existing evidence that environmental sampling is a rhythmic process in which covert selective attention and overt exploratory movements are separable yet tethered to theta-band activity in the attention network (e.g., Juan et al., 2008). They point out that the fronto-parietal aspect of this network is at the nexus of sensory and motor functions. It directs these coupled processes of sensory input and exploratory movements (of eyes, whiskers, etc.).

Their review paper argues that significant evidence supports the argument that this network's theta rhythms resolve potential sensory and motor conflicts by periodically re-weighting connections between higher brain regions and either sensory or motor regions. This rhythmic re-weighting alternately promotes either sensory sampling or shifting of exploratory movements to another location. This alternation between sampling and shifting involves theta-frequency control over, for example, enhanced sensory processes at gamma frequencies, attenuated sensory processes at alpha frequencies, and attenuated motor processes at beta frequencies.

These authors speculate that the theta alternations between sampling and shifting likely evolved because they brought flexibility to attention, allowing it to disengage and shift to new objects. This rhythmic cycling through alternative representations (rather than fully processing items simultaneously) may also be evident in, for example, working memory where multiple items are entertained together.

Bastos et al. (2018) showed how various frequencies have their own roles in attention. They recorded spiking in the frontal cortex layers of monkeys performing working memory tasks. These recordings indicated that ascending gamma-frequency oscillations are linked to sensory activity while descending beta oscillations are linked to attention's inhibition of the gamma activity. Beta rhythms thus help sculpt the focus of attention and content of working memory which is crucial to voluntary control over behavior.

Narikiyo et al. (2020) found that the claustrum, a thin structure that connects cortical and subcortical areas, plays a role in allocating attention and synchronizing cortical activities (As already noted, this neuronal synchrony is no longer treated, by itself, as a binding mechanism for unifying experience; however, it does contribute to binding by EM fields at various spatiotemporal scales, which arguably does play such a role, as argued above). They showed how the claustrum has extensive reciprocal connections across the cortex and transmits signals not to specific areas but all across many cortical areas.

They reported that the claustrum coordinates the generation of slow waves in neocortex. They used optogenetic activation of neurons in slices of mouse claustrum to show how certain claustrum neurons silence neural activity in all layers of many cortical areas, then globally synchronize cortical activity at slow frequencies.

This shows a role of the claustrum in synchronizing inhibitory interneurons across the neocortex to coordinate brain states. It indicates that the claustrum is a major hub for synchronizing global neocortical slow-wave activity.

5.4. Working memory and imagination

Neural oscillations may also play a strong role in working memory. Bahramisharif et al. (2018) started with Lisman and Idiart's (1995) proposal that working memory's representation of multiple items (such as a phone number) uses a neural mechanism in which items are repeatedly activated in sequence by means of coupled oscillatory neural activity in theta/alpha and gamma-range.

Bahramisharif et al. offered experimental support for this proposal. They showed subjects three letters in brief sequence then asked several seconds later whether a fourth letter matched one of the three. Intracranial recordings of the subjects' electrocorticographic activity showed that as subjects recalled the list of items, this activated theta/alpha oscillations: "Simultaneously, the brain exhibited item-specific activations of gamma activity that appeared at a theta/alpha phase corresponding to the item's position in the sequence." This shows how interacting cortical oscillations contribute to working memory. It's a form of cross-frequency coupling (CFC), which is a general term for different frequencies interacting in a synchronized manner in the same brain region (Lisman and Jensen, 2013).

Kay et al. (2020) showed that theta oscillations may play a role in working memory. In this role, these oscillations are instrumental to some forms of imagination, planning, and decision making. Such activities can represent hypothetical future experiences quickly and constantly over time during escape, predation, and other demanding situations.

They used rats fitted with electrodes in their dorsal hippocampus who were seeking rewards by navigating mazes. They found that different hippocampal place cells (which are used in navigating) actually fired in constant alternation at 8 Hz as rats weighed alternative routes to take in a maze. The point is not that the rats actually thought back and forth about the alternatives many times per second, but just that the theta activity kept the images constantly alive in working memory like a tuning fork keeps sustains a pitch. This rhythmic firing of the different cells presumably enables the alternatives to remain separate in imagination while uniting them in the same decision process.

This rhythm matched the hippocampal theta frequency known to entrain hippocampal neural firing. The authors speculated that the rhythmic firing of these place cells suggests the existence of "a single common dynamical process that generates representations of hypothetical scenarios, including possible futures." They suggest that this computational process may help shed light on the origins of imaginative activity, which is currently poorly understood.

Other studies focused on theta rhythms in the grid cells of the entorhinal cortex. These grid cells are connected to hippocampal place cells and respond to the place cells. Unlike place cells, hexagonally arranged grid cells allow navigation without landmarks (as when blindfolded) using just distance and direction. Like place cells, grid cells have roles in imagination. For grid cells represent not just spatial dimensions but also conceptual dimensions. In both cases, the grid cells produce characteristic hexagonal signals detectable by fMRIs.

For example, as subjects watched a bird silhouette with stretching and shrinking legs and neck, the hexadirectional signal appeared—as if the subjects were navigating a two-dimensional (neck and legs) bird space (Constantinescu et al., 2016). Similar, grid-like hippocampal cells seem to help us imagine social spaces with dimensions of affiliation and hierarchy (Schafer and Schiller, 2018).

The point is that grid and place cells work together and exhibit theta oscillations. Yet it's not clear whether the theta cycle helps grid cells simultaneously imagine conceptual dimensions like they help place cells simultaneously imagine alternative routes. But it's still possible that the theta cycle is a fundamental computational unit that the hippocampal-entorhinal system uses to imagine conceptual dimensions and alternatives. As some of these authors suggest, maps in this system may help us model relational structures ranging from the spatial to the purely conceptual, allowing our imaginations to find shortcuts and infer hidden relationships.

Riddle et al. (2020) also tried to establish a causal role for theta and alpha oscillations in working memory. Previous studies showed that working memory involves prioritizing relevant information and suppressing irrelevant information. These studies also showed that the activities are linked to theta frequency oscillations in lateral prefrontal cortex and alpha oscillations in occipito-parietal cortex, respectively (e.g., Wallis et al., 2015; de Vries et al., 2020). But many of these studies relied on EEGs whose limited spatial resolution hinders their ability to isolate causes and effects—especially compared to the precision of transcranial magnetic stimulation (TMS).

To investigate whether these links between oscillations and working memory were genuinely causal in nature, rather than only correlational, Riddle et al. set up a working-memory task that cued human subjects as to which displayed item should be attended to. The past evidence above predicted (for example) that if the task triggered the prefrontal cortical response, this response would exhibit the theta oscillations linked to this cortex.

The researchers then applied transcranial magnetic stimulation (TMS) of theta, alpha, and arhythmic frequencies to prefrontal and parietal regions (identified by functional magnetic resonance imaging, fMRI). They found that the effect of the TMS depended on whether its frequency matched the oscillations in these areas that was predicted above. For example, if the working memory task was predicted to cause theta oscillation in prefrontal cortex, and the TMS was applied there at this theta frequency, then they found that working memory performed well. But if the oscillations mismatched, then working memory did not perform well. These results (and others in their paper) provide support for causal roles for prefrontal theta oscillations and parietal alpha oscillations in the inner control of working memory.

Siebenhuhner et al. (2020) looked more broadly at this role of lower theta and alpha frequencies in coupling with higher frequencies (another example of cross-frequency coupling) to coordinate brain activities. They argued that this coupling enables various frequencies of activity in anatomically distributed areas to coordinate neuronal processing. They view the different kinds of this cross-frequency coupling as essential to large-scale coordination of activities between anterior and posterior brain areas.

Working with MEG (magnetoencephalography) and EEG (electroencephalogram) techniques, Siebenhühner et al. developed their own methods of distinguishing genuine coupling from spurious artifacts to reliably identify human brain-wide coupled networks. The strength of these large-scale networks predicted cognitive performance in a separate assessment. They drew on numerous previous studies of how theta-alpha oscillations are associated with top-down regulation of brain activities, and how beta and gamma oscillations are associated with bottom-up sensory processing, as well as how beta oscillations are associated with sensorimotor processing.

5.5. Long-term memory

Neuronal oscillations may also play a role in long-term memory. Lisman and Jensen (2013) examined studies of theta and gamma oscillations engaged in cross-frequency coupling in the hippocampus, which is involved in memory consolidation. They reviewed evidence from various animal species that the different spatial information in memories is represented in different gamma subcycles which are nested in the overall theta cycle. They also reviewed evidence that these frequencies and their couplings are functionally important to memory performance. They conclude that theta and gamma oscillations interact in the same brain regions (such as the hippocampus) to represent multiple items in an ordered way—and these frequencies coordinate communication between brain areas for perception and memory.

Heusser et al. (2016) started with the preexisting hypothesis (which appears at various points above) that elements in an experience are represented by neuronal assemblies firing at gamma frequencies while sequential order in the experience is represented by the specific timing of the firing with respect to theta frequency. They give evidence that, during successful episodic memory formation in humans, "items in different sequence positions exhibit relatively greater gamma power along distinct phases of a theta oscillation." This supports claims that the memory of events relies on theta-gamma coupling.

Meyer et al. (2017) showed how retrieving certain kinds of fear memories involves modifying delta and gamma oscillations in hippocampus. Memory retrieval involves interactions of hippocampus with cortex, but it increasingly becomes more regulated by the cortex. Yet some fear memories resist this change. These memories are state-dependent, that is, they remain heavily hippocampal dependent and are best retrieved if neural states for encoding and retrieval are similar in the hippocampus. These states can be induced by activating hippocampal GABA receptors via the analgesic gaboxadol. For this activates hippocampal neurons while inhibiting cortical neurons.

These authors show that in rats conditioned by electric shocks to a fear response, gaboxadol "may cause this effect by increasing delta and reducing gamma oscillations in the hippocampus and disrupting retrieval-induced hippocampal–cortical theta coherence." The chemical activation of GABA receptors thus alters neural oscillations which in turn affect retrieval of fear memories. In this way, fear memories "encoded in a state-dependent manner remain trapped within the region that encodes them—the hippocampus—and do not become cortically dependent with the passage of time."

Ezzyat et al. (2018) showed that the oscillations help us perform memory tasks. They gave people lists of words to recall while electrodes monitored their lateral temporal cortex's oscillations. A computer algorithm spotted the neural waves that appeared when the people were most likely to recall the words. When those good-performance waves were absent, the researchers filled in for them by stimulating the cortex electrically. This nudge to the waves enhanced performance. So the good-performance waves seem to be needed for recalling words.

To summarize Section 5, there is considerable evidence that neuronal oscillations help guide conscious cognition. This evidence fits alongside other evidence above that this conscious cognition is unified by EM fields, not by these neuronal circuits, and that these oscillating fields also regularly influence synaptic firing and neuronal oscillations at various scales. These lines of evidence support our overall conclusion that EM fields help guide and unify conscious cognition.

6. Conclusion

Most of this paper has been dedicated to reviewing evidence that oscillating EM fields help guide and unify conscious cognition. This evidence implies that EM fields aren't epiphenomena of brain operations and are, instead, functionally relevant in various important ways. The same body of evidences, while far from conclusive at this time, suggests also that the brain's regional and global electromagnetic fields may in fact be the primary seat of consciousness, while being produced by, but not identical with, the neuroanatomical backbone of the brain. This relationship, we suggest, is similar to a large tree with a trunk, branches, twigs and leaves. While the tree produces the twigs and leaves, the twigs and leaves have a more granular spatiotemporal structure. The brain's various electromagnetic fields are analogous to the trees twigs and leaves and, as such, have their own causal structure over and above the neuroanatomy of the brain. While skepticism of these claims exists, evidence mounts steadily to support these claims and we look forward to further research shedding additional light.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

MJ wrote the first draft with support from TH and then TH and MJ iterated and revised numerous times. All authors contributed to the article and approved the submitted version.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

References

Anastassiou, C., and Koch, C. (2015). Ephaptic coupling to endogenous electric field activity: why bother? *Curr. Opin. Neurobiol.* 31, 95–103. doi: 10.1016/j.conb.2014.09.002

Anastassiou, C., Perin, R., Markram, H., and Koch, C. (2011). Ephaptic coupling of cortical neurons. *Nat. Neurosci.* 14, 217–223. doi: 10.1038/nn.2727

Bahramisharif, A., Jensen, O., Jacobs, J., and Lisman, J. (2018). Serial representation of items during working memory maintenance at letter-selective cortical sites. *PLoS Biol.* 16:e2003805. doi: 10.1371/journal.pbio.2003805

Bandyopadhyay, A. (2019). Resonance chains and new models of the neuron. Available at: https://medium.com/@aramis720/resonance-chains-and-new-models-of-the-neuron-7dd82a5a7c3a.

Bastos, A., Loonisa, R., Kornblitha, S., Lundqvista, M., and Miller, E. (2018). Laminar recordings in frontal cortex suggest distinct layers for maintenance and control of working memory. *Proc. Natl. Acad. Sci. U. S. A.* 115, 1117–1122. doi: 10.1073/pnas.1710323115

Baumeister, J., Barthel, T., Geiss, K., and Weiss, M. (2008). Influence of phosphatidylserine on cognitive performance and cortical activity after induced stress. *Nutr. Neurosci.* 11, 103–110. doi: 10.1179/147683008X301478

Busch, N., and VanRullen, R. (2010). Spontaneous EEG oscillations reveal periodic sampling of visual attention. *Proc. Natl. Acad. Sci. U. S. A.* 107, 16048–16053. doi: 10.1073/pnas.1004801107

Buzsaki, G. (2005). Theta rhythm of navigation: link between path integration and landmark navigation, episodic and semantic memory. *Hippocampus* 15, 827–840. doi: 10.1002/hipo.20113

Buzsaki, G. (2006) *Rhythms of the brain*. Oxford: Oxford University Press.

Buzsáki, G., and Draguhn, A. (2004). Neuronal oscillations in cortical networks. *Science* (New York, N.Y.) 304, 1926–1929. doi: 10.1126/science.1099745

Buzsaki, G., Logothetis, N., and Singer, W. (2013). Scaling brain size, keeping timing: evolutionary preservation of brain rhythms. *Neuron* 80, 751–764. doi: 10.1016/j.neuron.2013.10.002

Chiang, C., Shivacharan, R., Wei, X., Gonzalez-Reyes, L., and Durand, D. (2019). Slow periodic activity in the longitudinal hippocampal slice can self-propagate non-synaptically by a mechanism consistent with ephaptic coupling. *J. Physiol.* 597, 249–269. doi: 10.1113/JP276904

Cohen, S., and Mao, J. (2014). Neuropathic pain: mechanisms and their clinical implications. *BMJ* 348:f7656. doi: 10.1136/bmj.f7656

Constantinescu, A., O'Reilly, J., and Behrens, T. (2016). Organizing conceptual knowledge in humans with a grid-like code. *Science* 352, 1464–1468. doi: 10.1126/science.aaf0941

Crick, F. C., and Koch, C. (1990). Towards a neurobiological theory of consciousness. *Semin. Neurosci.* 2, 263–275.

de Vries, I., Slagter, H., and Olivers, C. (2020). Oscillatory control over representational states in working memory. *Trends Cogn. Sci.* 24, 150–162. doi: 10.1016/j.tics.2019.11.006

Dehaene, S. (2014). *Consciousness and the brain: deciphering how the brain codes our thoughts*. London, England: Penguin.

Dong, Y., Mihalas, S., Qiu, F., von der Heydt, R., and Niebur, E. (2008). Synchrony and the binding problem in macaque visual cortex. *J. Vis.* 8, 30–16. doi: 10.1167/8.7.30

Ezzyat, Y., Wanda, P. A., Levy, D. F., Kadel, A., Aka, A., and Pedisich, I., et al. (2018) Closed-loop stimulation of temporal cortex rescues functional networks and improves memory. *Nat. Commun.*, 9,:365. doi: 10.1038/s41467-017-02753-0

Fiebelkorn, C., Pinsk, M., and Kastner, S. (2018). A dynamic interplay within the frontoparietal network underlies rhythmic spatial attention. *Neuron* 99, 842–853.e8. doi: 10.1016/j.neuron.2018.07.038

Fingelkurts, A. A., Fingelkurts, A. A., and Neves, C. F. H. (2010). Natural world physical, brain operational, and mind phenomenal space-time. *Phys. Life Rev.* 7, 195–249. doi: 10.1016/j.plrev.2010.04.001

Fries, P. (2005). A mechanism for cognitive dynamics: neuronal communication through neuronal coherence. *Trends Cogn. Sci.* 9, 474–480. doi: 10.1016/j.tics.2005.08.011

Fries, P. (2015). Rhythms for cognition: communication through coherence. *Neuron* 88, 220–235. doi: 10.1016/j.neuron.2015.09.034

Frohlich, F., and McCormick, D. (2010). Endogenous electric fields may guide neocortical network activity. *Neuron* 67, 129–143. doi: 10.1016/j.neuron.2010.06.005

Gallotto, S., Sack, A., Schuhmann, T., and de Graaf, T. (2017). Oscillatory correlates of visual consciousness. *Front. Psychol.* 8:1147. doi: 10.3389/fpsyg.2017.01147

Gourdie, R. (2019). The cardiac gap junction has discrete functions in electrotonic and ephaptic coupling. *Anat. Rec.* 302, 93–100. doi: 10.1002/ar.24036

Grossberg, S. (2017). Towards solving the hard problem of consciousness: the varieties of brain resonances and the conscious experiences that they support. *Neural Netw.* 87, 38–95. doi: 10.1016/j.neunet.2016.11.003

Gundlach, C., Müller, M., Nierhaus, T., Villringer, A., and Sehm, B. (2016). Phasic modulation of human somatosensory perception by transcranially applied oscillating currents. *Brain Stimulat.* 9, 712–719. doi: 10.1016/j.brs.2016.04.014

Hahn, G., Bujan, A. F., Fregnac, Y., Aertsen, A., and Kumar, A. (2014). Communication through resonance in spiking neuronal networks. *PLoS Comput. Biol.* 10:e1003811. doi: 10.1371/journal.pcbi.1003811

Hales, C. (2014). The origins of the brain's endogenous electromagnetic field and its relationship to provision of consciousness. *J. Integr. Neurosci.* 13, 313–361. doi: 10.1142/S0219635214400056

Hales, C., and Ericson, M. (2022) Electromagnetism's Bridge Across the Explanatory Gap: How a Neuroscience/Physics Collaboration Delivers Explanation Into All Theories of Consciousness. *Front. Hum. Neurosci.* 16 June 2022.

Han, K.-S., Chen, C. H., Khan, M. M., Guo, C., and Regehr, W. G. (2020). Climbing fiber synapses rapidly and transiently inhibit neighboring Purkinje cells via ephaptic coupling. *Nat. Neurosci.* 23, 1399–1409. doi: 10.1038/s41593-020-0701-z

Han, K., Guo, C., Chen, C., Witter, L., Osorno, T., and Regehr, W. (2018). Ephaptic coupling promotes synchronous firing of cerebellar Purkinje cells. *Neuron* 100, 564–578.e3. doi: 10.1016/j.neuron.2018.09.018

Helfrich, R., Huang, M., Wilson, G., and Knight, R. (2017). Psychological and cognitive sciences prefrontal cortex modulates posterior alpha oscillations during top-down guided visual perception. *Proc. Natl. Acad. Sci. U. S. A.* 114, 9457–9462. doi: 10.1073/pnas.1705965114

Helfrich, R., Schneider, T., Rach, S., Trautmann-Lengsfeld, S., Engel, A., and Herrmann, C. (2014). Entrainment of brain oscillations by transcranial alternating current stimulation. *Curr. Biol.* 24, 333–339. doi: 10.1016/j.cub.2013.12.041

Heusser, A., Poeppel, D., Ezzyat, Y., and Davachi, L. (2016). Episodic sequence memory is supported by a theta-gamma phase code. *Nat. Neurosci.* 19, 1374–1380. doi: 10.1038/nn.4374

Huber, R., Ghilardi, M., Massimini, M., and Tononi, G. (2004). Local sleep and learning. *Nature* 430, 78–81. doi: 10.1038/nature02663

Humphries, P. J. (2020). *The Spike: Journey Through the Brain in a Millionth of a Second*. Princeton University Press.

Hunt, T. (2011). Kicking the Psychophysical Laws into Gear A New Approach to the Combination Problem. *J. Conscious. Stud.* 18, 11–12.

Hunt, T. (2014) *Eco, Ego, Eros: Essays on Philosophy, Spirituality and Science*. Santa Barbara: Aramis Press.

Hunt, T. (2020). Calculating the boundaries of consciousness in general resonance theory. *J. Conscious. Stud.* 27, 55–80.

Hunt, T., and Schooler, J. W. (2019). The easy part of the hard problem: a resonance theory of consciousness. *Front. Hum. Neurosci.* 13:378. doi: 10.3389/fnhum.2019.00378

Hunt, T., Ericson, M., and School, J. W. (2022). Where's my Consciousness-Ometer? How to test for the presence and complexity of consciousness. *Perspect. Psychol. Sci.* doi: 10.1177/17456916211029942.

John, E. R. (2001). A field theory of consciousness. *Conscious. Cogn.* 10, 184–213. doi: 10.1006/ccog.2001.0508

Jones, M. (2017). Mounting evidence that minds are neural EM fields interacting with brains. *J. Conscious. Stud.* 24, 159–183.

Jones, M. (2019). Growing evidence that perceptual qualia are neuroelectrical not computational. *J. Conscious. Stud.* 26, 89–116.

Jones, M., and Hunt, T. (2023). Electromagnetic-field theories of qualia: can they improve upon standard neuroscience? *Front. Psychol.* 14:1015967. doi: 10.3389/fpsyg.2023.1015967

Juan, C., Muggleton, N., Tzeng, O., Hung, D., Cowey, A., and Walsh, V. (2008). Segregation of visual selection and saccades in human frontal eye fields. *Cereb. Cortex* 18, 2410–2415. doi: 10.1093/cercor/bhn001

Kawato, M. (1997). Bidirectional theory approach to consciousness. In M. Ito, Y. Miyashita and E. T. Rolls (Eds.), *Cognition, computation, and consciousness* (pp. 233–248). Oxford University Press. doi: 10.1037/10247-015

Kay, K., Chung, J., Sosa, M., Schor, J., Karlsson, M., Larkin, M., et al. (2020). The constant sub-second cycling between representations of possible futures in hippocampus. *Cells* 180, 552–567. doi: 10.1016/j.cell.2020.01.014

Koch, C. (2004). *The quest for consciousness: a neurobiological approach*. Englewood, Colorado: Roberts Publishers.

Koch, C., Massimini, M., Boly, M., and Tononi, G. (2016). Neural correlates of consciousness: progress and problems. *Nat. Rev. Neurosci.* 17, 307–321. doi: 10.1038/nrn.2016.22

Kostro, L. (2000). *Einstein and the ether*. Montreal: Apeiron

Lamme, V. (2004). Separate neural definitions of visual consciousness and visual attention; a case for phenomenal awareness. *Neural Netw.* 17, 861–872. doi: 10.1016/j.neunet.2004.02.005

Larkum, M. (2013). A cellular mechanism for cortical associations: an organizing principle for the cerebral cortex. *Trends Neurosci.* 36, 141–151. doi: 10.1016/j.tins.2012.11.006

Li, M., and Tsien, J. Z. (2017). Neural code—neural self-information theory on how cell-assembly code rises from spike time and neuronal variability. *Front. Cell. Neurosci.* 11:236. doi: 10.3389/fncel.2017.00236

Lisman, J., and Idiart, M. (1995). Storage of 7 +/− 2 short-term memories in oscillatory subcycles. *Science* 267, 1512–1515. doi: 10.1126/science.7878473

Lisman, J., and Jensen, O. (2013). The theta-gamma neural code. *Neuron* 77, 1002–1016. doi: 10.1016/j.neuron.2013.03.007

Martinez-Banaclocha, M. (2020). Astroglial isopotentiality and calcium-associated biomagnetic field effects on cortical neuronal coupling. *Cells* 9:439. doi: 10.3390/cells9020439

Meyer, M., Corcoran, K., Chen, J., Gallego, S., Li, G., Tiruveedhula, V., et al. (2017) *Neurobiological correlates of state-dependent context fear cold Learn Mem. 24*: 385–391. doi: 10.1101/lm.045542.117

Narikiyo, K., Mizuguchi, R., Ajima, A., Shiozaki, M., Hamanaka, H., Johansen, J., et al. (2020). The claustrum coordinates cortical slow-wave activity. *Nat. Neurosci.* 23, 741–753. doi: 10.1038/s41593-020-0625-7

Neuling, T., Rach, S., Wagner, S., Wolters, C., and Herrmann, C. (2012). Good vibrations: oscillatory phase shapes perception. *NeuroImage* 63, 771–778. doi: 10.1016/j.neuroimage.2012.07.024

Nunez, P. L., and Srinivasan, R. (2010). Scale and frequency chauvinism in brain dynamics: too much emphasis on gamma band oscillations. *Brain Struct. Funct.* 215, 67–71. doi: 10.1007/s00429-010-0277-6

Nyhus, E., and Curran, T. (2010). Functional role of gamma and theta oscillations in episodic memory. *Neurosci. Biobehav. Rev.* 34, 1023–1035. doi: 10.1016/j.neubiorev.2009.12.014

Palva, S., and Palva, J. (2007). New vistas for a-frequency band oscillations. *Trends Neurosci.* 30, 150–158. doi: 10.1016/j.tins.2007.02.001

Riddle, J., Scimeca, J., Cellier, D., Dhanani, S., and D'Esposito, M. (2020). Causal evidence for a role of theta and alpha oscillations in the control of working memory. *Curr. Biol.* 30, 1748–1754. doi: 10.1016/j.cub.2020.02.065

Roohi-Azizi, M., Azimi, L., Heysieattalab, S., and Aamidfar, M. (2017). Changes of the brain's bioelectrical activity in cognition, consciousness, and some mental disorders. *Med. J. Islam Repub. Iran* 31:53. doi: 10.14196/mjiri.31.53

Roth, G. (1994). Repetitive discharge due to self-ephaptic excitation of a motor unit. *Electroencephalogr. Clin. Neurophysiol.* 93, 1–6. doi: 10.1016/0168-5597(94)90084-1

Safron, A. (2020). An Integrated World Modeling Theory (IWMT) of Consciousness: Combining Integrated Information and Global Neuronal Workspace Theories With the Free Energy Principle and Active Inference Framework; Toward Solving the Hard Problem and Characterizing Agentic Causation. *Front. Artif. Intell.* 3:30. doi: 10.3389/frai.2020.00030

Samaha, J., Iemi, L., Haegens, S., and Busch, N. (2020). Trends in cognitive sciences spontaneous brain oscillations and perceptual decision-making. *Trends Cogn. Sci.* 24, 639–653. doi: 10.1016/j.tics.2020.05.004

Schafer, M., and Schiller, D. (2018). Navigating social space. *Neuron* 100, 476–489. doi: 10.1016/j.neuron.2018.10.006

Schmidt, H., Hahn, G., Deco, G., and Knosche, T. (2021). Ephaptic coupling in white matter fibre bundles modulates axonal transmission delays. *PLoS Comput. Biol.* 17:e1007858. doi: 10.1371/journal.pcbi.1007858

Shivacharan, R., Chiang, C., Wei, X., Subramanian, M., Couturier, N., Pakalapati, N., et al. (2021). Neural recruitment by ephaptic coupling in epilepsy. *Epilepsia* 62, 1505–1517. doi: 10.1111/epi.16903

Shivacharan, R., Chiang, C., Zhang, M., Gonzalez-Reyes, L., and Durand, D. (2019). Self-propagating, non-synaptic epileptiform activity recruits neurons by endogenous electric fields. *Exp. Neurol.* 317, 119–128. doi: 10.1016/j.expneurol.2019.02.005

Siebenhuhner, F., Wang, S., Arnulfo, G., Lampinen, A., Nobili, L., Palva, J., et al. (2020). Genuine cross-frequency coupling networks in human resting-state electrophysiological recordings. *PLoS Biol.* 18:e3000685. doi: 10.1371/journal.pbio.3000685

Somer, E., Allen, J., Brooks, J., Buttrill, V., and Javadi, A. (2020). Theta phase-dependent modulation of perception by concurrent transcranial alternating current stimulation and periodic visual stimulation. *J. Cogn. Neurosci.* 32, 1–11. doi: 10.1162/jocn_a_01539

Spaak, E., de Lange, F., and Jensen, O. (2014). Local entrainment of α oscillations by visual stimuli causes cyclic modulation of perception. *J. Neurosci.* 34, 3536–3544. doi: 10.1523/JNEUROSCI.4385-13.2014

Su, C., Menuz, K., Reisert, J., and Carlson, J. (2012). Non-synaptic inhibition between grouped neurons in an olfactory circuit. *Nature* 492, 66–71. doi: 10.1038/nature11712

Subramanian, M., Chiang, C., Couturier, N., and Durand, D. (2022). Theta waves, neural spikes and seizures can propagate by ephaptic coupling in vivo. *Exp. Neurol.* 354:114109. doi: 10.1016/j.expneurol.2022.114109

Thiele, A., and Stoner, G. (2003). Neuronal synchrony does not correlate with motion coherence in cortical area MT. *Nature* 421, 366–370. doi: 10.1038/nature01285

Varela, F., Lachaux, J., Rodriguez, E., and Martinerie, J. (2001). The brainweb: phase synchronization and large-scale integration. *Nat. Rev. Neurosci.* 2, 229–239. doi: 10.1038/35067550

Vernet, M., Stengel, C., Quentin, R., Amengual, J., and Valero-Cabré, A. (2019). Entrainment of local synchrony reveals a causal role for high-beta right frontal oscillations in human visual consciousness, nature. *Sci. Rep.* 9:14510. doi: 10.1038/s41598-019-49673-1

Walleczek, J. (2000). *Self-organized biological dynamics & nonlinear control toward understanding complexity, chaos, and emergent function in living systems*. Cambridge: Cambridge University Press.

Wallis, G., Stokes, M., Cousijn, H., Woolrich, M., and Nobre, A. (2015). Frontoparietal and cingulo-opercular networks play dissociable roles in control of working memory. *J. Cogn. Neurosci.* 27, 2019–2034. doi: 10.1162/jocn_a_00838

Whitehead, A. N., Griffin, D. R., and Sherburne, D. W. (1929). *Process and reality: An essay in cosmology*. New York: Free Press.

Wutz, A., Loonis, R., Roy, J., Donoghue, J., and Miller, E. (2018). Different levels of category abstraction by different dynamics in different prefrontal areas. *Neuron* 97, 716–726.e8. doi: 10.1016/j.neuron.2018.01.009

Young, A., Hunt, T., and Ericson, M. (2022). The slowest shared resonance: a review of electromagnetic field oscillations between central and peripheral nervous systems. *Front. Hum. Neurosci.* 15:796455. doi: 10.3389/fnhum.2021.796455

Zeki, S. (1993) *A vision of the brain*, Blackwell: London.

Zeki, S. (2003). The disunity of consciousness. *Trends Cogn. Sci.* 7, 214–218.

Zhang, Y., Tsang, T., Bushong, E., Chu, L., Chiang, A., Ellisman, M., et al. (2019). Asymmetric ephaptic inhibition between compartmentalized olfactory receptor neurons. *Nat. Commun.* 10:1560. doi: 10.1038/s41467-019-09346-z

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Don't forget the boundary problem! How EM field topology can address the overlooked cousin to the binding problem for consciousness

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The boundary problem is related to the binding problem, part of a family of puzzles and phenomenal experiences that theories of consciousness (ToC) must either explain or eliminate. By comparison with the phenomenal binding problem, the boundary problem has received very little scholarly attention since first framed in detail by Rosenberg in 1998, despite discussion by Chalmers in his widely cited 2016 work on the combination problem. However, any ToC that addresses the binding problem must also address the boundary problem. The binding problem asks how a unified first person perspective (1PP) can bind experiences across multiple physically distinct activities, whether billions of individual neurons firing or some other underlying phenomenon. To a first approximation, the boundary problem asks why we experience hard boundaries around those unified 1PPs and why the boundaries operate at their apparent spatiotemporal scale. We review recent discussion of the boundary problem, identifying several promising avenues but none that yet address all aspects of the problem. We set out five specific boundary problems to aid precision in future efforts. We also examine electromagnetic (EM) field theories in detail, given their previous success with the binding problem, and introduce a feature with the necessary characteristics to address the boundary problem at a conceptual level. Topological segmentation can, in principle, create exactly the hard boundaries desired, enclosing holistic, frame-invariant units capable of effecting downward causality. The conclusion outlines a programme for testing this concept, describing how it might also differentiate between competing EM ToCs.

KEYWORDS

consciousness, binding problem, combination problem, boundary problem, electromagnetic fields

1. Introduction

This paper elucidates a key challenge for theories of consciousness, the boundary problem, explaining its historical context, how it has not yet been adequately addressed, and a potential solution for electromagnetic theories based on topological segmentation.

Using the Seth and Bayne (2022) taxonomy, this paper focuses on the set of theories of consciousness (ToCs) that attempt to explain why some systems have subjective awareness with a particular phenomenology (Nagel, 1974) and others do not; specifically, what is the mechanism that results in a first person perspective (1PP).

We trust that the notion of a 1PP is understood by readers, as a version of it is near-universally experienced by awake, healthy humans. However, we emphasise that the term is used in an inclusive and basic sense: it corresponds solely to the locus at which the experience arises, rather than some more sophisticated experience of a particular singular self or self-awareness. In other words, the 1PP is consistent with phenomenal experiences of no-self, universal oneness, or fractured/multiple selves.[1] Similarly, we are focussed on the container of consciousness, rather than its contents; the hard problem rather than the easy problem (Chalmers, 1995); and unified experience as related to the global phenomenal binding problem rather than local, feature-specific, or computational binding (Revonsuo, 1999; Garson, 2001).

Our 1PP has a number of features which any prospective ToC must address. Winters (2021) states that our consciousness often appears unified and compositional; its contents are specific and meaningful, existing from a subjective point of view; it is temporally continuous and limited but coherent. Bayne (2010) provides a detailed account of how our consciousness is unified, typically integrating multiple parts. In other words, our consciousness somehow binds multiple discrete features into a single unified awareness (the binding problem). At the same time, our consciousness does not "bind" features without limit—what we experience varies over time and is thus always strictly a subset of what could be experienced. There is an edge to our awareness, a boundary around us that is generally felt to exist at the human-scale of experience, rather than at the cellular or societal level. While the unity of consciousness and the binding problem have received significant treatment, this article argues that the boundary problem has been inadequately addressed.

The boundary problem is not a trivial matter: any ToC that addresses the binding problem must also address the boundary problem. To a first approximation: once you've proposed a binding mechanism that creates larger, unified, macro 1PPs, what mechanism puts a stop to that process? What causes ontologically hard boundaries around these 1PPs and why do the boundaries appear where they do? If the binding mechanism could apply in principle to units smaller and larger than the human brain, what is happening in these cases? Why is our 1PP consistently at the meso-scale of human experience?

We begin with a literature review of the boundary problem, arguing that only a handful of papers have addressed it directly, while several others have groped toward the issue but struggled to capture it fully. None of them have yet provided a full account of all aspects of the explanatory challenge. In the third section, we refine the boundary problem issue into five specific problems, to aid assessments of which ones any given account might successfully address. In the fourth section, we present a conceptual overview of a promising novel avenue for addressing the problem, building on the physical features of topologically segmented electromagnetic (EM) fields and the potential for such a mechanism to generate hard boundaries. By placing a focus on topological segmentation, we tie together other desiderata in a ToC, notably: non-epiphenomenalism, no strong emergence, and frame invariance. Having established topologically segmented pockets as a conceptually sound mechanism for addressing the boundary problem, we use the conclusion to outline a simulation and empirical research programme for testing this concept. Such an exercise would also help differentiate between competing EM ToCs by analysing the different spatial scales at which they locate moments of experience.

2. Literature review of the boundary problem

In this section, we establish Rosenberg as the leading scholar to specify the boundary problem in detail, acknowledging others having touched on the issue previously. A systematic literature review using the Scopus dataset and citation tracing allows us to describe recent attempts to address the boundary problem, whether by name or by indirect discussion of its issues, before refining it into five specific problems in section "3. Precise statement of five specific boundary problems." Finally in this section, we review a range of EM ToCs to explore how they might address the boundary problem, whether explicitly or implicitly, before introducing in section "4. Topological segmentation of EM fields as a resolution direction" as aspect of EM field that has the characteristics to defeat the boundary problem but has not yet been capitalised on as such in EM ToCs.

2.1. Rosenberg's formulation of the boundary problem

Rosenberg (1998) is credited by Chalmers (2016) as the originator of the boundary problem concept, being one of several combination problem issues that Chalmers raises for theories of panpsychism.

Later authors have correctly flagged that these combination issues often apply to other ToCs as well, at least insofar as they wish to explain in a physically grounded fashion the complex, unified, bound macrophenomenology that humans typically experience (Mendelovici, 2019). Indeed Johnson (2016) adopts the same terminology in *Principia Qualia*, in which the boundary problem is one of eight subproblems of consciousness that all ToCs need to address: "how to determine the correct boundaries of a conscious system in a principled way."

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[1] Consistent in the sense of accepting the self-reported sensations of such experiences, rather than necessarily the ontology that some might adopt to explain them, being topics for separate papers.

For instance, information or causality driven solutions to the binding problem, e.g., functional or computational theories of mind (discussion in Gómez-Emilsson and Percy, 2022), might define phenomenal binding as occurring when two items interact causally or are associated with each other in a database. The challenge is that there is no neat boundary where the causal interactions or informational associations should stop—the solution over-delivers and everything ends up bound together. It would be necessary to define subtypes of causality or information linkage which generate phenomenal binding while others do not.

Such subtype definitions need to address topologies that are likely to arise in complex real world environments. For instance, it may be possible to define multiple, separate local maxima of connectivity (or high points of any mathematical construct used in the ToC) as differentiated from their surroundings by moats of low connectivity areas. However, in a continually changing, interacting environmental topology of connectivity strengths, it is necessary to address the challenge of separating systems from subsystems in a disciplined manner, particularly if a hard boundary is desired. How much lower the moat needs to be than the local maximum risks becoming an arbitrary distinction. Further, if a local maximum of connectivity is to have sufficient complexity to correspond to a 1PP that captures all the different experiences we typically have in a single moment, then it is likely to have its own internally varied topology. Such variations would likely create internal moats of relatively lower connectivity and yet more local maxima—how are these to be treated in the theory?

The requirements for such definitions include that subtypes or thresholds are not arbitrary, that the differentiations have a mechanic motivation for the presence/absence of binding, and that the definition encompasses binding such as it occurs in the human system. This issue was pointed out by Rosenberg and discussed indirectly by Bell (2005:165), e.g., "the wheel regarded as a wheel is discrete, but regarded as a piece of matter, it is continuous." The discreteness of the first perspective likely requires a third party's instrumental perspective, such as a human observer looking for something that would roll across the ground. Other third party observers may not recognise that first perspective, perhaps ants climbing over the wheel seeing it as a mountain growing out of the ground or hypothetical alien entities perceiving the world via radiowaves who scarcely see it at all. The second perspective of continuity is a more plausibly neutral, basal view that would be consistent across all observers and none.

Broadcasting to a global brainwide system or workspace might also be taken as the axiomatic definition of 1PP, e.g., Dehaene (2014), although Baars (1997) did not support this approach and was criticised as such for not addressing the hard problem (Dalton, 1997). In one sense, this resolves the boundary problem, by defining it axiomatically at the edges of the human brain. However, this means the ToC by definition either declares all non-human systems lacking a 1PP (including possible future evolutions of the human brain)[2] or is unable to comment on them and is therefore not a general ToC. In another sense, we might associate the 1PP with a general, substrate neutral workspace, which would lead back to the challenges in the previous paragraph for computationalists.

Rosenberg (2004, 2014) develops the boundary problem concepts further in his 2004 and 2014 accounts, framed in a general way that do not apply uniquely to one subtype of ToCs. Chalmers summarises Rosenberg's argument as "how do microexperiences come together to yield a bounded consciousness" but does not treat it as one of the three main aspects of the combination problem in his 2016 discussion. However, reviewing Rosenberg's full development of the boundary problem, there are novel issues raised which recent discussions of the unity of consciousness problem and the binding problem[3] grasp at but do not fully capture.

Rosenberg's original question concerns "how consciousness can exist at the middle level of nature" (2004, s4.1). He explains how the human body, as with other objects we observe at the middle level of nature, has only an intuitive, specious solidity within a particular boundary. Where you draw the boundaries depends on a particular observer's perspective and interests. In his words, "a cell may be an individual; also, at the same time, it may be part of an organ; at the same time, it may be part of an individuated bodily system such as the reproductive system; at the same time, it may be part of the organism as a whole and part of that organism's society; at the same time, it might be part of an ecosystem" (2004, s4.2).

To help us realise the arbitrariness of our strong intuitions of solidity, Rosenberg points to various psychiatric phenomena, thought experiments with human relay mechanisms in giant systems isomorphic to fish brains, and a vivid account of the complexity of the US economy. Rosenberg describes our account of the familiar middle layer of experience as trapped between a Scylla and a Charybdis, where the Scylla refers to why our experience does not exist at the subsystem level, i.e., the Russian dolls nested within us, and the Charybdis asks the parallel question of the larger systems within which individual human entities are nested.

Various mechanisms proposed for phenomenal binding establish in principle why the Scylla can be avoided. However, why does the merging stop at the meso-level of human experience? If researchers cannot define a mechanism that creates a hard boundary at the level of the brain (or their chosen space corresponding to our meso-level unified experience) but soft boundaries at every lower level, they must accept that merging into higher levels would happen under certain circumstances.

Rosenberg is not the first to identify this problem, although his is the earliest detailed treatment we have identified. Nobel-prize winning Schrödinger (1951) agonised over the same question, drawing on similar observations as Rosenberg in a brief paragraph discussion in his 1951 book: "Why is it precisely at this *intermediate level* in the hierarchy of successively superimposed unities (cell, organ, human body, state)—why, I ask, it is precisely at the level of my body that unitary self-consciousness comes into the picture, whereas the cell and the organ do not as yet possess it and the state possesses it no longer?" (p. 33, emphasis in original). Schrödinger at least did not doubt the difficulty of this question, indeed it was part of his "impenetrable thicket of questions" (p. 33) that arrived when he thought about his introspected unity of the self.

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[2] In general, we use "brain" as a concise, common synecdoche for a central nervous system embodied in a functioning human system, acknowledge imprecision and uncertainty around exactly which components are essential.

[3] Chalmers (2016) does not use the phrase "binding problem" as part of the family of combination problem issues, but other researchers have used language that connects to the subject combination problem, e.g., Garson, 2001 account of phenomenal binding.

In section "3. Precise statement of five specific boundary problems," we unpack Rosenberg's account in more detail and take inspiration from it to specify five specific problems that help set out the full range of challenges for a candidate ToC to address.

2.2. Literature review of the boundary problem

Despite identified above as a distinct problem for ToCs to address, the boundary problem has received little scholarly attention, with only a few papers that address the topic directly and a few that address it indirectly.

Searches in the Scopus database in March 2023 identified 92 papers with the "binding problem" in the title, abstract or key words, requiring also at least one of the following to increase the probability of topic relevance: consciousness, conscious, qualia, "philosophy of mind." A total of 47 were identified for the "combination problem." Only 5 were identified for the "boundary problem," of which three are relevant for discussion below.[4] Citation tracing in Google Scholar of Rosenberg's three papers referenced in section "2.1. Rosenberg's formulation of the boundary problem" did not identify any further researchers proposing features of ToCs that would resolve his concerns.

Fekete et al. (2016) discuss a similar "boundary problem," albeit restricted to computational ToCs. They report the idea as original but without citing Rosenberg's work. In their presentation, the relevant boundary problem is that if quantitative, graded measures of consciousness label a particular system as conscious, it would often also label some of its subsystems and irrelevantly extended systems as conscious. The described issue is that this either leads to a bizarre proliferation of minds or to the possibility of various appendages/subsystems/extensions labelled as conscious that are epiphenomenal to the main system measure of consciousness.

Fekete et al. (2016) suggest a solution, asking researchers to look for properties that offer a principled mechanism for singling out intrinsic systems, demarcating systems as a matter of fact rather than being a matter of interpretation from different observers' viewpoints. Later discussions in this section on phase transitions and the field topology in section "4. Topological segmentation of EM fields as a resolution direction" are suggested as examples of such intrinsic mechanisms. We build on Fekete et al. by specifying a broader set of specific problems and extending the analysis to any ToC that claims to solve the binding problem, being an issue for most non-mysterian ToCs grounded in physical reality, whether via supervenient, weakly emergent, or implementational relationships.

The other two papers from the Scopus review are from Hunt, of which the first, Hunt (2016) criticises IIT's approach to the boundary problem issues, i.e., the exclusion principle by which only the subsystem with the most integrated information (highest phi) possesses phenomenal consciousness out of all those available within a given system. IIT remains under development with recent theoretical overviews available in Oizumi et al. (2014) and Barbosa et al. (2021). In brief, IIT equates a system's consciousness to its causal properties, which can be measured mathematically ("phi") via algorithms mapped from five specific properties claimed to capture human phenomenology. Causal integration of a particular type is proposed as the binding mechanism.

In later work, Hunt (2020) discusses how the slowest shared resonance could motivate boundaries in the general resonance theory of consciousness (GRT), providing a detailed mathematical heuristic for calculating the specific spatiotemporal boundaries of any conscious entity. GRT similarly remains in development, with its main theoretical approach described in Hunt and Schooler (2019) and Hunt (2020). In brief, GRT starts from panpsychism and explains how shared resonances between micro-consciousness entities can overcome the binding problem. The slowest shared resonance across different systems is taken to define the subsequent scope of macro-consciousness, with electromagnetic field synchrony (resonance) being the primary type of shared resonance relevant to the scale of human life and consciousness. In other words, GRT is primarily an EM field theory of consciousness in terms of its practical implications.

We welcome these researchers' work on this topic and see these as potential avenues that could be further explored to address Rosenberg's concerns more fully. For instance, with Rosenberg's Charybdis, the current computational difficulty of calculating phi for real-world systems (e.g., Kim et al., 2018) limits confidence in identifying candidate system and subsystem boundaries. Such analyses would be needed to test the hard boundary that is supposed to exclude the cerebellum from the cerebral cortex 1PP or the soft boundaries between subsystems within the cerebral cortex that are to be extinguished by the exclusion principle (Tononi, 2015). Further, if the cerebral cortex is damaged and later repaired, why does our 1PP (appear to) disappear rather than shifting for the interim to the next highest phi subsystem in the overall system, e.g., a cerebellum module or elsewhere?

GRT also needs to address even slower shared resonances in larger interpersonal systems, such as singing choirs or rhythmic dancing. Indeed some have argued that GRT may therefore be able to account for phenomena such as group consciousness (Young et al., 2022). It is possible that all nested levels of resonance represent separate levels of consciousness, as Hunt (2020) suggests, but then we must explain why the human experience is so consistently at the meso level. Alternatively, there may be some phase transition mechanics, pointed to by Hunt and Schooler (2019), that means such macro-level phenomena beyond a single human entity fail to establish resonance of a level to drive consciousness. One such heuristic is proposed in Hunt (2020) – using various candidate synchronicity indexes to measure complex resonance chains – paving the way for further mathematical and empirical work to test it.

2.3. Indirect discussions of the problem

In addition to the structured database search and citation tracing above, we selectively reviewed other studies that might indirectly address the boundary problem.

Bayne (2010) discusses the binding problem at length, but does not address the boundary issues, with no citation of Rosenberg

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[4] The other two are: Hunt (2011) which equates the boundary problem to James (1895) account of the combination problem (which does not address Rosenberg's full concerns). In Hunt (2011) later work, cited here, the concerns are addressed more directly. The second is entirely out of scope, concerning the interpenetration of consciousness and media technologies.

and no explicit discussion of the boundary problem. An indirect discussion suggests an assumed possible resolution: "the biological account enables us to determine the boundaries between selves with relative ease," i.e., presumably boundaries of the physical body/brain system. However, there is no further discussion that would account for the challenges Rosenberg raises. In his 2014 response to reviewers' comments, Bayne (2014) surfaces his difficulty with the underlying issue, albeit without the precision that comes with Rosenberg's framing of it. Bayne suggests the reviewer is asking for "an account of why particular experiences are parts of the experiences that they are parts of whereas others are not," which Rosenberg might translate into why some experiences are contained within a given phenomenal boundary whereas others are not. Bayne states that he is unsure what it would take to answer such a question and would welcome a theory that could do this as part of a comprehensive ToC, but is not himself advancing one at this stage. Goff (2020) highlights the combination problem as an important open problem for panpsychism, with several promising avenues, but does not draw out the related boundary problem issues or cite Rosenberg.

Winters (2021) also gets close to the boundary problem in his comparison of how different ToCs account for the "limited and coherent" nature of our phenomenality, although his primary focus is on why the majority of incoming data streams go unnoticed by our 1PP, i.e., unconscious information processing. Nonetheless, his broader discussions of this point contain explanation that address aspects of Rosenberg's concern. His preferred theory looks at systems of temporally integrated causality (TIC), arguing that the system containing the highest degree of TIC is naturally bound by surrounding areas of lower TIC. While this avenue may be vulnerable to the same concern as with IIT and other computational approaches specified above, it nonetheless has the potential in principle to address important aspects of the boundary problem.

Bond (2023) suggests coherence fields as atomic nodes within expanses of integrating photonic waves as the fundamental units of 1PP. While part of his discussion captures a "fading with distance" logic, it is also possible that a phase transition between coherence/decoherence in his electric currents might motivate a hard boundary. Keppler (2021) similarly appeals to phase transitions, pointing to superradiance as a potential model to follow. In both cases, the details by which the mechanism would produce an ontologically hard boundary are not fully explicated, with the underlying physics perhaps yet to be fully understood. Nonetheless, as with resonance theories, such potential phase transition mechanisms are a fruitful avenue for future research. A more directly specified phase transition is the pre-collapse quantum entanglement motivated as the basis for consciousness by Barkai (2018), subject to ongoing research into the maintenance of entanglement at sufficient scales to motivate the complexity and diversity of our phenomenal experience (e.g., Goh et al., 2020).

In general, further mathematical and empirical work in these areas, as with GRT, IIT, TIC, or Fekete's system properties, may lead to more precisely specified phase transitions and boundary problem solutions. Their mathematical properties can then be tested against boundary identification in topologically complex environments (like the example in section "2.1. Rosenberg's formulation of the boundary problem") and the five boundary problems in this paper, alongside other requirements for a ToC. These avenues all merit exploring as potential solutions.

2.4. Further EM-field theory perspectives on the boundary problem

Finally, we investigate additional high profile EM theories to assess their explicit or implicit positions on the issues posed by the boundary problem, focussing on EM field theories given their success with the binding problem and because the conceptual solution we propose in section "4. Topological segmentation of EM fields as a resolution direction" is a tool available to such field theories.

EM-field ToCs regularly reference the ease with which they defeat the binding problem, typically noting that fields are ontologically unified by their physical nature and automatically integrate all the information contained in the underlying EM activity that generates them (Jones, 2016; Keppler, 2021; Ward and Guevara, 2022; McFadden, 2023; etc.). However, the discussion of boundary problem issues is typically more implicit and does not account for all the concerns raised or implied by Rosenberg. In these additional EM ToC papers reviewed, we did not identify any to address the problem by name, cite Rosenberg, or discuss the full extent of the potential explanatory challenge.

In Jones (2010, 2019) "realist field theory" it is the energy in EM fields that is conscious, unlike for instance the way consciousness emerges out of integrated information in McFadden's ToC, provided those fields also have influence over motor activity to avoid the pointlessness of epiphenomenality. Jones sees all such fields as conscious, but it is only when they bind together into larger EM fields that we get the kind of complex macrosubject consciousness of primary interest (i.e., our own first person perspectives). This suggests a continuous increase in scale rather than something with a phase transition demarcating consciousness being on or off.

A closer discussion of boundary problem issues comes in Jones (2013) discussion of how EM fields can be consistent with mental privacy, e.g., no telepathy even when our brains are close together such that some of the EM fields might overlap or merge. His solution is to identify consciousness of the relevant scale only in highly localised fields, unlike for instance the larger, more brain-wide fields of McFadden's ToC. By requiring more local, stronger fields created in ion currents, the rapid decline in EM field strength with distance is sufficient that nothing gets past the boundaries of the physical brain and thus into telepathic territory. This perhaps resolves the "macro" side of Rosenberg's problem, but not the "micro" side. There must be many candidates for boundaries within the brain that enclose sufficiently strong EM fields; why does it appear—at least most of the time—that we only experience one? Which one is it and why?

Invocations of rapid declining strength with distance are found elsewhere in EM-theorists' accounts of boundaries. Ward and Guevara (2022) say at "distances larger than a few centimetres, the activity of non-synchronised neuronal networks is indistinguishable from neural noise." However, Ward and Guevara acknowledge the deeper issues of Rosenberg's concern, noting that the brain has many EM fields, with various nested and overlapping sizes and boundaries, and asking which create our subjective perspectives.

Ward and Guevara (2022) set out the case for a particular EM field generated by the thalamus, suggesting that axiomatically a 1PP is an EM field that expresses a model of an external environment, a self-entity, and various actions that entity can take to influence its environment. Other fields do not express such models, although they may interface with it (e.g., subconscious inputs into our 1PP), and hence are not themselves phenomenally conscious—they lack a 1PP. This is a powerful argument, although it presumably implies that even relatively simple EM systems (which cannot but generate EM fields) would naturally have fields endowed with 1PP. For instance, a digital computer using a camera, a robotic hand, and AlphaGo to play a game of Go would meet a de minimus version of these requirements. If this is inadequately "complex" or "intense" in some manner to spark a true 1PP, then we are back to a fuzzy boundary or some unspecified phase transition.

Another field related theory invokes phase transitions, this time in the zero point field (ZPF), the ubiquitous substrate understood to mediate the EM force in quantum electrodynamics (Keppler, 2021). Shani and Keppler (2018) present an explanation of how cosmo-panpsychism can address various (de)combination problems, including a discussion of boundary formation, carving out smaller 1PP entities out of the omnipresent zero-point field underlying all quantum behaviours. They describe a "clear demarcation criterion between conscious and non-conscious systems in such a way that the formation of transiently stable attractors distinguishing themselves by a high degree of coherence is an essential prerequisite for conscious processes." From one perspective, they describe a continuous spectrum of increasing consciousness: "simple quantum systems, such as atoms and molecules, are probably equipped with a very rudimentary, limited, and monotonous form of consciousness." From another, they suggest possible phase transitions that might point to strong boundaries, whereby "system-specific ZPF modes undergo a phase-locked coupling (accompanying the formation of an attractor) while all the other modes remain unaffected." Various intensified regions are described as vortices "in constant interaction with, yet functionally distinct from, the surrounding field."

McFadden invokes a metaphysical argument to explain mental privacy as discussed by Jones (2013). The information in fields, when experienced privately from the inside, has a 1PP phenomenology. From the outside, the same information can be read but not experienced. Such principles can be applied outside of fields as well, as in the relativistic theory of consciousness from Lahav and Neemeh (2022) which can be applied in any physicalist setting. However, in the specific EM setting, we can ask what happens when EM fields from one brain merge with EM fields from another brain. Elsewhere McFadden (2006) says that the high conductivity of the cerebral fluid creates an effective Faraday cage, such that external fields would not influence what happens on the inside. On this account, if the fluid were somehow safely removed or some functionality used to connect fields between brains, we would expect a single merged 1PP emerging from the two 1PPs in two adjacent human brains. McFadden (2020) later invokes an unspecified threshold argument which might assume away the practical feasibility of such merging: "minimal characteristic of an EM field to qualify as conscious must surely be that it possesses sufficient complexity."

3. Precise statement of five specific boundary problems

The original formulations and reformulations of the boundary problem (Rosenberg, 1998; Fekete et al., 2016; Johnson, 2016) can be usefully translated into five specific problems, briefly summarised below before discussing each in detail. The gauntlet for candidate ToCs is to identify the resolution (eliminative or otherwise) they favour, explaining the mechanism that drives it and its consistency with the rest of their theory.

- **The hard boundary problem**. We experience, at least sometimes, an absolute boundary between our 1PP and the outside world, which consists of events that could be experienced by us and are currently being experienced by others. What produces this absolute, i.e., non-fuzzy boundary?
- **The lower-levels boundary problem**. Our 1PP is capable of experiencing diverse and multiple experiences, often simultaneously or co-jointly. To the extent our 1PP is considered to arise out of a complex, multi-part mechanism, there could be boundaries, whether hard or fuzzy, that enclose some of these nested or constitutive sub-experiences. Are there 1PPs also existing at these lower levels? If not, what creates the important boundary at our meso-level but over-rides or renders meaningless any lower level boundaries? If yes, what mechanism ensures our 1PP remains at the meso level of human experience and not also at some of those lower levels, at least at times?
- **The higher-levels boundary problem.** Our 1PP is in turn nested in larger more complex structures. At times, these operate with considerable physical and causal synchrony, such as singing choirs or football teams. Other times, our collective behaviour has resulted in complex systems, often with a degree of persistence through time and emergent properties, such as cities, price setting and goods transfer via marketplaces, and large language models. Are there 1PPs also existing at these higher levels? If not, what makes the meso-level boundary qualitatively different to each higher level boundary? If yes, what mechanism ensures our 1PP remains at the meso level of human experience and not also at some of those higher levels, at least at times?
- **The private boundary problem.** The boundary we experience, whether hard or fuzzy, demarcates our phenomenal experiences from the external environment, which includes other people's first person perspectives, i.e., other meso entities separate from our own as well as other physical phenomena more generally. What mechanism makes this a private boundary? Why can we not routinely bridge into others' minds?
- **The temporal boundary problem.** There are often multiple possible bounded entities in a given system, potentially with many at similar, lower, and higher spatial levels. These entities might persist, for some definition of pattern stability, for different, overlapping periods of time. However, our normal experience is typically of a single bounded entity persisting through time, at least for some non-trivial periods of time. How is a broadly stable sense of self stitched together across a sequence of such entities?

3.1. The hard boundary problem

The hard boundary problem is one of the introspective explananda of consciousness. It observes that our phenomenal field, or our first person perspective, appears to be enclosed by a firm, absolute boundary. There is a qualitative difference between the things that enter that phenomenal field and things that do not. Such an approach does not deny highly varied experiences within that boundary, potentially including gradations of how "aware" or how "conscious" (in the vernacular sense) we sometimes feel. Drifting in and out of sleep, fading into anaesthesia—such experiences still happen within a boundary, they merely refer to the contents within that boundary gradually dissipating.

The strong statement of this explanandum is that our first person perspective is always walled by a hard boundary. The weak statement is that our first person perspective is at least sometimes walled by a hard boundary. For our purposes, the weak statement is sufficient to demand some explanation of how the perceived hard boundary might be generated. As with all introspective explananda, the hard boundary problem takes its force either from a reader's ability to relate to it in their own introspection or, in its weak statement, a willingness to believe or an ability to empathise with the self-report of others who claim to have experienced it, as we do.

At least two eliminative responses can be made to the hard boundary problem. One might argue back from introspection to assert that if we probe the very edges of our awareness, the boundaries are in fact fuzzy rather than hard, although arguably this would leave the weak statement intact. For instance, Lidström and Allen (2021) suggest there are no clear boundaries between conscious and unconscious behaviour, so perhaps there is similarly no true boundary in its phenomenology. This account appears to be adopted by some EM-field theorists, as discussed in section "2. Literature review of the boundary problem," motivated perhaps by the very rapid decline in EM field strength with distance which creates a "sufficiently" hard boundary to account for the introspective phenomenality.

Another eliminative account might argue from indirect realism that when we perceive a hard boundary, this is only an illusion. The underlying reality is continuous, but the complex processing of our perceptual apparatus sees fit to present it as firmly bounded. In this case, the processing mechanism needs accounting for as does the evolutionary argument for why our brain has found reproductive fitness in that particular simplification of presentation. More subtly, such illusory claims only move the explanandum rather than remove it. The very illusion of unity *as an experience* is itself something that requires multiple pieces of information to be simultaneously expressed and phenomenally bound—surfacing a hard boundary indirectly.

If these eliminative responses are not palatable, then some mechanism needs to be explained by which nature produces a hard boundary. Indeed, the problem gains its force because most phenomena that might be co-opted to explain consciousness, at least at the meso level of human experience, appear to be continuous in nature. Many events are synchronous with those that appear in our first person perspective, but do not themselves appear in that perspective. At the end of any edge of physical causality, information-exchange, or spatial proximity in a particular system are yet more proximate interactions, whether extending out forever or nested internally. This includes interactions that have complex feedback loops beyond an immediate biological unit (e.g., for the body when typing on a keyboard or driving a car, or the gut nervous system as connected to the brain stem). EM fields do not automatically close in neat boundaries, they extend out forever, albeit weakening rapidly with the cube of distance.

To fully resolve the hard boundary problem, we wish to identify a mechanism that results in an ontological boundary that is impermeable to the relevant processes, patterns, or substances determined to make up the 1PP.

One example given in section "2. Literature review of the boundary problem" is when systems are in exact resonance with each other, provided we do not need any appeal to resonances lower or higher. A more general phenomenon to call upon is that of phase transitions, although a full solution must identify where the transition takes place, the mechanism that drives it, and motivate why the hard boundary it generates is adequate for enclosing phenomenal consciousness.

3.2. The lower-levels boundary problem

The lower- and higher-levels problems correspond to Rosenberg's original question of "how consciousness can exist at the *middle* level of nature" (2004, s4.1, emphasis added). Appealing to visually apparent "physical boundaries" is not as successful as it might first seem. An alien observer whose eyes exist at the pixel scale of micrometres or light-years would see the physical boundaries of our seemingly solid human system very differently, porous in the former and imperceptibly blended in the latter. Even more strongly, consider an alien observer who does not rely on photons to construct a model of the outside world, but instead relies solely on senses of sound waves or gravitational waves. The boundaries of the human system relative to the lower/higher levels around it no longer necessarily look as unique.

One response to this challenge, common to panpsychic arguments, is to accept (indeed, to celebrate) that all of these different levels have appropriately many 1PPs of differing complexity and persistence. Advocates would ask how we can be sure that the other levels do not exist, given there is no reason to think evolution had to equip us with the senses to perceive them or communicate with them. Is the notion really more bizarre than black holes and the dual slit experiment in physics, or split-brain experiences and Cotard syndrome in neuropsychology? Our intuitions often fail us when extrapolated beyond our comfortable, common surroundings. However, even if such a pluralising account were advanced, we must have some explanation for why our experience is consistently at the meso-level.

Any other response must meet Rosenberg's challenge—we must identify a mechanism that pushes the 1PP out from the subatomic level but only just so, only up to the human level and no further. This is primarily a question for the natural sciences: boundary-making mechanisms must be identified and tested, both for their ability to generate the necessary features in principle and for whether they actually operate in that way in the human system.

3.3. The higher-levels boundary problem

Having explained the lower-levels problem, the higher-levels problem can be understood as the symmetrical question applied to entities larger than the human brain within which the brain is nested. However, it is worth illustrating as a distinct problem because some ToC mechanisms address one but not the other.

Rosenberg (2004) explains how Lockwood's materialism might solve the lower-levels problem by binding together small experiences via the lines of interactions in the world, but it does not explain why it stops at the human level, given we also nest within larger systems of interactions. Microexperiential panpsychists that do not incorporate binding mechanisms do not have to worry about the higher-levels problem, but struggle to explain why any experience exists at our meso-level at all, perhaps needing to motivate the apparent multi-feature complexity of our experience as illusory.

3.4. The private boundary problem

Jones (2013) discusses the experience of mental privacy as one that ToCs should account for. This is a distinct problem from the lower-levels and higher-levels problems, since the latter are focussed on the subsystems nested within us or the macrosystems we nest within, whereas the private boundary problem is between meso-level entities. For instance, if the coherence of consciousness is laid at the foot of neural synchrony, resonant frequencies, or EM fields, then why does our consciousness not somehow link with or merge into another person's consciousness when they are sufficiently in sync, in resonance, or connected via EM fields with us?

Several EM fields have a natural privacy-preserving explanation for this part of the boundary problem and some resonance theorists explicitly allow for privacy to be violated, as discussed in the literature review in section two. Neuralink advocates would likely argue this is a technical barrier to overcome, rather than an absolute philosophical or biological barrier. Some experiments point weakly to this barrier being weakened today and some studies on conjoined twin suggest that the privacy of a single brain is not absolute (de Haan et al., 2020).

Any of these accounts are adequate in principle for resolving the private boundary problem. The duty on ToC theorists is to choose their preferred explanation and explain why it is consistent with the other binding and boundary problems and with their broader vision of consciousness and human experience.

3.5. The temporal boundary problem

The binding problem and associated boundary problems typically begin with a static view of features and experiences. The feature binding problem asks how our experience of a blue chair knits together all the individual neural signals corresponding to bits of the chair into an overall shape and colour.[5] The phenomenal binding problem asks how all the different experiences in a moment can be experienced from a single unified perspective: perhaps the chair is experienced in a garden along with a particular smell and an unrelated twinge of back pain. Once some mechanism for phenomenal binding is specified, the boundary problem interrogates why the mechanism stops where it does and the consistency of such explanations.

For a static moment, the concept of bound experiences within a boundary can be well defined. For a subsequent moment, the experiences being bound together will often be different and the boundary of 1PP may have shifted. As such, additional constraints are imposed by the requirement to line up with the common, awake and sober experience of continuous perception from one moment to the next. The boundary of our 1PP may sometimes feel like it is contracting or expanding, but it will generally do so without severe discontinuities. The temporal binding problem asks how the moments are knitted together over time to feel like part of the same experience. The temporal boundary problem asks how, once we have a boundary around a static experience or a particular moment of 1PP, that boundary can shift mostly contiguously to have different shapes in future moments. In both cases, we require an explanation that allows this temporal contiguity (whether felt or remembered) to be non-permanent, since our lives are replete with examples of interruption and resumption of 1PP, such as in blows to the head, sleep cycles, and general anaesthesia.

This problem builds on critiques of persistent personal identity (Parfit, 1984). Regardless of whether a theorist argues for empty, open, or closed individualism in response to these challenges, they still need to account for the introspective phenomenology of self-persistence in a way that is consistent with the mechanisms they think generate, bind together, and place boundaries around conscious experiences.

At the simplest end, we might experience a moment bound together over at least a second or so—from the start of a musical note to its end, for instance. Does this correspond to a single bounded 4D entity, operating within a constrained spatio-temporal space? Or is it a spatially identically 3D space that persists over time without changing? Or is it spatially varying 3D spaces? If the latter, what about them joins them over time without extending before/beyond the desired period? Can we apply the same account for binding over a single second to binding over longer perceived persistence, such as a single waking day or a lifetime?

4. Topological segmentation of EM fields as a resolution direction

This section begins by explaining how field topology creates ontologically hard boundaries in principle. We then explain how particular topologies have the potential to meet three desiderata for

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[5] Various theories provide accounts for feature binding for specific subcontents of conscious experience, without necessarily seeking to explain the overall unity of phenomenal conscious experience. For instance, in the Seth and Bayne (2022) account of predictive processing theories, when the brain uses learned or inferred patterns to predict what a partly perceived object should be, the unity of that informational pattern naturally links features together. Even if such computational approaches prove correct for feature binding, a separate mechanism would likely be required for overall 1PP unity, given the challenges highlighted in section "2.1. Rosenberg's formulation of the boundary problem."

any ToC: downward causation as a unit, no strong emergence, and frame invariance. We close by describing how field topology can be combined with an EM account of 1PP to account in principle for the five problems described in section "3. Precise statement of five specific boundary problems."

4.1. How field topology can create hard boundaries

Field topology refers to the geometric properties of an EM field object that are preserved under continuous transformations, such as stretching, bending, or twisting (e.g., Rañada, 1989). In an EM context, topology can be used to describe the patterns of field lines or equipotential surfaces that define the distribution of the field. EM fields are associated with the movement of charged particles, such as occurs in abundance and diversity in the human brain (e.g., with many for every single neuron), giving rise to correspondingly complex and ever-changing field topology.

Within the complex topology of EM fields produced by the brain, we can consider what patterns might emerge with different levels of stability and at different spatial scales, from the sub-neuron level through to potential brain-wide fields (see section "5. Conclusion" for further discussion of spatial scales). One type of stability emerges when field lines occur in closed loops, potentially enclosing an EM field which itself might have complex patterns and vortices within it. As Wolski (2011) explains, lines of magnetic flux almost always occur in closed loops, whereas lines of electric field may occur in closed loops, but not necessarily.

Closed EM structures with certain durations can be understood as enclosing electromagnetic space so as to temporarily prevent the transit of energy with that same EM spectral range outside of the space.[6] For its duration, there is an ontologically closed space for the relevant phenomena in that spectral range, in the sense that the information encoded in that field cannot exchange information externally on the same wavelength. The charged particles nonetheless continue to operate, subject to downward causation from the field, and as the closed structure collapses, causal interactions and information exchange with surrounding entities can continue.

One analogy is via the twisting of balloons to create knots or pinch points, such that it is possible to have complex inside/outside dynamics. Irvine and Bouwmeester (2008) employed such principles to identify solutions to Maxwell's EM equations based on Hopf fibration (see Figures 1–3 in their paper). These solutions lead to various closed loop patterns, including knotted beams of light, and potential applications in fluid dynamics, plasma confinement, and particle trapping. An alternative mechanism generating closed EM activity is total internal reflection and the family of topologically stable solutions discussed by Fedchenko et al. (2022).

The construction of closed EM field loops in the form of light knots, which persist until some EM disturbance, has continued in recent years, with further work on isolated optical vortex knots (Dennis et al., 2010), identified knots in quantum field theory (Hall et al., 2016), and technologies for manipulating increasingly tunable optical vortices (Shen et al., 2019).

These applications being found in physics, information processing, and communication, as well as the complexity of potential EM field topologies at different spatiotemporal scales of the brain, are sufficient to motivate at a conceptual level the potential presence of topologically segmented, temporarily ontologically closed 4D pockets generated by the brain's EM activity.

4.2. Potential for frame-invariant topologies that work as a unit to exert downward causation

4.2.1. Frame invariance and desirability for consciousness-generating mechanisms

By framing boundaries in terms of topological features, we gain an important benefit: Lorentz invariance. Subject to various uncertainties and inconsistencies yet to be resolved (e.g., Melia, 2022; Frankel, 2023), modern physics accepts that relative speed and mass distort spacetime. Under special relativity, simultaneity is also relative to the reference frame. To the extent proposed consciousness generating mechanisms rely on synchronicity or in-phase frequencies at different locations (necessary if they are to resolve the binding problem between those locations, for instance), those consciousness would not be bound together from the perspective of anyone in any reference frame moving relative to the first.

If exact synchronicity or exact in-phase resonance is required, then even walking relative to someone else would be enough to disrupt it. If inexact synchronicity were sufficient, we should ask what threshold mechanism generates a qualitative distinction from along a spectrum of inexactitude or at least what mechanism generates the illusion of qualitative differences between the having of 1PP and not. One candidate threshold is the limiting temporal resolution of perception in that particular system, at the cost of allowing different thresholds in different systems or at different times. Alternatively, where inexact synchrony is enabled by design in the binding mechanism, similar thresholds of inexactness may be sufficient at spatiotemporal scales where any special relativity effects can be tolerated within the resulting fuzzy boundary definitions. For instance, physical objects can resonate with each other at similar but not identical frequencies; such coupled systems might then gradually exchange energy until they are exactly in sync (phase-locking). Hunt (2020) suggests several possible synchrony indexes that calculate synchrony as a continuum rather than all or nothing. Please see Hunt (2011) footnote 28 for a discussion of other reasons why special relativity may not be a barrier to synchronisation solutions.

Frame invariance may not be strictly necessary for consciousness, but it is likely to be desirable. For instance, if inexact thresholds do not apply, a lack of frame invariance suggests an unexpected proof of solipsism. Unless someone is exactly in my reference frame – hard to achieve, given the

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[6] Some related phenomena might trivially transit this boundary (e.g., sound waves, x-rays) and others (e.g., WIMPs) could transit any other currently conceivable boundary relevant to everyday human experience. The key requirement is that the relevant phenomena that construct the closed field, i.e., the same EM field, do not transit the boundary.

difficulty in coordinating small movements between bodies–then the only consciousness that binds together from my perspective is my own. Of course, everyone else is in the same camp, so their own 1PP may be consistent internally. Unfortunately, we can extend this argument to micromovements and changes within the body as well. If truly exact synchronicity is required, arguably there can be no binding within a brain either, at least not between a large number of points, as many are moving at very slightly different speeds to each other. For these reasons, if we wish to preserve special relativity (and good luck to anyone looking to replace it with something better), frame invariance is an attractive feature for consciousness generating mechanisms.

In the case of relativity, a particular type of frame invariance is necessary: Lorentz invariance (e.g., Ehlers and Lämmerzahl, 2006). This is sustained in the topological features of fields. Even though the specific timing of events and spatial distances may stretch and shift based on frames of references, topological features like interconnected areas, gaps, the aggregate of vortices and antivortices, knot structures, Euler characteristic, and boundaries remain consistent up to certain isomorphisms, as does the sequence of cause and effect. Provided it is these features that matter for the experience of 1PP, then a 1PP can be consistently generated within a brain despite micromovements and different internal frames of references and would still have the features necessary to identify as a 1PP for any external observer no matter their frame of reference.

4.2.2. Desirability of non-epiphenomenalism

A further desideratum for consciousness-generating mechanisms is non-epiphenomenalism. We note this as a potential challenge for IIT, since the local maximum of phi is a denotive feature of a given subsystem that does not change what that subsystem does. For instance, the subsystem's probability transition matrix can remain the same even if some other subsystem at a later stage ends up having higher phi and "takes over" the 1PP in the system.

Epiphenomenalism, in this context, is not the argument that phenomenal consciousness is entirely invisible to the world—if so, we could not be talking about it or experiencing it as an illusion or otherwise (see the meta-problem discussed in Chalmers, 2020; for possible defences of stronger epiphenomenalism see Robinson, 2019). Rather it is the weaker claim that the 1PP experience is a by-product of particular physical processes in the human system that does not directly causally interact with those particular processes. Classic examples are Huxley (1874) steam whistle on a train. The train's motion causes the sound, which has a real physical existence and can influence other things (it can be heard and talked about), but does not influence the train's motion, being what causes the sound. A stronger example might be an object's shadow, since the whistle's sound may have some trivial influence on the train's motion, e.g., as it dissipates energy.

Non-epiphenomenalism is valuable for at least one of two reasons, depending on your philosophical position. If consciousness has no direct causal effect on the systems producing it, then it would be an extraordinary coincidence that natural selection appears to have universally selected for it in human organisms, and likely many other complex organisms as well. Extraordinary coincidences do happen, but mechanisms that explain why they were more likely (or indeed necessary) gain some plausibility as a result. Secondly, for some theorists, the combination of system-level causation with a 1PP provides a route to rescue the sensation of free will in an otherwise deterministic universe (e.g., McFadden, 2006). Weak emergence provides one channel to deliver non-epiphenomenalism.

4.2.3. Weak emergence as a route for non-epiphenomenalism

Different topologies of EM fields have been shown to operate as a unified whole that has weakly emergent, downward causation on the types of activities that happen and are possible in their neighbourhood. McFadden (2013) provides a discussion of non-epiphenomenality in EM fields, with research continuing to make progress in recent years. For instance, Pinotsis et al. (2023) draw together work on ephaptic coupling: showing how electric fields sculpt neural activity in the context of brain infrastructure, potentially tuning it to process information more efficiently, as well as influencing memory formation (Pinotsis and Miller, 2023). In other words, EM fields are not merely a side-effect of electrical activity in the brain, but in fact influence the activity of individual neurons and their parts.

To provide some illustrative references for this paper of how field topology in particular has been found to have downward causality: experimentally observed differences in resonances when light transits a Möbius strip topology compared to an ordinary ring (Wang et al., 2023), the proposed topological dynamics of skyrmion bundles (Tang et al., 2021), and perhaps most dramatically the release of twisted magnetic field structures in the sun causing coronal mass ejections (NOAA, n.d.).

A brief definition of weak emergence is in order, where causal influence rather than ontological fundamentality is sufficient to support non-epiphenomenalism. In this paper, weakly emergent causality is where a structure influences the behaviour of its constituent parts, perhaps by constraining the space of actions available to individual parts. However, that structure and its properties are fully defined, albeit potentially incompressibly, by the (local) interactions of those parts in the given environment. For a fuller discussion and opposing positions, please see O'Connor (2021).

Two notes are worth appending to this definition. While all interactions are local, they might only exist the way they do with the full structure in place, as each local interaction is itself constrained/shaped by its neighbouring interactions, recursively through to the whole structure. Secondly, while the outcomes are fully defined (or vary only by some irreducible randomness), they may still be unknowable or incomputable in practice to an observer, e.g., uncertainty principles, non-linear macrosystem dynamics, and chaos theory are all consistent with this weak emergence. By contrast, strongly emergent causality entails some inherent nature of the system that cannot be predicted or explained by the lower-level components alone, even with perfect knowledge, in a way that goes beyond these computability or observability caveats.

One toy example is provided as an intuition pump. Traffic congestion is a dynamic property emerging weakly from entirely local interactions among the more fundamental unit of vehicles operating in a given environment. Once that property has emerged, a fundamental unit's space of operations is constrained by the property relative to what it has if isolated (e.g., the car can no longer drive over 10 mph if that is the congested speed). Only "local interactions" are ontologically real (in this toy universe), but their dynamics still matter in a way that is not solely perspective dependent. Emergent structures can, for instance, result in features that can "block passage": exactly what is needed to solve the boundary problem.

4.2.4. Weak emergence in the brain

The examples of weak emergence from fields span a sufficiently wide range of endeavours that we might reasonably expect to find them in the human brain if properly analysed. Such downward causation helps to explain why the mechanism might be visible to evolutionary processes. If it is visible and has benefits in some circumstances, then we would expect it to have been co-opted by natural selection on at least some evolutionary pathways. Combined with the anthropic principle (we can only comment on its presence, since in its absence we would be unable to comment on it), it is no longer surprising that individual humans have a 1PP.

The relatively weak downward causation from the field, relative to say the computational behaviour of neuronal interactions, can be construed perhaps surprisingly as an asset of the theory. As is widely known in neuropsychology, the brain does an enormous amount of processing at the subconscious level. Our conscious experience is often of making relatively few, relatively focussed decisions. Downward causation from a weakly emergent structure may only make a difference in a few circumstances, aligning with this experience. For instance, when complex systems are close to criticality and unable to predict themselves, the occurrence of one route over another may be deliverable via a small nudge of downward causation from a field integrating information surfaced to it at the endpoints of various complex computational modules.

This account of decision making is similar to a central coordinator or global workspace function, with the unified 1PP providing the glue that binds it all together. Where that field is a 1PP, it is understandable that this perspective experiences a sensation of choosing and, depending on your philosophical position, exerts its influence over the outcome based on its assessments, corresponding to what could be called a sensation of free will.

4.3. Applying topology in an EM-field ToC context to address the boundary problems

Field topology may be a useful tool for all EM-field theories to use, as discussed further in the conclusion. In this section, we present a conceptual account of how we might address the boundary problems where a 1PP arises in any 4D-topological pocket, i.e., an EM field pattern which provides hard boundaries around a specific object in spacetime. We will equate a 1PP ontologically and axiomatically with fields shaped into such bounded pockets. Other theorists may successfully draw on the topology principles to resolve the boundary problems but relate the underlying 1PP to other features, such as the field's energy (Jones, 2010) or its information content (McFadden, 2020).

4.3.1. Addressing the first problem

The first problem is resolved in a straightforward fashion given section "4.1. How field topology can create hard boundaries," asserting that the ontological boundaries of the pocket are sufficient to account for the hard boundaries we typically experience. Binding within the topological pocket is explained in the traditional EM field sense, noting that fields are unified by default. The complexity of the contents of unified experience, i.e., often containing multiple shapes or features, is explained because the field contains all the information of the EM activity that gives rise to it, including computational insights and assessments from relevant diverse brain modules operating via a neuronal architecture. Local perceptual binding, such as binding the colour green to the shape of a tennis ball, might also be supported topologically, for instance with the relevant features bound along a certain axis (e.g., a 2D vortex) but not fully bound when viewed from a 4D perspective, else it would itself satisfy the conditions necessary to provide a 1PP itself. Such topology may itself be the EM outcome of underlying neuron-based computations to analyse perceived features, as popular in computational neuroscience, computer vision, and the earlier discussion of predictive processing.

We acknowledge that the presented EM fields solution to the boundary problem is conditional on their solution to the binding problem being effective (see citations in section "2. Literature review of the boundary problem") and accurate to the human experience, noting that other explanations for phenomenal binding have been proposed. This conditionality could turn on future insights from physics and metaphysics, depending on whether the particular phenomenon that creates binding must be ontologically fundamental or can be an emergent structure. Some researchers from section 2. "Literature review of the boundary problem" may accept the latter (e.g., resonance requires a substrate), whereas others may assert the former (e.g., quantum entanglement). However, with no strong consensus on what is ontologically fundamental, progress is limited. Traditional views of particles (in the Standard Model) and space-time plus mass-energy (in general relativity) are known to be incomplete and are under challenge, with contenders arguing that the base layer of reality is variously fields (QFT, e.g., Peskin, 2018), information (Wheeler; see Plastino, 2004), multi-dimensional strings (Greene, 2000), mathematics (Tegmark, 2014), mental objects (Kastrup, 2019) or conscious agents (Hoffman and Prakash, 2014), among others.

Rather than one fundamental object and its interactions, it is also possible that multiple objects co-exist at the base layer or they interact over more dimensions than we can sense [e.g., Ney's (2021) discussion of wave function realism as a "local" resolution to apparent quantum non-locality]. There is even disagreement over whether the discipline of physics is capable of probing fundamental ontologies, perhaps being restricted to the results of relationships between whatever is fundamental (Russell, 1927; Jones, 2010; Goff, 2020). Through this lens, asserting what is ontologically fundamental may be unproveable in traditional scientific experiments but alternatives can still be debated rationally, considering which candidate axioms best satisfy a useful set of specified properties.

4.3.2. Addressing the second and third problems

The second and third problems are resolved by accepting all well-bounded 4D topological pockets to have their own 1PP, potentially of a very rudimentary and short-lasting nature. Depending on the mechanisms involved, there may be dozens or billions of these in any one system, both smaller than and larger than the meso-level humans typically experience and discuss with each other. Our inability to identify them is ultimately an empirical question of analysing and measuring field topology, not a firm epistemological boundary. Nonetheless, we would not take the identification of very many such pockets to be a fundamental challenge to the theory.

Rosenberg (2004, s4.8) worries that such an approach is "panpsychism run wild," arguing that an explanation "that promiscuous is not illuminating." We politely disagree. The promiscuity of such 1PPs is no more counter-intuitive, we suggest, than the multitude of smaller objects we are already made up of. A total of 30 trillion cells in the human body, some seven octillion atoms (10ˆ27), and an absurdity of quarks and gluons popping in and out of existence in the tiniest of seconds. The universe is home to an estimated 10ˆ25 planets orbiting stars and perhaps 10ˆ80 atoms. Our human-level intuition already glosses over these unfathomably large numbers because we have chosen to accept them; the same is possible of the mind-dust corresponding to topological pockets. To the extent that ants have a rudimentary consciousness, there are an estimated 20 quadrillion on earth. That certain phenomena exist in larger numbers than we normally observe is no reason to deny them.

If there are indeed a possibly large number of 1PPs nested within and beyond us, the second and third questions also ask why our 1PP remains relatively stable at the meso-level. Our answer to this simultaneously addresses the fifth problem by reference to the problem of identity at different scales.

4.3.3. Addressing the fifth problem

We consider three temporal scales to illustrate the potential mechanisms at work: micro (sub-second), single experience (e.g., several seconds, perhaps several minutes or hours in some cases), and lifetime (e.g., years or decades).

Without prejudicing future empirical investigation, we will consider a 4D topological pocket object that spans a modest proportion of the human brain in spatial terms (perhaps several centimetres) and short in temporal duration (perhaps a few milliseconds). The pocket is naturally defined over the fourth dimension (time)—indeed it may fail to have hard boundaries without the topology along its temporal dimension. Thus there is intrinsic temporal depth at the micro-level for the 1PP. However, the 1PP corresponding to that pocket only exists for that short duration. As the underlying EM activity changes (different neurons fire etc.), the field topology changes and a new 4D pocket emerges, which similarly satisfies the hard boundary conditions described in section "4.1. How field topology can create hard boundaries." At least some such pockets emerge predictably and consistently, since there is part of the brain optimised through evolution to generate them, recruiting the power of such fields to enhance information processing. This new 4D pocket is a new 1PP. Each one exists for a short period of time and almost certainly less than a few seconds in normal human experience.

What causes these ontologically distinct 4D pockets to link together over time at the scale of short experiences, e.g., parsing a sentence or enjoying a song? This is the key step for explaining the uniformity of our meso-level experience. Of all the well-bounded 4D topological pockets that might exist in the brain, we suggest that only one of them bounds a field that encloses (and hence integrates) EM activity emerging from the brain's immediate memory modules.

Various other modules may also be surfacing information that is bound into the pocket, whether those are making sense of our perceptions to construct the indirect realist world we experience, considering actions and decisions against some set of goals, or various other mental functions we experience. In the context of continually jostling topologies, we can imagine these different modules producing EM fields that "compete" to contribute information to the well-bounded 4D field that is integrated with the relevant memory modules, helping to account for the phenomenology of multiple inputs competing for our attention that inspires advocates of global workspace theories.

The necessary step is that the topological pocket of interest integrates information from sequential instances in the recent and immediate past. It is the immediate memory module whose EM activity surfaces that information into each sequential 4D pocket. Unless that module is designed to surface similar outputs to different parts of the brain (a potentially evolutionarily costly redundancy), the requirement that any one piece of EM activity can only be enclosed by a single closed pocket at any one time provides the uniqueness constraint. The time durations from memory overlap from pocket to pocket, creating a more prolonged sense of time or a "pseudo time-arrow" than would be present in any single 4D pocket that does not enclose the memory input. Other 4D pockets, however many might exist, evaporate almost as soon as they begin: mind-dust with no sense of persistence.[7] In setting out a conceptual direction for resolution at this stage, we are not specifying which specific part(s) of the brain might be necessary for this immediate memory function or whether they correspond to specific theories of memory/awareness that remain active areas of study.

The key thing for our experienced persistence over time is that link to memory—the constant and repeated referencing of memory by different, consecutive, internally bound 4D pockets is what creates the sense of persistence. Persistent identity over a lifetime, weak as it is, is then generated by references to longer term memories and senses of self. Such an account is consistent with observations that our self can change over time, especially over decades, and that our short-term sense of self can be disrupted by memory disorders or certain chemicals.

4.3.4. Addressing the fourth problem

The merging of two 1PPs into a single 1PP is only a relevant question for a single 4D pocket in any case, existing for a very short period of time. This may be possible in principle but extremely difficult, since any attempt to bring the necessary modules close enough would likely destroy the physical mechanisms that generate

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[7] Whether you consider the phenomenological persistence we describe between pockets as illusory in some relevant sense or real is perhaps a matter of personal aesthetics and in any case a subject for a separate paper.

a pocket with the right hard boundaries to enclose a 1PP with any temporal persistence (even microseconds). The merged field may also be sufficiently different to the two original 1PPs that it is more meaningful to talk of a new 1PP than a merger.

Perhaps certain cases of conjoined twins and shared awareness are cases of such joining happening and undoing itself at different points in time with different topologies. However, we suggest it is more likely that such cases reflect information being shared between 1PPs, even jointly and simultaneously surfaced by the same brain mechanism. From this perspective, privacy is more about consenting to communication, rather than ontological separation, and is likely more a technological issue than a metaphysical one.

5. Conclusion

This paper has re-introduced and refined the boundary problem for theories of consciousness, as puzzled Schrödinger (1951) and first framed in detail by Rosenberg (1998). Inspired by Rosenberg's account, we have specified five problems which can be considered siblings to the famous binding problem, in that any ToC which provides solutions to the binding problem must also provide an account for our five problems. To a first approximation: if mechanisms are proposed to bind phenomenal experiences into a unity, what is it that stops the mechanism from expanding? What puts boundaries around those unified experiences and why do the boundaries appear as they do?

Our literature reviews found very little scholarly discussion of the boundary problem, at least as compared to the binding problem. Some promising avenues to resolving aspects of the boundary problem can be found in the phase transitions motivated in some resonance, quantum field, and EM field ToCs. However, none of these ToCs yet provide a full account against all five problems we specify. Specifically for field theories, we introduce a physical feature that may be particularly useful for tackling the problems: topological segmentation. Without prejudicing the possibility of other accounts, we provide one conceptual account by which 4-dimensional topological pockets could address all five problems while meeting other ToC desiderata: non-epiphenomenalism, no strong emergence, and frame invariance.

Our purpose in this paper is not to advocate for any one EM field ToC. The topological segmentation we describe can operate, in principle, at different spatiotemporal scales. For instance, referencing the citations in section "2. Literature review of the boundary problem": Shani and Keppler might motivate it to create relevant boundaries at the tiny scale of ZPF attractors in SED quantum fields. Jones might use it for the highly localised fields along ion channels where he identifies the seat of consciousness. Ward and Guevara might examine the topology of EM fields produced around the thalamus to find the right boundaries, McFadden might find them at the whole brain level, or Bond might even find them beyond and between brains.

An indirect contribution of this paper is to provide a further tool for differentiating between these EM field theories. If we accept field topology as the solution to the boundary problem in human consciousness, then the exercise of testing whether boundaries exist becomes a mathematical and empirical exercise that might proceed in three stages. In the first stage, the relevant part of the brain should first be modelled to capture as much relevant EM-field producing activity as possible, building on the high-level EM field mapping of the brain by Singh et al. (2019). This relies on a combination of imaging, dissecting, and computational exercises, similar in spirit to the Human Brain Project for mapping our neurons,[8] as already successful for the fruit fly larva connectome (Winding et al., 2023).

Secondly, the topology of the resulting field must be analysed to identify where there are closed loops (or alternative topological features that draw boundaries in the fields) that create the relevant hard boundaries at the theorised scales.

Finally, and subject to safe and ethical design, targetted EM pulses might be used to disrupt the identified topology, testing whether subjects' experience of consciousness varies in the required manner. If the boundary of consciousness itself is disrupted by such efforts, then we would expect the 1PP to collapse temporarily before returning (similar perhaps to deep sleep or cessations in meditation), rather than merely altering the content of what the 1PP is conscious as part of a continuously conscious experience.

We predict that such exercises will only identify topologies at a broadly consistent spatial scale for the presence/absence of 1PP, although impacts elsewhere in the brain might affect what that 1PP is conscious of. Whether this scale turns out to be micrometres, millimetres, centimetres, or decimetres will help narrow down to the correct EM field theory. The success or failure in identifying such topologically hard boundaries will also inform any competing introspective intuitions about the hardness or fuzziness of the phenomenological boundary discussed in section "3.1. The hard boundary problem."

As a practical first step, the authors are developing a technical companion paper to provide a mathematical and heuristic description of the conceptual model outlined here. Such a paper will discuss the kinds of closed boundaries that might plausibly occur within common, simplified brain anatomy and how topological pockets inter-relate. In doing so, we are inspired by mathematical work in topology and phenomenology by such scholars as Baudot (2018), Prentner (2019), and Mason (2021). Such work can help find topologies that are likely to exist given the EM activity in the brain, that create hard boundaries, that have sufficient complexity in a 4D space to reflect our multi-featured macrophenomenology, and that have irreducible computational benefits. This research direction is supported also by the growing empirical research base around wave dynamics in human brain geometry (Pang et al., 2023), cytoelectric coupling in the brain (Pinotsis et al., 2023), neural field analysis (e.g., Robinson et al., 2016), and the broader literature on cross-frequency coupling and phase-amplitude coupling. The full three stage research vision is a major scientific task, but should be accessible to the same human ambition which landed a robot on Mars for US$ 1 bn,[9] found the Higgs Boson in a machine with some US$ 10 bn of budget,[10] or achieved the first full mapping of the human genome at an estimated total cost of US$ 0.5-1 bn.[11] The prize is surely also no smaller: understanding

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[8] www.humanbrainproject.eu

[9] https://www.planetary.org/space-policy/cost-of-the-mars-exploration-rovers

[10] https://en.wikipedia.org/wiki/Large_Hadron_Collider

[11] https://www.genome.gov/about-genomics/fact-sheets/Sequencing-Human-Genome-cost

the mechanisms that give rise to our first person perspective, in a way that explains why we experience it as unified and bounded at the scale we do.

Data availability statement

The original contributions presented in this study are included in the article, further inquiries can be directed to the corresponding authors.

Author contributions

AG-E came up with topological segmentation as a potential solution to the boundary problem, as well as core arguments around non-epiphenomenalism, and applications of topological segmentation in current research. CP conducted the literature review, developed the five boundary problems, and constructed the illustrative EM field account that could address all five problems. Both authors contributed equally to the manuscript, writing the manuscript and to testing, and refining the arguments throughout.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

References

Baars, B. (1997). *In the theater of consciousness*. New York, NY: Oxford University Press.

Barbosa, L. S., Marshall, W., Albantakis, L., and Tononi, G. (2021). Mechanism integrated information. *Entropy* 23:362. doi: 10.3390/e23030362

Barkai, A. (2018). *On the psycho-physical parallelism*. Available online at: https://s3-us-west-2.amazonaws.com/psyphy/PsyPhy_latest.pdf (accessed May 1, 2023).

Baudot, P. (2018). Elements of consciousness and cognition. Biology, mathematic, physics and panpsychism: An information topology perspective. *arXiv [Preprint]* doi: 10.48550/arXiv.1807.04520

Bayne, T. (2010). *The unity of consciousness*. Oxford: Oxford University Press.

Bayne, T. (2014). Replies to commentators. *Analysis* 74, 520–529. doi: 10.1093/analys/anu066

Bell, J. L. (2005). Oppositions and paradoxes in mathematics and philosophy. *Axiomathes* 15, 165–180. doi: 10.1007/s10516-004-6675-8

Bond, E. (2023). The contribution of coherence field theory to a model of consciousness: Electric currents, EM fields, and EM radiation in the brain. *Front. Hum. Neurosci.* 16:1020105. doi: 10.3389/fnhum.2022.1020105

Chalmers, D. (1995). Facing up to the problem of consciousness. *J. Consc. Stud.* 2, 200–219.

Chalmers, D. (2016). "The combination problem for panpsychism," in *Panpsychism: Contemporary perspectivess*, eds G. Bruntrup and L. Jaskolla (Oxford: Oxford University Press), 179–214. doi: 10.1093/acprof:oso/9780199359943.003.0008

Chalmers, D. J. (2020). Is the hard problem of consciousness universal. *J. Consc. Stud.* 27, 227–257.

Dalton, J. W. (1997). The unfinished theatre. *J. Consc. Stud.* 4, 316–318.

de Haan, E. H., Corballis, P. M., Hillyard, S. A., Marzi, C. A., Seth, A., Lamme, V. A., et al. (2020). Split-brain: What we know now and why this is important for understanding consciousness. *Neuropsychol. Rev.* 30, 224–233. doi: 10.1007/s11065-020-09439-3

Dehaene, S. (2014). *Consciousness and the brain: Deciphering how the brain codes our thoughts*. London: Penguin Random House.

Dennis, M., King, R., Jack, B., O'Holleran, K., and Padgett, M. (2010). Isolated optical vortex knots. *Nat. Phys.* 6, 118–121. doi: 10.1038/s41467-020-17744-x

Ehlers, J., and Lämmerzahl, C. (eds) (2006). *Special relativity: Will it survive the next 101 years?* Germany: Physica-Verlag.

Fedchenko, D. P., Kim, P. N., and Timofeev, I. V. (2022). Photonic topological insulator based on frustrated total internal reflection in array of coupled prism resonators. *Symmetry* 14:2673. doi: 10.3390/sym14122673

Fekete, T., Van Leeuwen, C., and Edelman, S. (2016). System, subsystem, hive: Boundary problems in computational theories of consciousness. *Front. Psychol.* 7:1041. doi: 10.3389/fpsyg.2016.01041

Frankel, M. (2023). *Great mysteries of physics: Do we really need a theory of everything? The conversation*. Available online at: https://theconversation.com/great-mysteries-of-physics-do-we-really-need-a-theory-of-everything-203534 (accessed April 12, 2023).

Garson, J. W. (2001). (Dis) solving the binding problem. *Philos. Psychol.* 14, 381–392.

Goff, P. (2020). *Galileo's error: Foundations for a new science of consciousness*. London: Penguin Random House.

Goh, B. H., Tong, E. S., and Pusparajah, P. (2020). Quantum biology: Does quantum physics hold the key to revolutionizing medicine? *Progr. Drug Discov. Biomed. Sci.* 3:a0000130.

Gómez-Emilsson, A., and Percy, C. (2022). The "Slicing Problem" for computational theories of consciousness. *Open Philos.* 5, 718–736. doi: 10.1515/opphil-2022-0225

Greene, B. (2000). *The elegant universe: Superstrings, hidden dimensions, and the quest for the ultimate theory*. New York, NY: W. W. Norton.

Hall, D., Ray, M., Tiurev, K., Ruokokoski, E., Gheorghe, A. H., Möttönen, M., et al. (2016). Tying quantum knots. *Nat. Phys.* 12, 478–483. doi: 10.1038/nphys3624

Hoffman, D., and Prakash, C. (2014). Objects of consciousness. *Front. Psychol.* 5:577. doi: 10.3389/fpsyg.2014.00577

Hunt, T. (2011). Kicking the psychophysical laws into gear: A new approach to the combination problem. *J. Consc. Stud.* 18, 96–134.

Hunt, T. (2016). Taking time seriously in Tononi's integrated information theory. *J. Consc. Stud.* 23, 88–110.

Hunt, T. (2020). Calculating the boundaries of consciousness in general resonance theory. *J. Consc. Stud.* 27, 55–80.

Hunt, T., and Schooler, J. W. (2019). The easy part of the hard problem: A resonance theory of consciousness. *Front. Hum. Neurosci.* 13:378. doi: 10.3389/fnhum.2019.00378

Huxley, T. (1874). "On the hypothesis that animals are automata, and its history," in *The fortnightly review 16 (new series): 555–580. Reprinted in method and results: Essays*, ed. T. H. Huxley (New York, NY: D. Appleton and Company), 1898.

Irvine, W., and Bouwmeester, D. (2008). Linked and knotted beams of light. *Nat. Phys.* 4, 716–720. doi: 10.1038/nphys1056

James, W. (1895). *The principles of psychology*. New York, NY: Henry Holt.

Johnson, M. E. (2016). *Principia qualia*. Available online at: https://opentheory.net/PrincipiaQualia.pdf (accessed May 1, 2023).

Jones, M. (2010). How to make mind-brain relations clear. *J. Consc. Stud.* 17, 135–160.

Jones, M. (2013). Electromagnetic-field theories of mind. *J. Consc. Stud.* 20, 124–149.

Jones, M. (2016). Neuroelectrical approaches to binding problems. *J. Mind Behav.* 37, 99–118.

Jones, M. (2019). Growing evidence that perceptual qualia are neuroelectrical not computational. *J. Consc. Stud.* 26, 89–116.

Kastrup, B. (2019). *Analytic idealism: A consciousness-only ontology*. Doctoral Dissertation. Nijmegen: Radboud University.

Keppler, J. (2021). Building blocks for the development of a self-consistent electromagnetic field theory of consciousness. *Front. Hum. Neurosci.* 15:723415. doi: 10.3389/fnhum.2021.723415

Kim, H., Hudetz, A., Lee, J., Mashour, G., Lee, U., and ReCCognition Study Group (2018). Estimating the integrated information measure phi from high-density electroencephalography during states of consciousness in humans. *Front. Hum. Neurosci.* 12:42. doi: 10.3389/fnhum.2018.00042

Lahav, N., and Neemeh, Z. A. (2022). A relativistic theory of consciousness. *Front. Psychol.* 12:704270. doi: 10.3389/fpsyg.2021.704270

Lidström, S., and Allen, R. E. (2021). Toward a physics description of consciousness. *Eur. Phys. J. Spec. Top.* 230, 1081–1087.

Mason, J. W. (2021). Model unity and the unity of consciousness: Developments in expected float entropy minimisation. *Entropy* 23:1444. doi: 10.3390/e23111444

McFadden, J. (2006). "The CEMI field theory: Seven clues to the nature of consciousness," in *The emerging physics of consciousness*, ed. J. A. Tuszynski (Berlin: Springer), 387–406.

McFadden, J. (2013). The CEMI field theory closing the loop. *J. Consc. Stud.* 20, 153–168.

McFadden, J. (2020). Integrating information in the brain's EM field: The cemi field theory of consciousness. *Neurosci. Consc.* 2020:niaa016. doi: 10.1093/nc/niaa016

McFadden, J. (2023). Consciousness: Matter or EMF? *Front. Hum. Neurosci.* 16:1024934. doi: 10.3389/fnhum.2022.1024934

Melia, F. (2022). A candid assessment of standard cosmology. *Public. Astron. Soc Pacific* 134:121001.

Mendelovici, A. (2019). "Panpsychism's combination problem is a problem for everyone," in *The Routledge Handbook of Panpsychism*, ed. W. Seager (London: Routledge), 303–316.

Nagel, T. (1974). What is it like to be a bat? *Philos. Rev.* 83, 435–450. doi: 10.2307/2183914

Ney, A. (2021). *The world in the wave function: A metaphysics for quantum physics*. Oxford: Oxford University Press.

NOAA (n.d.). *Coronal mass ejections*. Boulder, CO: National oceanic and atmospheric administration.

O'Connor, T. (2021). "Emergent properties," in *The stanford encyclopedia of philosophy (Winter 2021 Edition)*, ed. E. Zalta (Stanford, CA: Stanford University).

Oizumi, M., Albantakis, L., and Tononi, G. (2014). From the phenomenology to the mechanisms of consciousness: Integrated information theory 3.0. *PLoS Comput. Biol.* 10:e1003588. doi: 10.1371/journal.pcbi.1003588

Pang, J. C., Aquino, K. M., Oldehinkel, M., Robinson, P. A., Fulcher, B. D., Breakspear, M., et al. (2023). Geometric constraints on human brain function. *Nature* 618, 566–574.

Parfit, D. (1984). *Reasons and persons*. Oxford: Clarendon Press, 1984.

Peskin, M. (2018). *An introduction to quantum field theory*. Boca Raton, FL: CRC press.

Pinotsis, D. A., and Miller, E. K. (2023). In vivo ephaptic coupling allows memory network formation. *bioRxiv* [preprint] doi: 10.1101/2023.02.28.530474

Pinotsis, D. A., Fridman, G., and Miller, E. K. (2023). Cytoelectric coupling: Electric fields sculpt neural activity and "tune" the brain's infrastructure. *Progr. Neurobiol.* 226:102465. doi: 10.1016/j.pneurobio.2023.102465

Plastino, A. (2004). A conceptual framework for the Wheeler program. *Phys. A Stat. Mech. Appl.* 340, 85–91.

Prentner, R. (2019). Consciousness and topologically structured phenomenal spaces. *Consc. Cogn.* 70, 25–38. doi: 10.1016/j.concog.2019.02.002

Rañada, A. F. (1989). A topological theory of the electromagnetic field. *Lett. Math. Phys.* 18, 97–106. doi: 10.1007/BF00401864

Revonsuo, A. (1999). Binding and the phenomenal unity of consciousness. *Consc. Cogn.* 8, 173–185.

Robinson, P. A., Zhao, X., Aquino, K. M., Griffiths, J. D., Sarkar, S., and Mehta-Pandejee, G. (2016). Eigenmodes of brain activity: Neural field theory predictions and comparison with experiment. *Neuroimage* 142, 79–98. doi: 10.1016/j.neuroimage.2016.04.050

Robinson, W. (2019). "Epiphenomenalism," in *The Stanford encyclopedia of philosophy (summer 2019 edition)*, ed. E. Zalta (Stanford, CA: Stanford University).

Rosenberg, G. H. (1998). "The boundary problem for phenomenal individuals," in *Toward a science of consciousness: The second tucson discussions and debates*, eds S. R. Hameroff, A. W. Kaszniak, and A. C. Scott (Cambridge, MA: MIT Press).

Rosenberg, G. H. (2004). "The boundary problem for experiencing subjects," in *A place for consciousness: Probing the deep structure of the natural world*, ed. G. Rosenberg (Oxford: Oxford University Press).

Rosenberg, G. H. (2014). "Causality and the combination problem," in *Consciousness in the physical world: Perspectives on Russellian monism*, eds T. Alter and Y. Nagasawa (Oxford: Oxford University Press).

Russell, P. (1927). *The analysis of matter*. London: Kegan Paul.

Schrödinger, E. (1951). *Mein Leben, meine Weltansicht [My Life, My Worldview or My View of the World]*. Cambridge: Cambridge University Press.

Seth, A., and Bayne, T. (2022). Theories of consciousness. *Nat. Rev. Neurosci.* 23, 439–452. doi: 10.1038/s41583-022-00587-4

Shani, I., and Keppler, J. (2018). Beyond combination: How cosmic consciousness grounds ordinary experience. *J. Am. Philos. Assoc.* 4, 390–410.

Shen, Y., Wang, X., Xie, Z., Min, C., Fu, X., Liu, Q., et al. (2019). Optical vortices 30 years on: OAM manipulation from topological charge to multiple singularities. *Light Sci. Appl.* 8:90. doi: 10.1038/s41377-019-0194-2

Singh, P., Ray, K., Fujita, D., and Bandyopadhyay, A. (2019). "Complete dielectric resonator model of human brain from MRI data: A journey from connectome neural branching to single protein," in *Engineering vibration, communication and information processing. Lecture notes in electrical engineering*, Vol. 478, eds K. Ray, S. Sharan, S. Rawat, S. Jain, S. Srivastava, and A. Bandyopadhyay (Singapore: Springer).

Tang, J., Wu, Y., Wang, W., Kong, L., Lv, B., Wei, W., et al. (2021). Magnetic skyrmion bundles and their current-driven dynamics. *Nat. Nanotechnol.* 16, 1086–1091. doi: 10.1038/s41565-021-00954-9

Tegmark, M. (2014). *Our mathematical universe: My quest for the ultimate nature of reality*. New York, NY: Knopf.

Tononi, G. (2015). Integrated information theory. *Scholarpedia* 10:4164.

Wang, J., Valligatla, S., Yin, Y., Schwarz, L., Medina-Sánchez, M., Baunack, S., et al. (2023). Experimental observation of Berry phases in optical Möbius-strip microcavities. *Nat. Photonics* 17, 120–125. doi: 10.1038/s41566-022-01107-7

Ward, L. M., and Guevara, R. (2022). Qualia and phenomenal consciousness arise from the information structure of an electromagnetic field in the brain. *Front. Hum. Neurosci.* 16:874241. doi: 10.3389/fnhum.2022.874241

Winding, M., Pedigo, B. D., Barnes, C. L., Patsolic, H. G., Park, Y., Kazimiers, T., et al. (2023). The connectome of an insect brain. *Science* 379:eadd9330.

Winters, J. J. (2021). The temporally-integrated causality landscape: Reconciling neuroscientific theories with the phenomenology of consciousness. *Front. Hum. Neurosci.* 15:768459. doi: 10.3389/fnhum.2021.768459

Wolski, A. (2011). Theory of electromagnetic fields. *arXiv [Preprint]* doi: 10.48550/arXiv.1111.4354

Young, A., Robbins, I., and Shelat, S. (2022). From micro to macro: The combination of consciousness. *Front. Psychol.* 13:755465. doi: 10.3389/fpsyg.2022.755465

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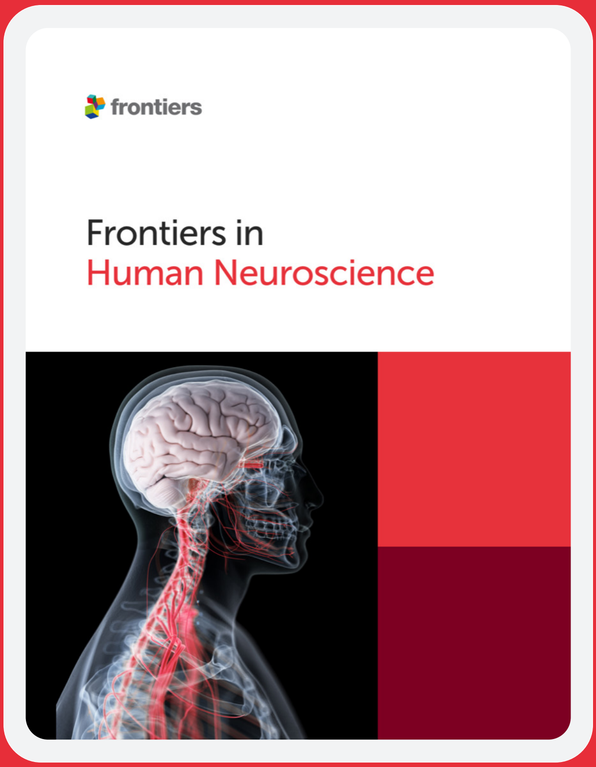

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