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Brief Report

Geomagnetism came first: Implications for animal translocation and the two-brains hypothesis

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Abstract

The relevance of the Two-Brains Hypothesis for induction between peripheral Schwann cells and their axon hosts and for intra- and trans-cranial bioengineering at the human-robotics interface is accompanied by particular attention to its significance for a biological wonder: the involvement of geomagnetism in avian directional behavior in migration, homing and navigation. Two sources of magnetism are considered here. The simpler is the polar (compass) direction, long reported as resulting in some birds in a manner unknown from the presence of magnetite (Fe_3O_4) in the avian ethmoid region. The second is certain chemical reactions that respond to applied magnetic fields. These usually involve radicals, molecules with unpaired electrons that spin in one of two possible states. A radical-pair mechanism, a light-dependent, chemical initiation of magnetic orientation, has been considered responsive to the axial inclination of the field in relation to Earth's field, but not to its polarity. The initiation is by optic but non-visually responsive cellular absorption of a photon of a specific wavelength. Radical pairs are short-lived and must be correctly aligned in the host receptors for directional sensitivity. The firmest evidence for the radical-pair theory of magneto-reception in birds remains the cryptochromes, the blue-light absorbing flavoproteins, but the receptor molecule has not been identified yet. Subjective thought and consciousness are also unexplained in birds, as in humans and animals. However, the novel, structured dichotomy of the Two-Brains Hypothesis may provide a fresh, biophysical approach to the connection between geomagnetism, life and the evolution of vertebrate translocation without recourse to philosophy or a universe expanding beyond imagination.

***Keywords**:* Geomagnetism, evolution, Two-Brains Hypothesis, homing, migration, magnetite, chemical optic magneto-reception, radical pairs, cryptochrome blue light-absorbing proteins, induction, complementary

1. Introduction

It is sometimes forgotten or ignored by biologists, even evolution experts, that geomagnetism preceded life on Earth and, being persistent and relatively invariable, would be likely integrated into some aspects of life, even though invisible. Though also preceding life, electric lightning is so sporadic in time, place and intensity, and it is unlikely to have contributed to evolution, even though it is very visible. Moreover, in the oceans and under Earth's surface, where life would presumably have first developed without exposure to extreme ultraviolet radiation, lightning also would have been absent, geomagnetism not so. Nevertheless, much more attention is given in biology to what is electric rather than magnetic.

The living world is indeed alive with electric fields [1-5]. For example, in the nervous system, they interact in adjacent neurons [6], influence the direction/rotation of growth cone neurites [7, 8], stimulate axon amino-acid uptake [9] and direct faster neurite growth towards cathodes rather than anodes [10]. Moreover, such seems to be the dominance of extensive review concerning electric fields in animals. In a recent relevant, extensive review concerning the nervous system, "electric" appears 159 times, "magnetic" not once, and even in a leading neuroscience text [11], magnetism is indexed only under imaging and encephalic radiological technique for examining the anatomy or body physiological processes. Yet magnetism is as fundamental as the electricity which it preceded, and presumably, there was no reason why it should lag in brain processes [12].

Recently, based on the Faraday laws accounting for mutual induction of electric current and magnetism, the Two-Brains Hypothesis (TBH) has argued that in animals, including man, the CNS evolved as two fundamentally different though interdependent, complementary organs [13-15]. One is electro-ionic (tangible, known and accessible), and the other is electromagnetic (intangible and difficult to access).

difficult to access). Thus, a unified set of different types of electro-ionic, neuron-based, functionally-linked brain regions interact complementarily in the Bohr-Copenhagen sense with a unified, structured and functional 3D grid of variously induced electromagnetic (EM) fields (see **Fig. 1**). The EM grid evolved independently as an integration of several different magnetic fields in the CNS associated with axon, dendrite and oligodendrocyte activities, is complementary to the parallel independent integration of the latter entities and resembles a self-organized EM small-world network modeled as dynamic constructs, artificial and neural in *Caenorhabditis elegans*, a nematode [16]. Surprisingly and critically, that model also exhibited enhanced signal propagation speed, computational power and synchrony, networks without topological structure can be of this type [16]. The precise manner of the integral operation of the grid is unknown, though dynamic continuity rather than neuronal "all-or-nothing" can probably be expected. Natural selection will have ensured the normally efficient, anatomic, metabolic and functional integration of the two-brains dichotomy, while disturbance to the latter may initiate some pathology.

McFadden [17] has reported synchronized firing patterns in large numbers of brain neurons feeding back to the neuron groups, which are their source. However, the TBH is differentiated from a suggestion that oscillations at certain frequencies in firing neurons perturb a global EM field external to them, creating a "pattern" representing neuronal information that is said to be fed back to the neurons 'consciousness' [17]. This feedback is regarded as modifying electric charges across neural membranes toward the probability that specific neurons will fire. Accordingly, the EM "pattern" is a closed-loop dependent on the neural electrical charges. In contrast, the evolution of TBH in the central nervous system has wide implications for many aspects of animal physiology. Thus, it has been considered for relevance to subjects as disparate as two-way induction between peripheral Schwann cells and and their axon hosts [18], life, if any, elsewhere in the universe [13], intra- and trans-cranial effects in bioengineering, such as in human robotics [14], avian directional behavior in migration, homing and navigation [19-22] and the nature of consciousness from a biophysical point of view [15].

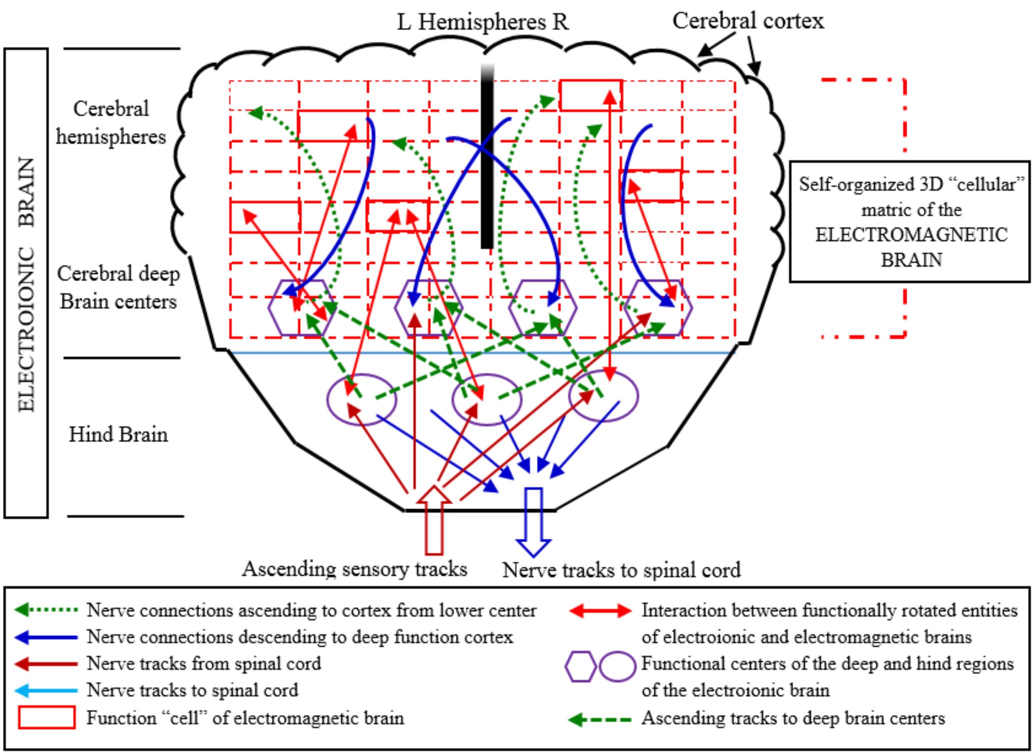

Fig. 1. *A schematic expression of the Two-Brain Hypothesis according to which an electro-ionic and an electromagnetic brain interact together as independent but complementary organs, thereby enhancing higher processes of recall, perception, thought, judgment and decision in a process engendering a uniquely individual consciousness. From [13].*

1.1 Magnetism: not a 'poor relation'

It is not clear that rapid "jumping" of action potentials is as critical in the central nervous system (CNS) as in the periphery, as action integral to the CNS tends to minimal distance. Partly reflecting exceptional crowding, CNS axons are much shorter, and a brain oligodendrocyte may wrap a number of axons. Still, the proposed related secondary magnetic fields in the CNS are unlikely to be weaker than in the periphery, while central magnetic functions are likely more varied. For example, the secondary magnetic field of a glial cell wrapping several short axons could bring a level of unity to the external environment around those axons. Also, though the magnetic fields of the neuronal dendrites massively present in the CNS were once believed to be inconsequentially minute and the axon magnetic field stronger than that in the dendrites because of the greater ionic currents flowing inside the axoplasm, the great mass of the dendrites in some magnetic field from this source [23], (see **Fig. 2**).

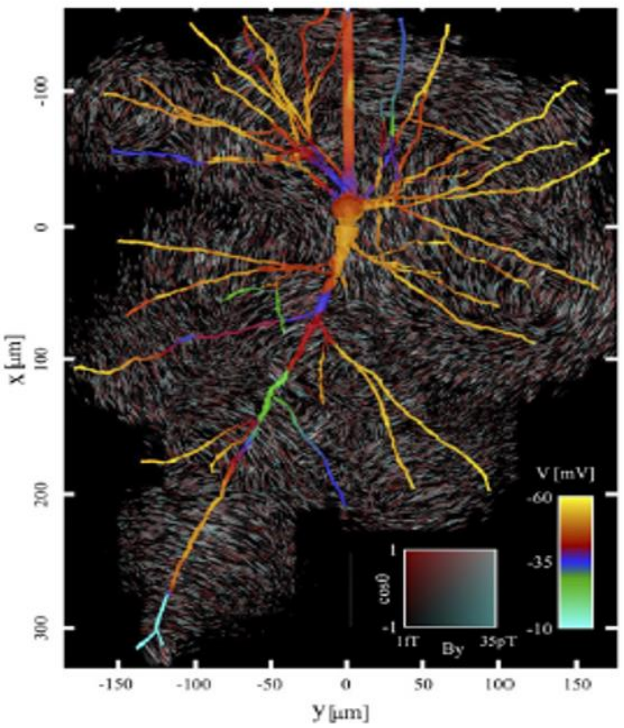

Fig. 2. *Reconstructed pyramidal neuron from macaque monkey with the simulated electrical activity and corresponding magnetic field at 30 ms after the start of the simulation. The neuron is viewed from a point in the z-direction, looking down on an x–y plane. The soma is at (0, 0, 0) in our coordinate system. The box's dimensions containing the neuron are 480 microns in x by 350 microns in y by 180 microns in z. The potential in the dendrites is color-coded. The two axes are labeled in microns, whereas the color scale represents millivolts (mV). The 3D magnetic field is represented by vortex-like clouds of vectors whose colors represent the direction and whose lengths represent relative magnitude. From [23].*

It was also recently demonstrated that cerebral white matter in humans and four primate species is not a chaotic mass of brain axons. It is an orderly, dense crisscrossing at 90 degrees of parallel layers of axons, side by side, with some intertwined [24], (see **Fig. 3**), so a possible additional source of brain EM vortices. Vortex spin direction and core polarity are well-known sources of EM fields [25,26]. Speculatively, matrices of such vortices may enable faster data handling by natural digital mechanisms providing speeds adequate for human thought. Yet, the technological utilization of magnetic fields, particularly for imaging, has far outstripped consideration of their contribution to natural physiological activity. This use has now been extended to human robotics, including invasive therapeutics. Indeed, in animal studies, magnetic fields are usually the poor relation to neuronal current: "unseen" and, if apparent, downplayed or disregarded.

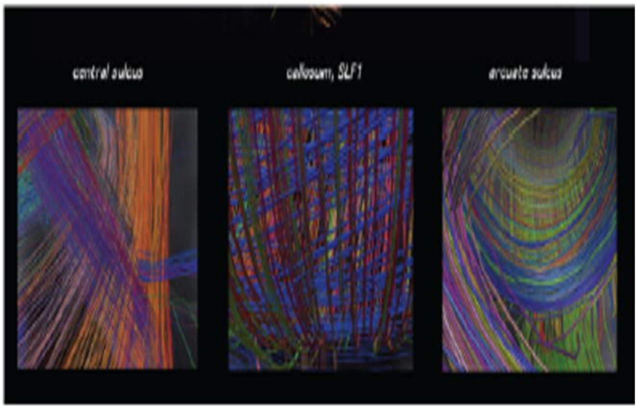

Fig. 3. *The continuous grid structure of rhesus frontal lobes. All cortico-cortical pathways show highly curved elements in a continuous sheet of interwoven paths in two nearly perpendicular orientations aligned with gyral topography in the arcuate sulcus and callosum but oblique in the central sulcus. From [24].*

1.2 Ionic cables

The myelinated axon has always been regarded as an electro-ionic entity, particularly since the findings of Hodgkin and Huxley [27] that the action potentials racing down a motor neuron sheathed by the myelin of Schwann cells "jump" between the successive nodes separating the sheaths, thus increasing signal conduction velocity. The role of the myelin had also long been regarded as reducing current leakage from the axons. Its possible involvement in magnetic induction aroused no interest. Indeed, unlike the highly visible neural "cables", very minute magnetic fields were unseen, relatively inaccessible, mainly masked by the Earth's field, i.e., assumed to be mere bye products of ionic activity. A recent re-evaluation of the relationship between the peripheral motor neuron and its satellites, the Schwann cells, argued that the Schwann cells cycle ion current through and around the myelin wrapping of the axon, inducing a secondary magnetic field that influences axons and the extracellular environment [18].

Moreover, it is particularly notable that there has been a long, controversial and debated relationship (g-ratio) between the motor axon diameter and the thickness of the Schwann cell myelin sheaths wrapped around it [28-31]. A secondary magnetic induction supports the further proposal that the g-ratio depends on the nature of the magnetic flux at any time and point within and along the axon [18]. The field-based g-ratio seems to be supported in some cold-blooded invertebrates [32, 18]. The fastest conduction known in myelinated fibers (up to 200 m/sec or more – the speed of sound) has been found in some shrimp species. However, though vertebrate axon conduction speed usually depends on the temperature, remarkably, in the poikilotherms, this is not so [32]. This weakens the argument that the g-ratio reflects metabolism. Overall, these shrimps too support the evolution of an anatomic physical ratio rooted in the evolution of an electromagnetic sheath-axon symbiosis based on a fundamental non-adaptive physical phenomenon.

2. 'Way home' - with the complementary EM brain

2.1. Directional preference, homing and migration.

The above suggests that knowledge of the EM brain may generally transform understanding of vertebrate cognition and behavior. However, long-standing questions concerning the evolution of natural directional preference in animals, including animal homing and migration, may be clarified. TBH suggests selection in the animal kingdom of central magnetic mechanisms serving direction-finding and navigation in possibly nearly all, if not all, animal species. This may be so, even in cases in which, for evolutionary reasons, the potential interaction of geomagnetism with the EM brain has been partly or mostly suppressed - as it has in humans. Thus, through additional guidance mechanisms have been realized, such as recognition of star positions and sensing of pheromones, some sharks, for example, react to the interaction of ocean currents and the geomagnetic field [33]. However, preferred movement in avian species is mainly considered here.

2.2 Magneto-reception in birds and the geomagnetic field

Birds evolved primarily in 3D environments unlimited by terrestrial or marine impediments and in many species driven by season. Avian direction-finding has remained a wonder (see **Fig. 4**). However, memory is not useful for migrants or homing birds flying through cloud cover, whether in the daytime or at night. Avian use of the geomagnetic field was proposed in the mid-nineteenth century and first demonstrated in 1966 for European robins [19]. The geomagnetic field can be used as a compass for direction and/or navigation as one of the elements in a mental "map" that aids in setting a course [20]. However, some juvenile birds without route experience or memory were found not to have a "map" but only their innate geomagnetic compass, mature birds had both [34].

There are two sources of magnetic information. Many species of birds have magnetite particles concentrated in the ethmoid region (at the root of the nose). These respond to a high-intensity magnetic pulse, changing orientation [35,36]. However, magnetite data have recently been questioned due to possible laboratory contamination [37]. A very different, chemically-based source of directive magnetism has also been mooted.

2.3 Chemical magneto-reception

Certain chemical reactions respond to applied magnetic fields [21]. These reactions, almost without exception, involve radicals, molecules having unpaired electrons with spin in one of two possible states. Thus, much attention now is to an unproved proposal for a radical-pair (RP) mechanism in a light-dependent chemical initiation of magnetic orientation, which is responsive to the axial inclination of the field, not to its polarity [22, 38]. The RP is two radicals reacting to a magnetic field in a complex manner [39]. In non-cryogenic conditions, the pairs are extremely short-lived. However, recently it was claimed that even in normal temperatures, a Robin species exhibited an RP sensitive to the geomagnetic field for a period remarkable enough to be possibly functional [40]. This will not be entered into here other than to note that RP's must be sensitive to a field direction and its intensity to act as a compass. Furthermore, they must be correctly aligned in the host receptor cells, or rotational disorder would cause them to cancel one another out and thus reduce the directional sensitivity of the receptor molecule molecule [40]. No such molecule has been identified as yet.

Unlike a compass needle, avian magneto-receptor-based orientation is maintained even when the field is reversed. Moreover, the orientation is initiated by the ambient light of a wavelength above a certain threshold and is sensitive to a narrow range of magnetic intensities [41]. However, interestingly fruit flies can orient in a magnetic field even in complete darkness. Moreover, in a behavioral experiment, a lack of magnetic response can indicate that the magneto-receptor is disrupted, but other nervous systems are also disrupted, though the receptor is not. So, although much has been reported, avian magneto-reception is still very poorly understood, from initial detection by an unknown putative ocular photoreceptor, hosting rapid photochemical reactions with radical pairs as extremely short-lived intermediates and down phototransduction pathways to final processing in the CNS [42]. Currently, the only photoreceptor proteins entertained as biomagnetic receptor transducers are two cryptochromes, cry 1 and cry 2. Remarkably once thought to be centrally localized, there is evidence that they are found widespread in the CNS and spatially within a bird's body [41]. The function of this is unknown. The conditions above are plausible, but when simultaneous, do they provide a biologically creditable magneto-receptor? However, though there are few known examples of magnetic field effects on biological processes, they may be because they were not sought.

2.4 Surprise, surprise

In 2007 the domestic chicken, neither a migrant nor homing species, was found to use a magnetic compass [43]. It will have evolved before domestication. It originated in the jungle fowl, a non-traveling inhabitant of a restricted location, probably a left-over from very early evolution and encouragement for the view that the EM brain has complex roles from earliest times. What other such surprises may come? Much of the evidence for the photochemical radical pairs is circumstantial. Perhaps the requirement for incident light is not connected to the magneto-receptor at all but derived from an independent mechanism. After several decades, the avian magnetic compass is still a mystery. It is a direct reaction to the geomagnetic field or an indirect, optically-involved inclination of a specific molecule to Earth's magnetic field (see [44] for a review).

2.5 Blue light-absorbing proteins

The firmest evidence for the RP theory of magneto-reception in birds remains the cryptochromes, the blue-light absorbing flavoproteins first found in plants [45], later in bacteria, insects and animals, including birds [46]. They are believed to provide the photon which starts the magnetic ball rolling. However, though some entrain circadian clocks, not all cryptochromes are light-activated. Cryptochrome signaling is assumed to include conformational changes linked to unknown downstream molecules. While a cryptochrome is necessary for light-dependent magnetic responses in Drosophila [47], the protein may not generate radical pairs in that insect. However, there is contrary evidence [48]. Surprisingly, some plants react to magnetic fields without apparent magneto-reception but with cryptochrome blue light. Moreover, though a model has been shown to respond to Earth-like, 50μT fields, the constraints imposed on a chemical compass by molecular disorder and motion are formidable.

2.6 Magneto-reception and the two-brains hypothesis

Interaction of the Earth's geometric field with the EM brain is possibly an alternative to the mystery of animal magneto-reception. This interaction evolved in the CNS is potentially a source in most animals, if not all, for response to magnetically-based directionality of some kind. Suppose the influence of RP in animals is proven. In that case, this may have come later within the evolving context of the EM brain, with the non-polar influence of magnetic field inclination evolutionarily effective even during reversals of the Earth's poles. The number of animals in different Classes known now to be influenced by the Earth's geometric field is growing. Amongst birds alone, over 20 species are now said to experience magnetic direction. Not all are migrants, and it could be informative to know why magnetic directionality still exists in the domestic chicken. Perhaps transcending that question today is a much larger one: the nature of animal consciousness and psyche. In answer, TBH may be enough.

3. Consciousness, the animal psyche and two-brains hypothesis

TBH may provide a non-philosophical approach to what, for the human, Chalmers called the 'hard problem': why and how widely distributed detectors in the awake brain constantly sense different features such as size, color, tone, shape, sound and motion and bind them together with associated thoughts and memories into innumerable conscious experiences uniquely personal to the individual. He focused attention on information but, like others, shifted into the universal consciousness [49]. The Penrose–Hameroff consciousness model called on quantum gravity and collapse of the wave function and arrived at universal consciousness [50], Crick and Koch [51] limited themselves to 35–74 Hz neural oscillations in the cerebral cortex. It is unknown what animals other than man experience consciousness. Can they be drawn into the 'universal consciousness' debate? Or are they destined to be left to fend for themselves on Mother Earth? Likely - and probably beneficial.

Animal interaction usually entails relatively simple, conscious vocal signaling and body language in the social context. In man, thought processes around communication evolved in a complex of language and symbolism at the heart of human creativity while suppressing the development of direct, interpersonal communication between human EM brains [13]. Similarly, the advanced human ability to map and navigate may have suppressed tapping of the geomagnetic field, in contrast to the proposed evolution, for example, of a unified extra-corporeal EM field extending across close-formation swarming of starlings ([15], see **Fig.4**). Subjective thought and consciousness are unexplained in birds, as in man. For birds, too, is it necessary to go beyond physical reality?

It was suggested that interaction between the relatively slow sensory system responded to by the electro-ionic brain and the incomparable speed of the EM brain in recall, abstraction, permutation and judgment is analogous to human conversational intimacy between two individuals, each perceiving the other's subjective outlook, allowing the emergence of a synthesis objective to both [14, 15]. Would this also apply to the bird and its psyche? We are well aware that the novel, structured dichotomy of TBH may provide a fresh approach to phenomena such as imagination, dreaming and sudden recovery from total coma and psychological and psychiatric disorders. Moreover, temporary silencing of one side of the proposed intimate Two-Brains "conversation" may apply to those rare clinical cases in which a person is long assumed to be in a coma but is aware of the surroundings - and suddenly "wakes". Can some birds too similarly 'awaken' and sing homewards?

Fig. 4. *Starling murmuration. This image, generously provided, was photographed at 16:23 on 10 December 2013 at the Village of Rigg, Nr Gretna, Dumfries and Galloway, Scotland, with a Canon EOS 5D Mark III at 1/50Sec - F2.8 - ISO 2500 by Tom Langlands Photography*

The avian brain is truly remarkable [52]. Its cells are smaller and more densely packed than mammalian brains. Indeed, part of their brains that corresponds to the cerebral cortex supports higher cognitive functions such as planning forwards has surprisingly large numbers of neurons. The brains of parrots and songbirds contain very large numbers of small neurons at densities exceeding those in mammals Thus they have about twice as many neurons as primate brains of the same mass and 2-4 times as many neurons as equivalent volumes in rodent brains [53]. The goldcrest's body mass is a ninth of that of a mouse, but its brain has 2-3-fold more neurons. Accordingly, some birds show cognitive ability at least as complex as some primates and are capable of vocal learning. Moreover, in parrots and other birds, the proportion of forebrain neurons is significantly higher, so they demonstrate higher cognitive ability per kilo than mammals [53].

Whether many avian, small neurons in the CNS have a correspondingly large energy cost. Their effort against gravity is more expensive than in landlocked animals. This is an argument for the benefit of birds, especially by the evolution of a complementary electromagnetic brain. Whereas individuals cannot share muscle power, mass sharing of the information processing necessary in thought, within the framework of an EM field, could allow, in appropriate circumstances, the economy in energy consumption (see **Fig 4**).

4. Conclusion

In 1933, stirred by the emergence of atomic physics and the probabilities of quantum theory, Bohr [54] considered those fundamental advances concerning life and its biological processes. He tried to apply the principle of complementarity, which he had enunciated as appropriate to physical phenomena: both the wave and particle properties of atomic dimensions are necessary for understanding both, as they are independent yet inseparable. Troubling was that the methodology of physics is bottom-up, whereas biology breaks down life into smaller parts. Bohr failed to bridge this gap and accommodated quantum probability with 'purpose'.

Biologists today should be less concerned about that gap and much more about the fact that physical findings by Michael Faraday have long been relatively side-tracked in evolutionary aspects of biology. For example, Faraday demonstrated how "magneto-electricity" combined with mechanical energy in the "induction" of an electric current, unlike Earthly lightning. Only recently, too, was it asked if it was possible that natural selection did not precede Faraday in full, widespread exploitation of magnetism as a fundamental, physical, animal phenomenon [14] or whether geomagnetism has been given its due in a quantum dynamic treatment of consciousness, as it has now [55]. The laws expressing mutual induction of electric current and magnetism underpin the two fundamentally separate but interdependent, complementary organs, electro-ionic and electro-magnetic, formulated in the Two-Brains hypothesis. Many newer techniques are available to study this [23,25,26,56,57]. More is needed - also to show how the geomagnetic field is integrated with alternative visual cues in the compass of migratory birds [58].

Conflict of Interest

The authors declare that they have no conflict of interest

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