PERSPECTIVE

MODERN BIOELECTROMAGNETICS & FUNCTIONS OF THE CENTRAL NERVOUS SYSTEM

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ABSTRACT

Contrary to prevailing neuron doctrine," the glial substrate and other perineural structures of the central nervous system, through their sensitivity to extremely low levels of electric currents and magnetic fields, may directly control brain functions. The neuronal brain is not only supported by, but modulated by, the glial brain. Decades of research findings which support this view are examined, and genetic and behavioral effects evaluated. Electromagnetism and its effects on the "integration of brain function" in consciousness are considered, and in conclusion it is hypothesized that DC and low-frequency extraneuronal electric currents generated in, or transmitted by, the glial components of the brain may be the basis of perceptual awareness.

KEYWORDS: Magnetic field, electrical current, perineural cells, neurons, glial, brain, perception, mind, behavior

INTRODUCTION

In the first article of this series,[1] I attempted to indicate the theoretical reasons requiring the existence of a "nervous" system more primitive than that associated with neurons and the second article,[2] presented some of the actual laboratory data that supported this concept. This evidence indicated that this system may reside in the perineural glial and Schwann cells and operate as an analog data transmission system using actual direct electrical currents. The DC electrical microenvironments thus produced in the brain were postulated to modulate the activities of the neurons proper and to be the primary integrative mechanism for brain function.

This concept is obviously at variance with established "neuron doctrine" which ascribes all functions of the brain and nervous system to actions of the neurons alone. In addition, it challenges the most basic established paradigm of biophysics which holds that *all* life functions are primarily chemical in nature. In that view, in order to produce any alteration in biological function electrical currents or electromagnetic fields must alter chemical activity by disrupting chemical bonds, or produce heating of the tissues in excess of kT, the inherent thermal level normally present. The levels of electromagnetic parameters required to produce such chemical actions are quite high, many orders of magnitude greater than any DC potentials that had been measured. As a result, these electrical observations were ignored. In the present article I summarize recent data indicating that extremely small levels of electrical currents or magnetic fields *do* have major biological effects.

That an electrical heating effect can occur is evident in any microwave oven, presumably because the wave lengths are sufficiently short to permit the deposition of energy in the aqueous organic materials. However, this effect requires a specific strength for the microwave field. Below this thermal-effect level there was thought to be no possibility of bioeffect. This property of microwave frequencies has been regarded as confirming the concept that sufficient energy had to be deposited in the tissues to cause heating before any bioeffect could occur. In the Extra Low Frequency (ELF) range, of 1 to 1000 Hz, the wave lengths are many orders of magnitude too long for any conceivable coupling to occur, and therefore this region was declared totally devoid of any bioeffect whatsoever. In short, no electromagnetic field of any frequency could have any bioeffect, other than tissue heating.

Over the past two decades, however, credible scientific evidence has been presented indicating that electrical currents and electromagnetic fields of a strength far below tissue-heating levels can have profound bioeffects. While initially there was strong opposition to this data, now the scientific consensus is that the evidence for non-thermal effects is overwhelming and that an exciting new discipline of research has been opened with useful applications already beginning to become evident. The new discipline, termed Bioelectromagnetics (BEM), encompasses all of the previously forbidden inter-relationships between electromagnetic energy and living organisms. In the area of neurophysiology, many of its findings lend credence to the postulated dual nervous system concept I discussed in the preceding two articles.

At present, several thousand scientists are deeply involved in bioelectromagnetics research in this country alone and two recognized scientific journals have been in continuous publication of their data for more than a decade. The volume of data is overwhelming and it appears that the best way to introduce the inexperienced reader to this field is to briefly, chronologically sketch the most important events that have led to the present situation.

1970 - 1980

The direct origin of BEM can be traced to several incidents that occurred during the decade of the 1970's, a time when only the established chemical paradigm was accepted by serious scientists. In 1973, I was asked by the US Navy to be on a committee to evaluate the possible bioeffects of a massive antenna system, code named "Sanguine", that was to be constructed in the northern half of Wisconsin. It was to transmit electromagnetic (EM) signals to submerged submarines around the world using ELF at 45 or 75 Hz, frequencies just above and below the commercial power frequency of 60 Hz. Despite the large size of the antenna, the EM field it would produce was considerably lower than that produced by most electrical power facilities, which had never been shown to pose any environmental biohazard. While these studies of potential bioeffects were considered to be a sterile exercise, in view of the physical impossibility of any such effect, Congress had directed the Navy nevertheless to conduct them. The results were what the committee members were to evaluate. To the complete surprise of the

group, many of the 20 projects reported, including one conducted on human volunteers, indicated direct, potentially hazardous, bioeffects. The committee advised the Navy to conduct several additional studies and in particular, to advise the Federal Administration that the studies indicated that major segments of the American civilian population may be at risk from the stronger ELF fields radiating from power transmission lines and similar installations.[3]

Shortly after the meeting, I became aware of a proposal to build a number of ultra high power transmission lines in New York State and informed the State regulatory agency of the Navy's results. This subsequently led to extensive public hearings and ultimately to a five-year study of the problem by the New York state Department of Health, funded by a five million dollar assessment on the utility companies. This study, which did not begin until 1981, corroborated and extended the Navy's findings.[4] Throughout the course of the project, interest in this area increased within the scientific community and the publication of the final results in 1986 provided the first extensive data base on the subject. Bioelectromagnetics as a funded discipline may therefore have originated from the question of public health and the electromagnetic fields associated with electric power facilities. It is probable that if it had not been initially brought into the public-health arena, much less progress would have been made. Studies preceding the New York State Department of Health Project were generally along the lines of basic science, not aimed specifically at relationships between electromagnetic parameters and living organisms.

In 1975, Dr. Richard Blakemore of the Woods Hole Oceanographic Institution published a paper entitled "Magnetotactic Bacteria" in which he described a motile, marine bacterium that sensed the direction of the Earth's magnetic field by means of an organized collection of crystals of magnetite within the cytoplasm.[5] Movements of the bacteria in response to this structure were of survival value. This report led to the possibility that other organisms, such as the homing pigeon, might have a similar mechanism for sensing and responding to the extremely weak geomagnetic field. Also in 1975, the first detection of a weak, external magnetic field produced by activity of the human brain was reported by Dr. David Cohen at MIT.[6] This observation was made possible by the development of the SQUID magnetometer, a superconducting device that is extremely sensitive to very-low-strength magnetic fields. The magnetic record of the brain, which has become known as the magnetoencephalogram

(MEG), is similar to but not identical with the well-known electroencephalogram (EEG). The importance of this observation was that it indicated the existence of actual electrical currents flowing within the brain.

While all of this was unfolding, Drs. Susan Bawin and Ross Adey reported in 1976 that brain cells lost significant amounts of calcium ions when exposed to extremely low-level EM fields at 16 Hz.[7] Since calcium is an important determiner of neuron function and since the field strength that produced this perturbation was extremely weak, this report elicited much interest and was one of the factors that led to a meeting of the Neurosciences Research Program in which the possibility of other mechanisms of communication and coding in neurons, additional to the nerve-impulse system, were discussed.[8]

The relationships between bone growth and DC electrical currents previously discussed[2] led (in 1978) to approval by the FDA for the clinical use of a number of electromagnetic devices as stimulators for human bone growth. These devices ranged from implanted or percutaneous types that administered a very small DC electrical currents, to non-invasive devices that irradiated the fracture site with pulsed magnetic fields. All of these had been shown to stimulate new bone growth and to be useful in the treatment of human fractures that had failed to heal. This commercialization stimulated many additional studies of other potential applications producing additional basic data.

Also in 1979, Dr. Nancy Wertheimer, studying the distribution of cases of childhood leukemia in Colorado, reported that a significant number of such children lived in homes in close proximity to local electric power wires that carried high currents.[9] While Dr. Wertheimer had initially been searching for an environmental chemical agent, she speculated that the local 60-Hz magnetic field radiating from the lines might be the specific factor related to the increased incidence of leukemia. This study was later duplicated in the New York State Department of Health's Power Line Project.

Finally, in the same year, magnetite mineral deposits, similar to those first noted by Blakemore in bacteria, were reported to be present in a specific area of the homing pigeon's brain by Walcott, Gould and Kirschvink.[10] Since the homing abilities of these animals had originally been shown by Keeton,[11] to be magnetically related, the possibility that the magnetite crystals represented the sensitive component of a magnetic field-sensing organ was confirmed in a higher organism.

DECADE SUMMARY

Thus, by the end of the 70's, DC electrical currents and time-varying magnetic fields in the ELF frequency range, at strengths far below heat-producing levels, had been shown to have important biological effects including stimulation of growth processes, a possible relationship to the incidence of cancer and alterations in the functions of neurons. At the same time, the existence of a brain-generated magnetic field external to the head and a specific biological structure for possibly sensing the geomagnetic field had been established.

All of the above findings raised serious questions regarding the validity of the then-current biophysical paradigm. Though mechanisms of action were unknown, existing theory could not explain the biological effects of non-thermal EM parameters, and that theory had to be revised or replaced. Since some of the studies raised the possibility of adverse effects on human health of man-made electromagnetic fields, each of these incidents drew media and political attention and generated increased interest in the scientific community. This led to the establishment of several scientific societies and journals all of which have expanded their membership and scope of activities. Today, Bioelectromagnetics is a recognized, vital science.

1980 - 1990

The next decade was one of rapid growth and expansion based upon the discoveries of the 70's. The first major observation was the report of Semm, Schneider & Vollrath[12] showing that DC magnetic fields of the same strength as the geomagnetic field produced significant alterations in the rate of spontaneous discharge of specific cells of the guinea-pig pineal gland. The possibility was raised that this represented a second magnetic-field sensing system. Later, Welker *et.al.*[13] showed that similar fields could alter the serotonin and melatonin metabolism of the pineal gland in rats. Since serotonin and melatonin are important neurohormones connected with biocyclic behavior, a possible linkage of magnetic fields with human behavioral alterations was considered. This new area of research has become very fruitful. For a recent review, see Olcese, Reuss & Semm.[14]

Many further studies were conducted on the magnetite deposits initially reported by Blakemore in bacteria[5] and Walcott in pigeons.[10] This structure has now been identified in a wide variety of organisms, always in relationship to some portion of the central nervous system. The most significant research, conducted by Walker, Kirschvink and Dixon on the Yellowfin Tuna,[15] reported that this organ permitted the fish to resolve the direction of a magnetic field to within a few seconds of arc and detect magnetic-field intensities as low as a few milliGauss (mG), firmly establishing the magnetite deposits as being parts of an organ used specifically for detecting the direction and intensity of weak magnetic fields. Thus, by the middle of the decade, both magnetite deposits and the pineal gland had been identified as linking living organisms to the geomagnetic field. At present, these areas are being explored extensively in regard to their relationship to human behavior and health.

The next observation of note was that of a neurophysiologist well known for research on major behavioral alterations produced by electrical brain stimulation; Dr. Jose Delgado.[17] Recognizing the potential of the relationship between external EM fields and nerve function, in a significant study Delgado made use of a sensitive biological indicator, the early-stage chick embryo. He exposed embryos to 10, 100 and 1000-Hz magnetic fields each at three different levels of strength, 0.12, 1.2 and 12 microTesla (μT). (1.0 μT = 0.01 Gauss = 10 milliGauss. Delgado, along with colleagues Leal, Monteagudo, and Gracia, reported that the incidence of developmental abnormalities was significantly higher in the embryos exposed to 100 Hz, even at the 0.12 μT level.[18]

Several subsequent attempts were made to replicate both Bawin and Adey's[7] and Delgado's[18] reports. Some were confirmatory, some negative, and others reported similar effects but with different frequencies. This raised the question of a hidden variable, and both Drs. Carl Blackman of the Environmental Protection Agency and Dr. Abraham Liboff of Oakland University, postulated a complex resonant effect on biologically-significant ions involving (1) the frequency of the administered field, (2) the strength of the DC geomagnetic field extant at the locale of the laboratory, and (3) the charge-to-mass ratio specific for each species of ion.[19,20]

The first proof of the validity of this concept was furnished the following year by Dr. J. R. Thomas at the Naval Medical Center, Bethesda, MD, in conjunc-

tion with Drs. Schrot and Liboff.[21] In this interesting study the concept of cyclotron resonance was applied to the lithium ion. Both a DC magnetic field and an ELF magnetic field were generated to resonate with the time varying field and the charge to mass ratio of the lithium ion. Lithium is known to exert a depressant effect on behavior and is often used therapeutically in cases of manic-depressive psychosis. In this experiment lithium was not administered to the test animals. Instead resonance was achieved using only the extremely small concentration of naturally-occurring lithium in the brain. Resonance transferred energy to these naturally-present lithium ions, thus increasing their activity and Thomas and his colleagues reported a significant decline in activity of the exposed animals compared with the controls.

Simultaneously with this work, the US Navy initiated a large program, known as Project Henhouse, in which a number of laboratories at several different locations were to attempt to replicate Delgado's results.[18] Each laboratory was to be furnished with identical equipment and was to follow the same experimental protocol. The results, reported jointly in 1990 by all the project directors,[22] indicated that 2 of the 6 laboratories obtained highly significant numbers of embryonic defects, while 3 reported increased abnormalities but not in significant numbers. Pooled data from all projects indicated a significant increase in the incidence of developmental defects in exposed embryos. Blackman later noted that the results reported by each laboratory appeared to be related to the strength of the local geomagnetic field.[23] These studies, done in the latter half of the decade, not only confirmed the existence of several important bioeffects but also revealed the basic role played by the underlying geomagnetic field in such interactions.

DECADE SUMMARY

By 1990, the evidence for a direct connection between non-thermal electromagnetic parameters and living organisms was incontrovertible. Organs whose function was to detect the geomagnetic field had been identified and a start had been made in determining at least one of the mechanisms. A few scientists still insisted that this was all nonsense, it could not be true, but the majority agreed that a scientific revolution was in progress.

As this manuscript was being written, a news release was issued by the California Institute of Technology[16] indicating that Drs J.L. Kirschvink, A. Kobayashi-Kirschvink and B. J. Woodford had identified magnetite particles in the human brain identical to those previously found in many other organisms. The particles were found in all areas of the brain with the highest amounts in the meninges. Full details are to be published at a later date in the Proceedings of the National Academy of Sciences. The techniques used, however, were not able to identify any specific magnetic organ. Nevertheless, this discovery shows that the association between magnetite crystals and central-nervous-system structures is an evolutionarily-conserved mechanism, indicating that it is of basic importance.

EPIDEMIOLOGICAL STUDIES

Since this entire research development began with the question of possible health effects from exposure to 60-Hz fields generated by electrical power facilities, much time and effort was expended on epidemiological studies to evaluate this possibility and, on economically and politically-generated attempts to disprove it. The history and details of this effort are not germane to the subject of this paper and the interested reader is referred to books that review data from many studies.[24,25,26]

Suffice it to say that at this time it appears unequivocal that chronic exposure, either residential or occupational, to 60-Hz magnetic fields with strengths of 3 mG or higher is associated with significant increase in the incidence of several types of malignant tumors. These occur in tissues having a continuous rate of cellular replication, such as bone marrow and lymphatic tissues, thus raising the question of a possible genetic effect at the time of mitosis.

The only apparent exception is a well-established increase in brain tumors of glial origin. While glial cells can replicate, it is usually in response to injury (gliosis). Glial cells do not usually demonstrate a pattern of continuous replacement. Therefore the question was raised of a direct effect of magnetic fields on glial cells. This led to studies of a fundamental nature that have provided significant support to the primary thesis of the present series of papers.

DIRECT MAGNETIC EFFECTS ON GLIAL CELLS

It must first be noted that studies in the area of bioelectromagnetics began in the Soviet Union as early as the 1940's and by the late 1960's several thousand scientists were involved. In 1966, Drs Kolodov and Aleksandrovskaya at the Institute of Higher Nervous Activity and Neurophysiology, Soviet Academy of Sciences in Moscow, reported[27] that following one hour of exposure to a constant (DC) magnetic field of several hundred Gauss intensity, there was a significant increase in animals in the number of glial cells, presumably by mitosis or some other mechanism of cell multiplication. This was accompanied by changes in the EEG such as a predominance of slow waves and bursts of spiking in the motor cortex. Similar changes were noted in the EEG of humans exposed to the same field for the same length of time. In experimental animals, continuation of the exposure for 10 hours resulted in marked hyperplasia of individual glial cells. Exposures of 60-70 hours resulted in destruction of glial cells and dystrophic changes in neurons. Since initial effects began in glial cells, and dystrophic changes in the neurons followed changes in the glia, the authors postulated that glial cells were the primary receptors of magnetic fields and that neurons were influenced only secondarily to glial effects.

Subsequently there was very little interest in DC magnetic field effects until the resonance concept was proposed. Since then most work has involved the combination of a DC magnetic field with a time-varying field. Most recently, Drs. Balaban, Bravarenko and Kuznetzov, also of the Institute for Higher Nervous Activity, have reported[28] that exposure of snail neurons in vitro to DC magnetic fields of different strengths resulted in reproducible changes in membrane resistivity and excitatory postsynaptic potentials, with degree of change directly related to the strength of the DC magnetic field . In preparations of this type, single neurons are easily removed intact and placed in appropriate media for electrode insertion. Such neurons always had their normal complement of glial cells still attached to them. In the past, these glial cells were considered to be of no consequence in such research, but the authors of this study removed the glial cells with a proteolytic enzyme that left the neurons intact and electrically normal. Following this the previously noted changes in membrane resistivity and post synaptic potentials with DC magnetic

field exposure were no longer observed, and the authors proposed that functional changes produced by magnetic field exposure are mediated in neurons through the effect of the magnetic field on the glial cells, and that the intact neuron itself does not respond to magnetic fields unless it is surrounded with its normal accompaniment of glial cells.

Thus, pathological, perceptual, and behavioral changes produced by exposure to magnetic fields, while appearing to be mediated through the neurons are probably the result of the sensitivity of the perineural cells to this energy field. This supports the concept that the original "nervous" system resided in what we now term the perineural cells, and that the primary perceptual function of these original cells was the detection of magnetic fields originating from the geomagnetic field, *and possibly from fields produced by other organisms.*

GENETIC EFFECTS

The question as to whether the increases in malignant tumors noted epidemiologically with time-varying field exposure are due to a direct carcinogenic effect, or simply enhancement of pre-existing tumors, has not been settled. However, the nature of carcinogenesis is now much better understood and specific genetic sequences known as oncogenes have been identified as the final common pathway by which all carcinogens operate. In this light, the observations[29,30] of Drs. Goodman and Henderson of Columbia University on alterations in genetic activity, such as transcription and translation, produced by exposure to such fields, are particularly significant. While not yet confirmed by direct experiment, the consensus of opinion is beginning to hold that all direct cellular effects of magnetic field exposures (including increases in growth rates and carcinogenesis) occur at the time of mitosis, possibly because at that time the DNA is aggregated into chromosomes. This is certainly in keeping with the epidemiological data presently available and raises the interesting question of the relationship between alterations in the natural geomagnetic field and evolutionary changes.

EFFECTS OF EM FIELD EXPOSURE ON BEHAVIOR

The literature abounds with anecdotal reports of alterations in behavior and perception with magnetic field exposure but few controlled studies have been reported. In an early study, Drs. Friedman, Becker and Bachman reported[31] that DC magnetic fields of 5 and 17 Gauss had no effect on human reaction time performance but that significant changes were produced by short exposures to time-varying fields of 11 Gauss modulated at 0.1 and 0.2 Hz.

Later, in 1979, Dr. F. Stephen Perry, a practicing physician in England, and members of my research group reported a statistically-significant relationship between suicide in a rural area of England and the proximity of patient's homes to electrical power lines.[32] This study was triggered by Dr. Perry's observation that his patients living in such proximity appeared to be more subject to depression then patients living further away. Since the publication of this initial study, many more reports have appeared. The latest, by Dr. Barry Wilson of Pacific Northwest Laboratory, reviews the presently available information and presents data indicating that the depression may be the result of a direct effect of 50 or 60-Hz magnetic fields on pineal gland functions.[33]

Dr. Michael Persinger of Laurentian University, has conducted a lengthy series of experiments involving human volunteers exposed to a variety of magnetic fields, He has concentrated on the effects associated with exposure to normally occurring frequencies and has reported that the theta frequency range (4-8 Hertz) produced alterations in the extent of short term memory recall.[34] Persinger has also studied the relationship between the Earth's geomagnetic field and the incidence of paranormal experiences. He reported in 1985, in a retrospective analysis relating paranormal activity to the status of the geomagnetic field, that paranormal experiences were much more likely to occur on days that the field was quiet.[35] In a recent review of relevant data I found that several other studies confirmed this observation, some by direct experiment.[36]

One of the projects in the New York State Department of Health study on overhead power lines[4] was directed by Dr. Kurt Salzinger of the Brooklyn Polytechnic University.[37] It involved exposure of pregnant rats during the last

22 days of gestation and of the new-born rats for 8 days following birth, to a 60-Hz magnetic field. The offspring were subsequently raised under normal laboratory conditions until adulthood. At that time, the performance of the exposed animals was compared with unexposed animals of the same age in conditioned operant behavioral testing. The exposed animals exhibited significantly lower response rates, in other words, they were slower learners.

According to one school of thought, stress is a physiological function mediated by the central nervous system in response to the *perception* of being in a threatening situation. While the physiological response to a situation of acute, short term crisis is useful, long term, or chronic, stress is considered to be unfavorable. Since the majority of humans cannot sense their being exposed to electromagnetic fields a question arose as to the ability of such fields to directly influence the neural structures responsible for the stress response, in essence by-passing the perceptual system. The earliest studies were done in my own laboratory with a multi-generational, exposure of mice to 60-Hz electric fields.[38] Exposed animals demonstrated a number of the physiological changes associated with stress while unexposed control animals did not. Most recently, short term exposure to low-intensity non-thermal microwave radiation has also been shown to produce alterations in benzodiazepine receptors in the cerebral cortex of exposed rats.[39] Since benzodiazepine receptors play a significant role in mediating anxiety and stress responses, it appears that low-intensity microwave exposure can be a source of stress. As with low-frequency experiments, microwave frequencies at these levels are well below the threshold of perception and the stress response elicited by microwave exposure also by-passes conscious awareness.

In another area, relationship between solar activity and its effect upon the geomagnetic field as related to violent human behavior was recently explored in a statistical study extending over 30 years of data.[40] Contrary to expectation, no relationship between direct indices of the geomagnetic field and violent human behavior was found. However, a significant relationship was noted between this behavioral variable and the yearly number of sunspots, raising the possibility of an energetic, but non-magnetic effect or some presently unknown aspect of the magnetic field being responsible.

Thus, man-made, electromagnetic fields of frequencies and strength levels not normally represented in the Earth's natural electromagnetic spectrum have direct effects on the operation of the brain that are reflected in behavioral and learning abilities. It is not possible at this time to define any specific pathway by which these effects are mediated, but it appears quite likely that all of the magnetically-sensitive elements of the brain, the magnetic organ, the pineal gland and the perineural cells themselves are involved. Also, as discussed below, these structures may also play a role in another, more basic function of the brain.

ELECTROMAGNETISM AND INTEGRATION OF BRAIN FUNCTION

How does one relate the single unit activity of the multitude of individual sensory neurons into the conscious awareness of an integrated external environment? In the visual cortex, for example, some cells respond to different colors, others to edges, some to motion and others to intensity. These cells are clustered into distinct areas according to their type and such areas may be separated by a centimeter or more. How is the final perceptual integrated image of a person, plant or any other object in the environment formed from the individual signals from these disparate elements separated by large distances in the brain? The final output of our visual window is an integrated whole in our consciousness and these questions come very close to the question of consciousness itself. Recently, bioelectromagnetics has begun to provide some answers to these questions.

The development of the SQUID magnetometer and the discovery of the MEG has led to a new branch of neurophysiology termed "neuromagnetics" which investigates the magnetic correlates of brain functions. While still in its embryonic state, this discipline has already identified magnetic-field-evoked responses to visual and auditory stimuli. The magnetic fields detected are relatively large and appear to be generated by electrical current sources that are nonstationary, i.e., demonstrating "successive movement of the source in the anterior and inferior directions" within the auditory cortex.[41] This may be interpreted as a relatively large-scale electrical current moving over large areas of the auditory cortex. While one can attribute this to the coordinated activity of large numbers of neurons, it is equally as valid to postulate the extra-neuronal

direct currents of the perineural system. Another interesting observation in neuromagnetics is the report that magnetic fields may be detected from the appropriate motor areas of the cortex prior to the occurrence of actual motor movement.[42] In this instance, extra-neuronal electrical current sources appear to be generated in the motor area before the respective motor neurons discharge. It is possible to postulate that the voluntary action is initiated in the perineural cell system before the actual motor neuron action occurs. If this is so, it is not beyond possibility that conscious volitional activity resides in the same system.

These observations of large-scale electrical currents in the brain by means of externally-detected magnetic fields must be compared with very recent observations made by Dr. Wolf Singer at the Max Plank Institute for Brain Research, utilizing electrodes implanted in the brain. In brief, he has reported the existence of electrical currents oscillating at 40 Hz extending over large areas of the visual cortex which he postulates to be the basis for perceptual integration.[43] Commenting on Singer's observations as well as his own on similar activity in the visual cortex, Dr. Walter J. Freeman of the University of California, Berkeley , CA states that, "perception depends on the simultaneous, cooperative activity of millions of neurons spread throughout expanses of the cortex."[44] He postulates, as does Singer, that the oscillatory currents are the basis for conscious perception by integrating the activity of millions of individual neurons. Freeman clearly indicates that the currents are extraneuronal, but stops short of attributing them to the glial cells. Examples of Singer's actual recordings, as reproduced in a recent science news report,[45] show two very different electrical recordings, one of a continuous oscillatory current and the other of the firing patterns of a pair of neurons showing that they fired in synchrony with the low points of the oscillatory wave.

Obviously, much more work needs to be done before firm conclusions can be drawn. However, both the existence of the slow waves in the extra-neuronal matrix and the apparent synchronization of neuronal firing with them suggests some sort of a direct relationship. It should be noted that glial cells are capable of electrical activity[46] and long range signaling.[47] At this time, it is quite possible to speculate that these DC and low-frequency extraneuronal electrical currents are the basis for perceptual awareness and that they are generated and/or transmitted via the glial cell components of the brain.

Some support for this concept may be derived from experiments in which integrated semiconductor circuitry was used to mimic the action of the mammalian retina. In the usual photo-electric image systems in commercial or scientific use, each retinal cell is represented by a single photoelectric element and the digital image is the result of subsequent computerized integration of the entire single-unit matrix. In experiments done by Drs. Misha Mahowald and Carver Mead at the California Institute of Technology, the retina is represented as a single integrated circuit operating in an analog fashion with multiple interconnections between each photoelectric element.[48] This device is capable of producing many of the phenomena observed in the human visual system, even including optical illusions, while the usual multi-element, digitally integrated image detectors have no such capability.

The evidence acquired over the past decade, utilizing the newly available methodologies of monitoring electromagnetic parameters has thus provided strong evidence for the existence of extra-neuronal DC electrical currents serving as the integrational mechanism for neuronal functions. While technologically much more advanced, these new data are practically identical to those reported fifty years ago and reviewed in the second article of this series.[2]

SUMMARY

Over the short span of a few decades, the new scientific devices and disciplines represented in bioelectromagnetics have provided the basis for a major shift in biology's theory. No longer are electricity and magnetism excluded from living organisms, rather these energies are now considered to be intimately involved in their basic sensing and communicating systems. The existence of specific biological magnetic-field receptors and a direct link between external magnetic fields and organismal behavior appears to have been established. The evidence for the production of external magnetic fields by the operations of the brain is likewise incontrovertible. Not only must we take the status of the geomagnetic field into consideration in experimental studies, but we must also consider it an important parameter of the ambient environment.

This relationship appears to be mediated, at least in part, through a complex resonance arrangement involving the charge to mass ratio of ions, the strength and direction of the quasi-static geomagnetic field, and the presence of ambient electromagnetic field frequencies either as part of the geomagnetic field (i.e., micropulsations, sudden enhancements and magnetic storms), or as man-made frequencies associated with electrical power or communications facilities. While there are, no doubt, other mechanisms that will be isolated, it appears probable that they will be equally complex in nature. However, based upon the known mechanisms of data transfer in neurons, it appears unlikely that such functions as action potentials can be directly influenced in this fashion, nor can these neuronal functions be entirely responsible for the magnetic fields generated by the brain.

Further, to return to one of the original themes of this series, "magnetic sense" is the only likely candidate for the original sensing system in the earliest organisms and it appears valid to postulate that this mechanism has been retained, with evolutionarily-derived refinements, in present day organisms where it continues to function as a detector for the ambient field and as the basic integrating mechanism for brain function.

It requires but a small conceptual step to postulate that this entire system resides within the perineural cells of the brain and spinal cord and the Schwann cells of the peripheral nerves. Certainly, both the expansion of our understanding of the energetic capabilities of the total nervous system and the newer studies of the perineural cells strongly suggest such an interpretation. It may be difficult to accept the possibility that consciousness resides in the perineural system and that the neurons are simply the "tools" of this underlying system. It appears evident, however, that answers to the most fundamental questions of being and consciousness require that we look at more than the neuronal half of the brain.

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REFERENCES AND NOTES

1. R. O. Becker, The Machine Brain and Properties of the Mind, *Subtle Energies* **1**, 1 (1990), pp. 79-87.
2. R. O. Becker, Evidence for a Primitive DC Electrical Analog System Controlling Brain Function, *Subtle Energies* 2, 1 (1991), pp. 71-88.
3. Proceedings of the Ad Hoc Committee for the Review of Biomedical and Ecological Effects of ELF Radiation, Bureau of Medicine and Surgery, Dept of the Navy, Washington, DC, 6-7 December, 1973.
4. A. Ahlbom, E. Albert, A. Frazer-Smith, A. Grodzinsky, M. Marron, A. Martin, M. Persinger, M. Shelanski, & E. Wolpow, *Biological Effects of Power Line Fields* (New York State Powerlines Project, Scientific Advisory Board Final Report, 1987).
5. R. Blakemore, Magnetotactic Bacteria, *Science* **190** (1975), pp. 377-379.
6. D. Cohen, Magnetic Fields of the Human Body, *Physics Today* **28** (1975) pp. 34-43.
7. S. Bawin, & W.R. Adey, Sensitivity of Calcium Binding in Cerebral Tissue to Weak Environmental Electric Fields Oscillating at Low Frequency, *Proceedings, National Academy of Science US 73* (1976), pp.1999-2003.
8. W.R. Adey, *In Neurosciences Research Bulletin* **15** (The MIT Press. Cambridge, MA, 1979), pp 1-129.
9. N. Wertheimer, & E. Leeper, Electrical Wiring Configurations and Childhood Cancer, *American Journal of Epidemiology* **109** (1979), pp. 273-284.
10. C. Walcott, J. Gould, & J. Kirschvink, Pigeons Have Magnets, *Science* **205** (1979), pp. 1027-1028.
11. W. Keeton, Effects of Magnets on Pigeon Homing, Proceedings, National Academy of Science, US **68** (1977), pp. 102-108.
12. P. Semm, T. Schenider & L. Vollrath, Effects of an Earth Strength Magnetic Field on Electrical Activity of Pineal Cells, *Nature* **288** (1980), pp. 607-608.
13. H. Welker, P. Semm, R. Willig, J. Commentz, W. Wiltschko & L. Vollrath, Effects of an Artificial Magnetic Field on Serotonin N-Acetyltransferase and Melatonin Content of the Rat Pineal Gland, *Experimental Brain Research* **50** (1983), pp. 426-432.
14. J. Olcese, S. Reuss & P. Semm, Geomagnetic field Detection in Rodents, *Life Science* 42 (1988), pp. 605-613.
15. M. Walker, J. Kirschvink & A. Dixon, A Candidate Magnetic Sense Organ in the Yellowfin Tuna, Thunnus Albacares, *Science* 224 (1984), pp. 751-753.
16. California Tech. Office of Public Relations, Pasadena, CA, May 4, 1992 for release May 11, 1992.
17. J. Delgado, Physical Control of the Mind; Toward a Psychocivilized Society. Vol XLI, World Perspectives, (Harper & Row, New York, 1969).
18. J. Delgado, J. Leal, J. Monteagudo, & M. Gracia, Embryological Changes Induced by Weak, Extremely Low Frequency Electromagnetic Fields, *Journal of Anatomy* **134** (1982) pp 533-551.
19. C.F. Blackman,, Ca Efflux with ELF Field, Relationship to Earth's Magnetic Field, *Bioelectromagnetics* **6** (1985) p. 327.
20. A. Liboff, Theory of Cyclotron Resonance, *Journal of Biological Physics* **13** (1985), p. 99.
21. J. Thomas, J. Schrot, & A. Liboff, Low Intensity Magnetic Fields Alter Operant Behavior in Rats, *Bioelectromagnetics* 7 (1986), pp. 349-358 .

22. E. Berman, D. Chacon, B. House, W. Koch, J. Leal, S. Lovtrup, E. Mantiply, A. Martin, G. Martucci, K. Mild, J. Monahan, M. Sandstrom, K. Shamsaifar, R. Tell, M. Trillo, A. Ubeda and P. Wagner, Development of Chicken Embryos in a Pulsed Magnetic Field, *Bioelectromagnetics* 11 (1990), pp.169-188.
23. C. Blackman, Observations on Project Henhouse, *BEMS Newsletter* #97 (Nov/Dec 1990). p. 3.
24. R. Becker, *Cross Currents* (Jeremy Tarcher, Los Angeles, CA, 1990)
25. A. Marino, Ed. *Modern Bioelectricity* (Marcel Dekker, New York, NY, 1988).
26. M. O'Conner & R. Lovely, Eds. *Electromagnetic Fields and Neurobehavioral Function* (Alan R. Liss, New York, NY, 1988).
27. M. Aleksandrovskaya & Y. Kolodov, The Potential Role of Neuroglia in the Onset of a Bioelectrical Reaction of the Brain to a Constant Magnetic Field, *Reports of the Academy of Sciences of the USSR* 170 (1966), pp. 482-485.
28. P. Balaban, N. Bravarenko & A. Kuznetzov, Influence of a Stationary Magnetic Field on Bioelectric Properties of Snail Neurons, *Bioelectromagnetics* **11** (1990), pp.13-25.
29. R. Goodman & A. Henderson, Exposure of Salivary Gland Cells to Low Frequency Fields Alters Polypeptide Synthesis, *Proceedings of the National Academy of Science* US **85** (1988), pp. 3928-3932.
30. R. Goodman, D. Weisbrot, A. Uluc & A. Henderson, Transcription in Drosophila Melanogaster Salivary Gland Cells is Altered Following Exposure to Low-Frequency Electromagnetic Fields, *Bioelectromagnetics* 13 (1991), pp. 111-118.
31. H. Friedman, R. Becker & C. Bachman, Effect of Magnetic Fields on Reaction Time Performance, *Nature* 213 (1967), pp. 949-956.
32. M. Reichmanis, F. Perry, A. Marino, & R. Becker, Relationship Between Suicide and the Electromagnetic Field of Overhead Power Lines, *Physiology Chemistry & Physics* **11** (1979), pp. 395-403.
33. B. Wilson, Chronic Exposure to ELF Fields May Induce Depression, *Bioelectromagnetics* **9** (1988), pp. 195-205.
34. L. Michaud & M. Persinger, Geophysical Variables and Behavior: XXV, Alterations in Memory for a Narrative Following Application of Theta Frequency Electromagnetic Fields, *Perception & Motor Skills* **60** (1985), pp. 416-418.
35. Persinger, M., Geophysical Variables and behavior: XXX. Intense Paranormal Experiences Occur During Days of Quiet, Global, Geomagnetic Activity, *Perception & Motor Skills* **61** (1985), pp. 320-322.
36. R. Becker, Electromagnetism and Psi Phenomena, Journal of the American Society of Psychical Research **86** (1992), pp. 1-17.
37. K. Salzinger, S, Freimark, M. McCullough, D. Phillips, D. & L. Birenbaum, Altered Operant Behavior of Adult Rats After Perinatal Exposure to 60 Hz Electromagnetic Field, *Bioelectromagnetics* 11 (1990), pp. 105-116.
38. A. Marino, R. Becker & B. Ullrich, The Effect of Continuous Exposure to Low Frequency Electric Fields on Three Generations of Mice: a Pilot Study, *Experientia* 32 (1976), pp. 856-857.
39. H. Lai, A. Carino, A. Horita & A. Guy, Single Versus Repeated Microwave Exposures: Effects on Benzodiazepine Receptors in the Brain of the Rat, *Bioelectromagnetics* 13 (1992), pp. 57-66.
40. A. Becker, Geomagnetic Activity and Violent Behavior, *Subtle Energies* **1**, 2 (1990), pp. 65-77.

41. R. Rogers, A. Papanicolaou, S. Baumann, H. Eisenberg & C. Saydjari, Spatially Distributed Cortical Excitation Patterns of Auditory Processing During Contralateral and Ipsilateral Stimulation, Journal of Cognitive Neuroscience **2** (1991), pp. 44-50.
42 L. Deeke, J. Boschert, H. Weinberg, & P. Brickett, Magnetic Fields of the Human Brain Preceding Voluntary Foot and Toe Movements, *Experimental Brain Research* **52** (1983), pp. 81-86.
43. C. Gray, P. Konig, A. Engel & W. Singer, Oscillatory Responses in Cat Visual Cortex Exhibit Inter-Columnar Synchronization Which Reflects Global Stimulus Properties, *Nature* **338** (1989), p. 334.
44. W. Freeman, The Physiology of Perception, *Scientific American* (February 1991).
45. M. Baringa, The Mind Revealed?, *Science* **249** (1990), pp. 856-858.
46. W. Hild, J. Chang, & I. Tasaki, Electrical Responses of Astrocytic Glia From the Mammalian Central Nervous System Cultivated in Vitro, *Experientia* **14** (1958), pp. 220-221.
47. A. Cornell-Bell, S. Finkbeiner, M. Cooper & S. Smith, Glutamate Induces Calcium Waves in Cultured Astrocytes: Long Range Signalling, *Science* **247** (1990), pp. 470-473.
48. M. Mahowald & C. Mead, The Silicon Retina, *Scientific American* (May 1991), pp. 76-82.