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The CEMI Field Theory

Closing the Loop

Abstract: *Several theories of consciousness first described about a decade ago, including the conscious electromagnetic information (CEMI) field theory, claimed that the substrate of consciousness is the brain's electromagnetic (EM) field. These theories were prompted by the observation, in many diverse systems, that synchronous neuronal firing, which generates coherent EM fields, was a strong correlate of attention, awareness, and consciousness. However, when these theories were first described there was no direct evidence that synchronous firing was actually functional, rather than an epiphenomenon of brain function. Additionally, any EM field-based consciousness would be a 'ghost in the machine' unless the brain's endogenous EM field is also able to influence neuron firing. Once again, when these theories were first described, there was only indirect evidence that the brain's EM field influenced neuron firing patterns in the brain. In this paper I describe recent experimental evidence which demonstrate that synchronous neuronal firing does indeed have a functional role in the brain; and also that the brain's endogenous EM field is involved in recruiting neurons to synchronously firing networks. The new data point to a new and unappreciated form of neural communication in the brain that is likely to have significance for all theories of consciousness. I describe an extension of the CEMI field theory that incorporates these recent experimental findings and integrates the theory with the 'communication through coherence' hypothesis.*

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1. Introduction: EM Field Theories of Consciousness

The starting point for most EM field theories of consciousness is the increasing evidence that synchronous firing of neurons is a strong correlate of conscious perception. For instance, work in the early 1990s by Wolf Singer and colleagues demonstrated that neurons in the monkey brain that responded to two independent images of a bar on a screen fired asynchronously when the bars were moving in different directions but fired synchronously when the same bars moved together (Kreiter and Singer, 1996). Interestingly, the same group demonstrated zero time-lag between synchronously firing areas of the brain (Roelfsema *et al.*, 1997), severely constraining any model to account for synchrony based solely on neural/synaptic signal transmission from a common source (since transmission times are likely to be different).

Many additional studies confirmed and extended these findings to many different experimental systems (reviewed in my 2002 papers and several more recent reviews, for instance, Singer, 2011). For instance, David Leopold's laboratory at Max Planck Institute for Biological Cybernetics, in Tübingen, Germany (Wilke *et al.*, 2006) investigated awake monkeys trained to respond to a visual stimulus — the removal of a red dot from a target area — by pulling a lever (to receive their fruit juice reward). Once the monkeys had grasped this skill they were tested with trials of more complex visual fields that contained both red dots and a random array of white dots as distractions. The red dot and its removal was still detected and encoded within the primary visual cortex of these monkeys, but sometimes they *saw* the dot's removal and responded appropriately, and sometimes they missed it. The experiment is similar in many ways to binocular rivalry experiments, but instead of two percepts competing for the same visual space this experimental set-up (known as generalized flash suppression or GFS) is more akin to the very familiar experience of failing (or not) to *see* an object in plain sight; but, using the monkey experimental system, the experimenters were able to simultaneously monitor neural activity in the monkey's visual cortex. The researchers monitored both neuron spiking and changes in local field potentials in V1, V2, and V4 regions of the monkey's visual cortex. They first demonstrated that spiking of neurons in cortical areas V1 and V2 was totally uncorrelated with the monkey's perception of the target. Whether the monkeys *saw* the target or not did not appear to make any difference to neuron firing in these areas.

This is entirely consistent with a large body of evidence that led Crick and Koch to propose that consciousness is not associated with the contents of the primary visual cortex (Crick and Koch, 1992; 1995). However, despite the fact that neuron firing in V1 and V2 did not correlate with perception, low frequency (alpha range, particularly 9–30 Hz) modulation of local field potentials in these same regions did correlate with perception! It seems that though the neuron firing rate in the primary visual cortex does not *see* the stimulus, the synchronicity of neuron firing, which generates the local field potentials, does indeed *see* the target. The researchers also investigated gamma range (30–50 Hz) oscillations. Modulations in this frequency range did not correlate with perception in V1 and V2 but strongly correlated with perception in the V4 visual area. The results, taken together, suggest the relationship that synchrony *per se* is the key correlate of consciousness, rather than any requirement for synchrony at a particular frequency or within a particular region of the brain.

Demonstrating that synchrony correlates with attention in experimental animals does not prove that it is associated with consciousness, as the conscious state of animals remains unclear. However, analogous studies in humans have been performed in conditions such as epilepsy, when a single electrode and multiple electrodes may be inserted into the brain of awake subjects. These procedures have allowed both single-cell measurements and measurement of extracellular local field potentials in the human cortex together with the correlation of these measurements with attention, memory, and perception. Just as in the animal studies, these rare and valuable studies provide strong evidence for assemblies of synchronously firing neuron areas in widely distributed regions of the brain to be strongly correlated with attention and awareness in humans (Engel *et al.*, 2005).

It is interesting to consider for a moment the implications of these findings taking, for an example, the familiar experience of failing to spot an object in plain sight. Take a look at Figure 1. Can you see an insect in the picture? You will I am sure soon spot the grasshopper sitting in the centre of the picture. But what was happening in your brain before you spotted the insect? The visual information was imprinted on your retina and signals were sent to your visual cortex where they were processed through the firing of many thousands of neurons. But you weren't aware that a subgroup of those firing neurons encoded the visual information corresponding to a grasshopper. After some several seconds the grasshopper *pops out* of the image. What happens to the neurons that previously recorded the visual information encoding the insect? Did they change their firing rate or amplitude? The answer

is no. The firing rates and amplitudes of the relevant neurons remain unchanged by the conscious experience of attending to an image. The key mechanistic difference between unconscious and conscious information in the brain is not the presence or absence of firing in any particular neuron or region of the brain but a particular level of synchrony of firing between distantly separated neurons. Information that you are not aware of is encoded in asynchronously firing neurons but when you become aware of that information those same neurons fire in synchrony. But why should this be? Synchronous firing is the most firmly established neural correlate of consciousness and the one that every scientific theory of consciousness needs to account for, but its functional significance remains unclear and controversial. Many neurobiologists have proposed that synchronous firing *binds* the information in distant neurons into a single percept. But why is the information in synchronously firing neurons bound any more tightly than information in asynchronously firing neurons?



Figure 1. A well-camouflaged grasshopper spotted in the French Alps, near Deux Alps.

Placing consciousness in the brain's EM field naturally and elegantly accounts for why synchronous firing is correlated with conscious percepts. Nerve firing is caused by electrochemical signals travelling down (the action potential) and between (synaptic transmission) neurons. Neurons tend to fire in bursts generating oscillations at particular frequencies (Basar, 1998; 1999; 2008; Buzsaki, 2006). These neuronal

oscillations cause correlated perturbations of the EM field (primarily the electric field) both within and between neurons (Freeman, 1975; 2003; Nunez, 2000). When neurons within a local group fire randomly then the peaks and troughs of their oscillations will be out of phase so that the resulting EM field disturbance will tend to sum to zero. However, if the neurons fire synchronously then the peaks and troughs of their oscillations will reinforce each other to generate a strong net EM field oscillation. It is these synchronous oscillations that are detected by measurement of local field potentials, EEG, or MEG (though the precise source of either remains unclear) (Freeman, 2003; 2011). So information encoded in asynchronously firing neurons will remain within the neurons and not be *visible* at the level of the brain's EM field; whereas information in synchronously firing neurons will be reflected into the brain's EM field. Placing the seat of consciousness in the brain's EM field naturally accounts for why its perturbations are correlated with attention and awareness. When the neurons encoding the grasshopper's form in Figure 1 were firing asynchronously then that information is not presented to the brain's (conscious) EM field; but when those same neurons fire in phase then that same information is reflected into the brain's EM field making *you*, the CEMI field of your brain, aware of the grasshopper.

The CEMI field theory¹ has much in common with the EM field theory of consciousness proposed by Dr Susan Pockett in her book *The Nature of Consciousness: A Hypothesis* (Pockett, 2000; 2002). The neurophysiologist E. Roy John also published a theory of consciousness involving EM fields (John, 2002); and Fingelkurts and Fingelkurts published a theory of consciousness which is based on the interactions of EM fields (Fingelkurts *et al.*, 2001; Fingelkurts and Fingelkurts, 2008). The key insight of each of these theories is the realization that, as well as generating chemical signals that are communicated via conventional synapses, neurons may also generate an EM field, and placing awareness in this field solves many of the most intractable problems of consciousness.

However, when these EM field theories of consciousness were published in 2002 there remained only circumstantial evidence for two key aspects of these theories. Firstly, it was not established that assemblies of synchronously firing neurons have a functional role. Secondly, it was not established that the EM fields in the brain (generated by

[1] The CEMI field theory was first outlined in my book *Quantum Evolution* (2000), though it was there referred to as the conscious electromagnetic field (cem) theory. The theory was more fully presented in 2002 (see McFadden, 2002a,b) as the conscious electromagnetic field theory and has been further elaborated in subsequent publications.

synchronously firing neurons) have a functional role. Although the EM field theory of consciousness proposed by Susan Pockett (2000; 2002) did not propose any functional role for the conscious EM field (it remains a ghost in the machine in Pockett's theory), the CEMI field theory proposed a feedback loop in which neurons both generated and are affected by EM fields. Although in my 2002 papers I amassed a considerable quantity of circumstantial evidence indicating that the brain's EM field affects brain function, the evidence was mainly circumstantial (see McFadden, 2002a,b). However, key experimental findings since 2002 have firmly established a functional role for the brain's EM fields which I will review here.

2. A Functional Role for Synchrony in the Brain

As described above, by 2002 there was abundant data to indicate that neuronal synchrony correlated with attention and awareness in man and animals. On the basis of these results many proposals were made for a functional role for synchrony, particularly in solving the binding problem whereby distributed parallel processing of features in a single object are combined to generate a unified percept. For instance, the 'binding by synchrony' (BBS) theory (von der and Schneider, 1986) proposed that the neurons representing features of an object are transiently coupled through synchronous firing. More recently, Pascal Fries formulated the 'communication through coherence' (CTC) hypothesis whereby neural communication between neurons was proposed to depend on their degree of synchrony (Fries, 2005). In this scheme only coherently oscillating (phase-locked) neuronal groups were proposed to be capable of communicating effectively because their inputs and outputs are open at the same time. A functional role for synchrony in memory has also been proposed with neural oscillations either serving a transient store for short-term memory and/or as a means of forming Hebbian cell assemblies that fire together and thereby wire to form long-term memories (Raffone and Wolters, 2001). More recently, a functional role for gamma and theta oscillations in episodic memory has been proposed whereby oscillations allow for the transient interaction between cortical structures and the hippocampus for the encoding and retrieval of episodic memories (Nyhus and Curran, 2010).

Most of the above proposals were made on the basis of observations of correlations between neural oscillations and the phenomenon in question (attention, memory, etc.). Correlation does not of course prove causation, but it is difficult to demonstrate a causal role without

some means of interfering with neural synchrony. This has been achieved in some systems, particularly in insects. For instance, Stopfer *et al.* (1997) used picrotoxin to disrupt neural synchrony in the honey bee and demonstrated that desynchronization of odour-encoding neural assemblies impaired the bee's ability to discriminate different odours. Similar experiments have been performed in several other insects, for instance drosophila (Tanaka *et al.*, 2009), and demonstrate that patterns of neuronal oscillations represent particular odours in the olfactory bulb and that disruption of these patterns disrupts odour discrimination (Kay *et al.*, 2009).

Disrupting neuronal oscillations without affecting neuron firing rates is more difficult in higher animals and man, but it is sometimes possible to induce or perturb oscillations and observe the effect. For instance, a study from Wolf Singer's laboratory investigated changes of neuronal discharge rates and synchrony in anaesthetized cats in response to centre and surround gratings of different orientations and phase relations such that neural discharge rate and neural synchrony could be independently varied (Biederlack *et al.*, 2006). By varying the orientation or the relative spatial phase of the surrounding grating it was possible to change the perceived brightness of the centre grating. Brightness enhancement by orientation contrast between the centre and surround was associated with an increase of neuron discharge rates but not with changes in spike synchronization. In contrast, phase offset also caused a perceptual brightness enhancement yet with no change in discharge rates but an increase in neural synchronization between neurons responding to the centre grating. The study demonstrated that increased neuronal synchronization increased perceived brightness independent of any effect on neuronal discharge rates. Studies in humans were reported by Bauer *et al.* (2009) whose subjects were shown a pattern of Gabor patches (sine wave grating) within which they had to detect a signal: a subtle change in spatial frequency of one of the patches. Prior to arrival of the signal, the target or control patches were modified by a inducing a subliminal 50 Hz flicker in the patch. Although the subjects could not detect the flicker it nevertheless synchronized their neurons at point of the flicker, generating phase locking of those neurons in the area of the visual cortex that responded to the image at the site of the flicker. The flicker, though subliminal, was found to significantly enhance target detection by the subjects at the site of the flicker. So inducing synchronicity appears to have a causal role in directing conscious attention in humans: it is not a steam whistle.

The above results clearly indicate that synchrony *per se* (independent of neural firing rates) plays a functional role in mediating selective attention and awareness in the brain of man and animals. Curiously, this role for consciousness was anticipated by the psychologist William James writing more than a century ago: ‘Whoever studies consciousness, from any point of view, is ultimately brought up against the mystery of selective attention.’ James concludes that the function of consciousness is to ‘choose out of the manifold experiences present to it at a given time some one for particular accentuation, and to ignore the rest’ (Richardson, 2007, p. 199). Of course, the significance of studies of selective attention particularly, in (sometimes anaesthetized) animals, to the phenomenon of consciousness in humans is questionable. However, there is little doubt that consciousness involves some degree of selective attention, so it is reasonable to conclude that the mechanisms, including neural synchrony, that play a role in focusing attention are also important component of consciousness.

However, the demonstration that synchrony is associated with consciousness does not say anything concerning the mechanisms by which synchrony might impact the conscious mind. In the following section I discuss evidence that the impact of synchrony on consciousness is likely to be due to EM field effects.

3. A Functional Role for EM Fields in the Brain

The first study I will consider comes from Yuji Ikegaya’s laboratory in Tokyo who examined gamma frequency rhythmic activity in rat hippocampal brain slice preparations (Fujisawa *et al.*, 2004). The researchers first demonstrated that the brain slices exhibited no spontaneous gamma oscillatory activity but gamma oscillations could be reliably induced by application of the muscarinic agonist, carbachol, and detected using extracellular electrodes. The researchers aimed to examine whether the EM fields generated by these rhythmic oscillations affected neural firing patterns in the tissue. To simulate the intrinsic gamma oscillation they placed parallel electrodes above the CA3 pyramidal cells in the (untreated) slice and applied an oscillating 40 Hz electric field that generated an extracellular field in the tissue with an amplitude and waveform similar to those of the carbachol-induced activity. They then stimulated a CA3 pyramidal cell (by injection of current) and measured the delay (latency) in the neuron’s repose: a spike. In the absence of an external field the delay was a latency of about 38 ms to obtain the first spike; but in the presence of an external oscillating field the initial spike was delayed to about 160

ms which was followed by a more sustained rhythmic firing burst. When the imposed field was terminated the spiking pattern returned to control levels. Clearly the external fields were modulating the firing pattern of individual neurons. Interestingly, the researchers found that the phase of the stimulus in relation to the phase of the externally applied field significantly affected the latency of the response. The researchers concluded that their experiments demonstrate the existence of 'a novel mode of interneuronal communication mediated by local electric field' (*ibid.*).

The next study, from David McCormick's laboratory at Yale (Frohlich and McCormick, 2010), examined the influence of fields in whole animals. The group used multi-site depth electrodes to record local field potentials (LFPs) in the primary visual cortex of anaesthetized ferrets. They measured slow oscillations in the endogenous electric field (EF) with peak strength of about 2 m V/mm. To examine whether these relatively weak fields were capable of influencing neural function they applied external sine wave fields with the approximate strength of the weak *in vivo* EF's to *in vitro* brain slice preparations of the ferret visual cortex that spontaneously generate a slow oscillation. They were able to demonstrate that application of the external field caused small membrane depolarizations (about 1 mV drop in the transmembrane voltage) in individual neurons and that these depolarizations accelerated the neocortical slow oscillations in the *in vitro* slices and made them more periodic: they *entrained* the slow oscillation. To demonstrate that this effect was not peculiar to the particular nature of the external sine wave fields they then applied a naturalistic waveform to the slices and demonstrated that this was also capable of strongly modulating the spontaneous oscillatory activity of the brain tissue; and EFs as weak as 0.25–0.5 mV/mm were able to modify network behaviour. These results led the researchers to propose that the endogenous EFs provide a positive feedback loop that entrains oscillatory networks. To test this hypothesis they calculated the fields generated by endogenous oscillations in the slices and then applied external fields that either positively or negatively interfered with the predicted endogenous fields. As expected, the externally-enhanced positive feedback promoted oscillatory activity whereas the externally applied negative feedback suppressed the same activity. Finally, they constructed a computer model of a simple neural network and used it to confirm the role of endogenous fields in modulating oscillatory activity of the network. The researchers concluded that their studies 'support a functional role of the endogenous field in

guiding physiological network activity by feedback interactions in neocortex' (*ibid.*).

Another exciting study was conducted by Christof Koch's laboratory at the California Institute of Technology (Anastassiou *et al.*, 2011). The experimenters managed to simultaneously monitor both extracellular and intracellular electric fields (EFs) by placing multiple electrodes both within and between pyramidal neurons in rat brain slices maintained *in vitro*. Using one of the electrodes as a source, the researchers were able to apply a weak external (to the neurons) EF (of about 1 mV/mm) and (whilst simultaneously blocking synaptic transmission) record both extracellular and intracellular EF changes in nearby neurons. Application of weak oscillating external fields (of similar magnitude and frequency as endogenous fields) caused measurable changes in the intracellular fields and extracellular EFs and thereby shifted the transmembrane potential of adjacent neurons by about 0.5 mV. These transmembrane potential perturbations oscillated at the same frequency as the externally applied fields. But does this weak induced field affect neural function? To answer this question the experimenters injected a constant current into the cell body of 25 target neurons to induce (2–4 Hz) spiking and examined the effect of applying an extracellular field on their firing. The applied field did not change the frequency of firing but it did affect their phase, causing them to preferentially fire at a preferred phase relative to the external field oscillations (in synchrony). Increasing the field strength enhanced the phase locking of the spikes to the applied field. The researchers concluded that, 'Endogenous brain activity can causally affect neural function through field effects under physiological conditions'; and that the resulting synchronization 'may have a substantial effect on neural information processing and plasticity' (*ibid.*).

Each of these exciting studies point to a new mode of EM field communication between neurons and a neglected feedback loop involving EM fields generated by neuron firing influencing the firing of the neurons that generate that field. They clearly indicate that endogenous EM fields play an important role in recruiting neurons into networks of synchronous firing which, as described above, are the strongest known correlate of attention and consciousness.

4. Discussion

The experimental studies described above clearly demonstrate a functional role for both neuron synchronization and the brain's EM field in creating networks of interacting neurons. The results indicate that the

brain's EM field is clearly not an epiphenomenon (the brain's steam whistle), a product of brain function but with no influence on its function. These studies are therefore relevant to theories of consciousness involving EM fields. Specifically, they are entirely compatible with theories which proposed a specific role for an EM field consciousness in modifying neural firing patterns (John, 2002; McFadden, 2006; 2007; 2002b); but it is not clear that they are compatible with alternative theories that propose that EM field consciousness is an epiphenomenon with no influence on brain function (Pockett, 2000; 2002).

The pioneering psychologist William James (1842–1910) suggested 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' (Richardson, 2007, p. 195). But how can an ephemeral consciousness *exert a constant pressure* on very physical nerves? The experimental studies described in this review provide a mechanism. The endogenous EM field generated by neural firing does indeed exert a pressure on neuron firing patterns, not influencing their firing rate but influencing their phase so that they fire in synchrony. And synchronous firing is a strong (probably the strongest) correlate of consciousness. So placing the seat of consciousness in the brain's electric field, pushing and pulling on its neural strings delivers James's 'invaluable service' and simultaneously accounts for why synchronous firing is so tightly correlated with consciousness: it is the product of the action of the brain's conscious electromagnetic field on brain activity.

Pascal Fries (2005) has proposed the 'communication through coherence' hypothesis. He first notes that neurons have an innate tendency to oscillate and these oscillations constitute fluctuations in excitability, effectively opening and closing a window of sensitivity to synaptic input. Therefore, for a sender neuron to communicate effectively with a receiver neuron, the sending neuron's output must arrive at the receiver neuron when it is potentially excitable, otherwise the neurons will not communicate effectively. This can only happen if the rhythmic opening and closing of both neurons' communication windows are coordinated. This, Fries argues, is the purpose of neuronal coherence. It creates flexible groups of neurons that can effectively communicate in order to influence downstream motor actions.

David McCormick has proposed that EM fields serve to recruit neurons into oscillatory networks (Frohlich and McCormick, 2010). It is a short step from McCormick's scheme to placing the seat of conscious-

ness within the brain's EM field, as in the CEMI field theory, and thereby allow consciousness to, via the EM field, 'exert a constant pressure in the right direction... feel what nerve processes are leading to the goal... reinforce and strengthen these and at the same time inhibit those that threaten to lead astray' (Richardson, 2007), and thereby provide the 'invaluable service' proposed by James. Equating consciousness with a real physical field may initially seem an outlandish suggestion, but it is in fact no more extraordinary a proposal than claiming the commonplace materialist position that consciousness is identical with certain configurations of the matter of the brain: its neurons. As Einstein famously proved, matter and energy have exactly equivalent ontological status ($E = mc^2$), so placing consciousness in the energy field of the brain (the left side of the above equation) is no more remarkable than placing the seat of awareness in the matter of the brain (the right side of the equation). However, as argued in my earlier papers, the EM field solution has the huge bonus of effortlessly solving the binding problem. The electrical mechanism of neural firing ensures that all the information encoded in the neurons of the brain is reflected into the brain's EM field where it will be unified: that is what we mean by a *field*. From the frame of reference of an electromagnetic field there is neither time nor space between any part of an EM field. So the vast quantity of information in the EM field of the human brain (surely the most complex object in the known universe) has the same level of unity as a single electron or photon. It is in this information-rich dimensionless point that, I claim, the seat of our experience is located.

That the brain's EM field does influence its function implies that it is subject to natural selection. It seems likely that, just as with electrical devices, EM fields are more likely to interfere with the action potential-mediated function of nerves than to provide a positive influence. Natural selection will thereby act to insulate these neural functions from EM field influences. The CEMI field theory claims that unconscious brain activity corresponds to these EM field-insulated neural operations. However, if there are brain operations that can benefit from EM field influences (e.g. to generate networks of communicating neurons) then natural selection will act on neural function to enhance and optimize these interactions between neurons and EM fields. The CEMI field theory claims that these brain functions correspond to conscious brain activity, and the influence of the EM field on neuron firing corresponds to the physical realization of our conscious will. The theory thereby claims that the brain utilizes two forms of neural communication. The first is performed without EM field

influences and corresponds to our unconscious action. The second involves neuronal interaction with the brain's endogenous EM field and these are experienced as our conscious actions.

As described above, the initial (and continuing) role provided by the EM field for brain function may have been to recruit neurons into and out of interacting networks. However, additional advantages of EM field interactions may also have been captured by natural selection. One possibility suggested in my first 2002 paper (McFadden, 2002a) was that EM fields could be involved in promoting neural plasticity and memory. It is well established that Hebbian learning depends on correlated firing between pre- and post-synaptic neurons. I proposed in 2002 that such a process could be mediated by EM fields that increase the probability of near-simultaneous firing in pre- and post-synaptic neurons and thereby increase synaptic strength. Although this conjecture remains unproven, synchronous firing has since been strongly implicated in memory (Axmacher *et al.*, 2006; Jensen *et al.*, 2007); so the likely associated EM field perturbations are at least implicated by association.

Another possible role for EM fields proposed in my 2002 paper was that the brain performs *field computing*, a form of computation that shares many features with quantum computation (MacLennan, 1999). That artificial selection is able to capture field computations has been demonstrated by a remarkable experiment performed by the School of Cognitive and Computing Sciences (COGS) group at the University of Sussex whose aim was to apply artificial evolution to evolve an electric circuit that would perform a particular task: in this case, distinguishing between two musical notes (Davidson, 1997; Thompson, 1996). The group used a silicon chip known as a field-programmable gate array (FPGA), comprised of an array of cells. Electronic switches distributed through the array allow the behaviour and connections of the cells to be software reconfigured. Starting from a population of random configurations, the hardware was evolved to perform the task. After about 5,000 generations the network could efficiently perform its task. When the group examined the evolved network they discovered that it utilized only 32 of the 100 FPGA cells. The remaining cells could be disconnected from the network without affecting performance. However, when the circuit diagram of the critical network was examined it was found that some of the essential cells, although apparently necessary for network performance (if disconnected, the network failed), were not connected by wires to the rest of the circuit! According to the researchers, the most likely explanation seems to be

that these cells were contributing to the network through electromagnetic coupling — field effects — between components in the circuit.

It is not yet known what kind of field interactions are responsible for the computations performed in the COGS FPGA arrays but it is clear that, if artificial natural selection can capture EM field effects, then natural selection, acting over millions of years, will similarly capture and hone any advantage provided by processing information between neurons via EM fields. I suggest that advantage was captured at some crucial stage of human evolution and provided our ancestors with conscious minds.

In conclusion, a decade on, the CEMI field theory remains the most firmly grounded scientific theory of consciousness. It is based on established neurophysiology, requires neither new physics nor infeasible physical states in the brain, accounts for the best known correlate of consciousness, solves the binding problem, and provides a novel framework to understanding the role of consciousness in minds.

References

- Anastassiou, C.A., Perin, R., Markram, H. & Koch, C. (2011) Ephaptic coupling of cortical neurons, *Nature Neuroscience*, **14** (2), pp. 217–223.
- Axmacher, N., Mormann, F., Fernandez, G., Elger, C.E. & Fell, J. (2006) Memory formation by neuronal synchronization, *Brain Research Reviews*, **52** (1), pp. 170–182.
- Basar, E. (1998) *Brain Oscillations: Principles and Approaches*, Heidelberg: Springer-Verlag.
- Basar, E. (1999) *Brain Function and Oscillations: II. Integrative Brain Function. Neurophysiology and Cognitive Processes*, Heidelberg: Springer-Verlag.
- Basar, E. (2008) Oscillations in ‘brain-body-mind’ — a holistic view including the autonomous system, *Brain Research*, **1235**, pp. 2–11.
- Bauer, F., Cheadle, S.W., Parton, A., Muller, H.J. & Usher, M. (2009) Gamma flicker triggers attentional selection without awareness, *Proceedings of the National Academy of Sciences USA*, **106** (5), pp. 1666–1671.
- Biederlack, J., Castelo-Branco, M., Neuenschwander, S., Wheeler, D.W., Singer, W. & Nikolic, D. (2006) Brightness induction: Rate enhancement and neuronal synchronization as complementary codes, *Neuron*, **52** (6), pp. 1073–1083.
- Buzsaki, G. (2006) *Rhythms of the Brain*, Oxford: Oxford University Press.
- Crick, F. & Koch, C. (1992) The problem of consciousness, *Scientific American*, **267** (3), pp. 152–159.
- Crick, F. & Koch, C. (1995) Are we aware of neural activity in primary visual cortex? [see comments], *Nature*, **375** (6527), pp. 121–123.
- Davidson, C. (1997) Creatures from primordial silicon — let Darwinism loose in an electronics lab and just watch what it creates. A lean, mean machine that nobody understands, *New Scientist*, **156**, pp. 30–34.
- Engel, A.K., Moll, C.K., Fried, I. & Ojemann, G.A. (2005) Invasive recordings from the human brain: Clinical insights and beyond, *Nature Reviews Neuroscience*, **6** (1), pp. 35–47.

- Fingelkurts, A.A., Fingelkurts, A.A. & Neves, C.F. (2001) Natural world physical, brain operational, and mind phenomenal space-time, *Physics of Life Reviews*, **7** (2), pp. 195–249.
- Fingelkurts, A.A. & Fingelkurts, A.A. (2008) Brain–mind operational architectonics imaging: Technical and methodological aspects, *Open Neuroimaging Journal*, **2**, pp. 73–93.
- Freeman, W.J. (1975) *Mass Action in the Nervous System*, New York: Academic Press.
- Freeman, W.J. (2003) The wave packet: An action potential for the 21st century, *Journal of Integrative Neuroscience*, **2** (1), pp. 3–30.
- Freeman, W.J. (2011) Tutorial on neurobiology: From single neurons to brain chaos, *International Journal of Bifurcation and Chaos*, **2**, pp. 451–482.
- Fries, P. (2005) A mechanism for cognitive dynamics: Neuronal communication through neuronal coherence, *Trends in Cognitive Sciences*, **9** (10), pp. 474–480.
- Frohlich, F. & McCormick, D.A. (2010) Endogenous electric fields may guide neocortical network activity, *Neuron*, **67** (1), pp. 129–143.
- Fujisawa, S., Matsuki, N. & Ikegaya, Y. (2004) Chronometric readout from a memory trace: Gamma-frequency field stimulation recruits timed recurrent activity in the rat CA3 network, *Journal of Physiology*, **561** (pt 1), pp. 123–131.
- Jensen, O., Kaiser, J. & Lachaux, J.P. (2007) Human gamma-frequency oscillations associated with attention and memory, *Trends in Neurosciences*, **30** (7), pp. 317–324.
- John, E.R. (2002) The neurophysics of consciousness, *Brain Research Reviews*, **39** (1), pp. 1–28.
- Kay, L.M., Beshel, J., Brea, J., Martin, C., Rojas-Libano, D. & Kopell, N. (2009) Olfactory oscillations: The what, how and what for, *Trends in Neurosciences*, **32** (4), pp. 207–214.
- Kreiter, A.K. & Singer, W. (1996) Stimulus-dependent synchronization of neuronal responses in the visual cortex of the awake macaque monkey, *Journal of Neuroscience*, **16** (7), pp. 2381–2396.
- MacLennan, B.J. (1999) Field computation in natural and artificial intelligence, *Information Sciences*, **119**, pp. 73–89.
- McFadden, J. (2000) *Quantum Evolution*, London: HarperCollins.
- McFadden, J. (2002a) Synchronous firing and its influence on the brain's electromagnetic field: Evidence for an electromagnetic theory of consciousness, *Journal of Consciousness Studies*, **9** (4), pp. 23–50.
- McFadden, J. (2002b) The Conscious electromagnetic information (CEMI) field theory: The hard problem made easy?, *Journal of Consciousness Studies*, **9** (8), pp. 45–60.
- McFadden, J. (2006) The CEMI field theory: Seven clues to the nature of consciousness, in Tuszyński, J. (ed.) *The Emerging Physics of Consciousness*, pp. 387–406, New York: Springer.
- McFadden, J. (2007) Conscious electromagnetic (CEMI) field theory, *Neuroquantology*, **5** (3), pp. 262–270.
- Nunez, P.L. (2000) Toward a quantitative description of large-scale neocortical dynamic function and EEG, *Behavioral and Brain Sciences*, **23** (3), pp. 371–398.
- Nyhus, E. & Curran, T. (2010) Functional role of gamma and theta oscillations in episodic memory, *Neuroscience and Biobehavioral Reviews*, **34** (7), pp. 1023–1035.
- 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, *Journal of Consciousness Studies*, **9** (4), pp. 51–56.
- Raffone, A. & Wolters, G. (2001) A cortical mechanism for binding in visual working memory, *Journal of Cognitive Neuroscience*, **13** (6), pp. 766–785.
- Richardson, R.D. (2007) *William James: In the Maelstrom of American Modernism*, New York: First Mariner Books.
- Roelfsema, P.R., Engel, A.K., König, P. & Singer, W. (1997) Visuomotor integration is associated with zero time-lag synchronization among cortical areas, *Nature*, **385** (6612), pp. 157–161.
- Singer, W. (2011) Dynamic formation of functional networks by synchronization, *Neuron*, **69** (2), pp. 191–193.
- Stopfer, M., Bhagavan, S., Smith, B.H. & Laurent, G. (1997) Impaired odour discrimination on desynchronization of odour-encoding neural assemblies, *Nature*, **390** (6655), pp. 70–74.
- Tanaka, N.K., Ito, K. & Stopfer, M. (2009) Odor-evoked neural oscillations in *Drosophila* are mediated by widely branching interneurons, *Journal of Neuroscience*, **29** (26), pp. 8595–8603.
- Thompson, A. (1996) Silicon evolution, in Koza, J.R., *et al.* (eds.) *Proceedings of Genetic Programming*, pp. 444–452, Cambridge: MIT Press.
- von der, M.C. & Schneider, W. (1986) A neural cocktail-party processor, *Biological Cybernetics*, **54** (1), pp. 29–40.
- Wilke, M., Logothetis, N.K. & Leopold, D.A. (2006) Local field potential reflects perceptual suppression in monkey visual cortex, *Proceedings of the National Academy of Sciences USA*, **103** (46), pp. 17507–17512.

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