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Synchronous Firing and Its Influence on the Brain's Electromagnetic Field

*Evidence for an Electromagnetic
Field Theory of Consciousness*

Abstract: *The human brain consists of approximately 100 billion electrically active neurones that generate an endogenous electromagnetic (em) field, whose role in neuronal computing has not been fully examined. The source, magnitude and likely influence of the brain's endogenous em field are here considered. An estimate of the strength and magnitude of the brain's em field is gained from theoretical considerations, brain scanning and microelectrode data. An estimate of the likely influence of the brain's em field is gained from theoretical principles and considerations of the experimental effects of external em fields on neurone firing both in vitro and in vivo. Synchronous firing of distributed neurones phase-locks induced em field fluctuations to increase their magnitude and influence. Synchronous firing has previously been demonstrated to correlate with awareness and perception, indicating that perturbations to the brain's em field also correlate with awareness. The brain's em field represents an integrated electromagnetic field representation of distributed neuronal information and has dynamics that closely map to those expected for a correlate of consciousness. I propose that the brain's em information field is the physical substrate of conscious awareness — the cemi field — and make a number of predictions that follow from this proposal. Experimental evidence pertinent to these predictions is examined and shown to be entirely consistent with the cemi field theory. This theory provides solutions to many of the intractable problems of consciousness — such as the binding problem — and provides new insights into the role of consciousness, the meaning of free will and the nature of qualia. It thus places consciousness within a secure physical framework and provides a route towards constructing an artificial consciousness.*

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Journal of Consciousness Studies, 9, No. 4, 2002, pp. 23–50

Introduction

The binding problem of consciousness — how our conscious mind integrates information distributed amongst billions of spatially separated neurones to generate the unity of conscious experience — is one of the fundamental questions in the study of mind. One possible solution was put forward by Karl Popper (Popper *et al.*, 1993) who suggested that consciousness was a manifestation of some kind of overarching *force field* in the brain that could integrate the diverse information held in distributed neurones. The idea was further developed and extended by Lindahl and Århem (1994) and by Libet (1994; 1996). However, these authors considered that the conscious mind could not be a manifestation of any known form of physical field and its nature remained mysterious.

Yet it has been known for more than a century that the brain generates its own electromagnetic (em) field, a fact that is widely utilised in brain scanning techniques. Electrical coupling via electromagnetic field effects have been suspected of playing a role in a number of neurological phenomena, particularly the generation of synchronous waveforms in neural assemblies and in epilepsy (Gluckman *et al.*, 1996; Jefferys, 1995). However, the influence and nature of field effects on the phenomenon of mind has not been fully considered.

Recently, synchronous firing of neurones has received considerable attention as a possible route towards conceptual binding stimuli (Eckhorn *et al.*, 1988; 1993; Eckhorn, 1994; Engel *et al.*, 1991a,b; Fries *et al.*, 1997; Gray *et al.*, 1989; Kreiter and Singer, 1996). For instance, Wolf Singer and colleagues demonstrated that neurones 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). It appeared that the monkeys registered each bar as a single pattern of neuronal firing but their *awareness* that the bars represent two aspects of the same object, was encoded by synchrony of firing. In another experiment that examined interocular rivalry in awake strabismic cats, it was discovered that neurones that responded to the attended image fired in synchrony, whereas the same neurones fired randomly when awareness was lost (Fries *et al.*, 1997). In each of these experiments, awareness correlated, not with a pattern of neuronal firing, but with synchrony of firing. Singer, Eckhorn and others have suggested that these 40–80 Hertz synchronous oscillations link distant neurones involved in registering different aspects (colour, shape, movement, etc.) of the same visual perceptions and thereby *bind* together features of a sensory stimulus (Eckhorn *et al.*, 1988; Singer, 1998). However, if synchronicity is involved in perceptual binding, it is unclear how the brain uses or even detects synchrony.

I here consider the nature and magnitude of the brain's endogenous em field and consider its influence in modulating neuronal activity. I show that the brain generates a dynamic and information-rich em field that influences neurone firing through electrical field coupling and its dynamics has many of the characteristics expected for a correlate consciousness. I also show that synchronous firing of neurones 'phase-locks' em field effects and thereby increases the level of

electrical coupling between the brain's em field and neurones, providing an explanation for the observed correlation between awareness and synchronous firing (Singer, 1999). This detailed argument supports my earlier proposal (McFadden, 2000) that the brain's electromagnetic field is the seat of consciousness. Susan Pockett has independently proposed a similar hypothesis (Pockett, 2000). The proposal that the physical manifestation of consciousness is an electromagnetic field that exhibits wave mechanical dynamics has profound implications for our understanding of the phenomenon of consciousness and the nature of free will.

Model and Results

My argument considers first the origin of the brain's electromagnetic field and its magnitude. I next consider the nature of the interaction between the brain's endogenous em field and neuronal computation. I then go on to propose that the brain's em field is the physical 'seat of consciousness' and make predictions that follow from that proposal. Lastly I examine the evidence pertaining to those predictions.

A. The source and magnitude of the brain's em field

First, in this section I will demonstrate that the brain generates a highly structured and dynamic extracellular electric field.

1. Theoretical considerations

The brain's endogenous em field is a product of the induced fields from neurone firing and also the fields generated by the movement of ions into and out of cells and within extracellular spaces. For simplicity, I will consider only the former source. Vigmond (Vigmond *et al.*, 1997) modelled the electrical activity of pyramidal cells and demonstrated that neurone firing induced a peak of intracellular potential in receiver cells that ranged from a few microvolts to 0.8 mV, decaying with approximately the inverse of distance between the cells.

The electrical field at any point in the brain will be a superposition of the induced fields from all of the neurones in the vicinity (superimposed on the fields generated by ion movement) and will depend on their firing frequency, geometry and the dielectric properties of tissue. For neurones that are arranged randomly, their induced fields will tend to sum to zero; but the laminar organisation of structures such as the neocortex and hippocampus, with parallel arrays of neurones, will tend to amplify local fields. Although it is not feasible to calculate the local field strength at any point in the brain without precise knowledge of all the structures, estimates of its magnitude can be gained experimentally.

2. Experimental evidence

Electroencephalography (EEG) has been used for more than a century to measure electrical activity in the brain from changes in the field potential recorded at

the surface of the scalp. Field strength fluctuations in the range of tens of microvolts (Cooper *et al.*, 1980; Haggard and Eimer, 1999) are routinely measured in healthy human subjects but may be raised to many hundred of microvolts in pathological conditions, such as epileptic seizures (Niedermeyer, 1998a).

The field measured at the scalp during EEG are likely to be both distorted and attenuated by their passage through brain tissue, cerebrospinal fluid, the skull and skin. Direct measurement of local field potentials within human brain tissue has however been possible in patients who, for therapeutic reasons, have had EEG recordings obtained from subdural, cortical or in depth electrodes implanted into their cerebral cortex. Extracellular potentials with peak intensities of several hundred microvolts up to about one millivolt across the recording electrodes are routinely obtained (Niedermeyer, 2001; Quesney and Niedermeyer, 1998). Measurements made on human neocortical slices excised from epileptic patients similarly record large field gradients (Kohling *et al.*, 1998). EEG electrodes are usually 40 mm apart and therefore do not provide spatially detailed information on the structure of the underlying fields, but studies with subdural and depth microelectrodes indicate that the brain's em field has detailed spatial structure in the millimetre and sub-millimetre domain and detailed temporal structure in the sub-second domain, over a range of frequencies (Bullock *et al.*, 1995a,b; Bullock and McClune, 1989). It is not possible to calculate the electrical sources of recorded EEG waves from potentials measured at the scalp, as the problem (known as the inverse problem) has no unique solution (many alternative arrangements of electrical sources may generate the same potentials measured at the scalp). Nevertheless, a striking feature of EEG is the differences in electrical activity from electrode to electrode, even when less than 1 mm apart (Speckmann and Elger, 1998), indicating that the brain generates a highly structured and dynamic extracellular electric field.

Direct measurement of local field potentials is also possible in some experimental and therapeutic situations. Local field potentials have been measured in the neocortex of experimental animals with implanted electrodes and demonstrate extracellular field gradients of up to about 20 V/m (Amzica and Steriade, 2000; Engel, 1998; Gray, 1994; Jefferys, 1995). Recordings from different cortical layers demonstrate potential fluctuations and phase reversals for sites separated by just a few hundred micrometers (Speckmann and Elger, 1998). Measurements made on hippocampus brain slices maintained *in vitro* record field potentials as high as 50–100 V/m, particularly during seizure activity (Green and Petsche, 1961; Jefferys, 1981; Swann *et al.*, 1986). It should be pointed out that these experiments have utilised electrodes spaced in the millimetre domain and thereby are likely to under-estimate field potentials in the sub-millimetre domain.

Another source of information on changes within the brain's em field is obtained from measurements of evoked potentials (event-related potentials). Sensory evoked potentials are detected when a sensory stimulation reaches the brain and evokes a characteristic sequence of waves in the EEG. Motor evoked

potentials are similarly recorded during induced motor activity. Evoked potentials have very low amplitudes (up to a few tens of microvolts, as measured on the scalp) that are normally drowned by the ordinary EEG rhythms (Chalupa *et al.*, 1976; De Giorgio *et al.*, 1993; Kaufman *et al.*, 1981; Kyuhou and Okada, 1993; Linseman and Corrigan, 1982). However, their signal can be detected by averaging the EEG patterns obtained after a large number of identical stimuli. Although weak, the existence of evoked potentials demonstrates that both sensory stimuli and motor activity are associated with temporally organized perturbations to the brain's em field. Walter Freeman's classic experiments (Freeman, 1991; Freeman and Schneider, 1982) measuring EEG activity within the olfactory bulb of rabbits and cats demonstrated bursts of EEG activity in response to sensory stimuli with average amplitude of about 100 microvolts across recording electrodes that were spaced at 0.5 mm and thereby corresponding to field gradients of 0.2 V/m. Interestingly, in these experiments information concerning the identity of a particular odour was not carried by the temporal shape of any particular EEG wave but by the spatial pattern of EEG amplitude (the contour plot) across the entire surface of the olfactory bulb.

The human (and animal) brain therefore contains a highly structured (in time and space) endogenous extracellular em field, with a magnitude of up to several tens of volts per metre. Although these extracellular fields are relatively weak, at the low frequencies characteristic of brain waves, cell membranes are much more resistive than either the cytoplasm or extracellular fluid. Consequently, within brain tissue, most of the potential drop occurs across cell membranes. In general, transmembrane fields are approximately 3,000 times the field in the surrounding tissue (Valberg *et al.*, 1997) but may be even higher in elongated cells orientated along the field. Consequently, endogenous em fields of tens of volts per metre are capable of generating fields of several tens of thousands of volts per metre, translating to up to several millivolts, across the 5 nm neuronal cell membrane.

The form and amplitude of these fields will be continually sculpted in response to changes in brain activity. I next consider the likely influence of modulations to these endogenous fields.

B. Influence of the brain's endogenous em field on nerve firing

In this section I will examine the influence of the brain's electromagnetic field on the probability of neurone firing.

1. Theoretical considerations

Endogenous electrical fields may influence the brain in a number of ways. The field may induce electrophoretic redistribution of charged ions both intracellularly and extracellularly and thereby directly modulate neuronal physiology. Additionally, various structures in the brain are sensitive to electromagnetic fields. Neurotransmission through gap junctions may be voltage dependent and thereby sensitive to local fields (Draguhn *et al.*, 1998; Jefferys, 1995). However, the role of gap junctions in information processing in the human brain is

presently unclear. The best-characterized sensor of the brain's electromagnetic field are the voltage-gated ion channels in neuronal membranes, which have a well-defined role in information processing in the brain.

The potential drop from resting to firing in a typical neurone is of the order of tens of millivolts across the cell membrane, corresponding to field strengths of about 6×10^6 V/m, far greater than the endogenous fields. However, potential changes of less than one millivolt across the membrane are capable of modulating neuronal firing (Schmitt *et al.*, 1976). Moreover, for neurones poised close to the firing potential, the opening of just a single ion channel may be sufficient to trigger firing (Århem and Johansson, 1996), indicating that very tiny changes in membrane potential — smaller than those associated with the endogenous em field — may influence firing. Several studies have demonstrated that extracellular fields play a role in recruitment and synchronisation of neuronal activity (Jefferys, 1981; Mann-Metzer and Yarom, 2000). Computer simulations of neurone firing patterns similarly indicate a role for extracellular fields (Bawin *et al.*, 1986; Richardson *et al.*, 1984; Traub *et al.*, 1985).

Nevertheless, for any induced field to have a significant effect, its strength would be expected to be greater than the spontaneous random fields generated by thermal noise in the neuronal membrane. The size of voltage fluctuations in the membrane due to thermal noise has been estimated (Valberg *et al.*, 1997) to be 2,600 V/m for the frequency range 1–100 Hz (encompassing the frequency range typical of the mammalian brain waves), which translates to 13 μ V across a 5 nm cell membrane. It should be noted that this value is well below the several millivolt transmembrane signal that is expected to be generated by the brain's endogenous extracellular em fields (above).

The excitability of 'receiver' neurones (neurones that are influenced by the em field) will depend on many factors. Neurones with membrane poised close to firing will be most sensitive to field effects; whereas neurones whose membranes are close to resting potential will be relatively insensitive to field effects. The geometry of neurones with respect to the field will also greatly influence their sensitivity. Neurones orientated along isopotentials (lines of equal electrical potential) will not 'see' the field at all; whereas neurones that are bent relative to isopotential lines will be most sensitive to the field (Abdeen and Stuchly, 1994; Rattay, 1999). In some cases the induced voltage may be depolarising and thereby push the neurone towards firing, whereas in other cases the induced transmembrane voltage may be hyperpolarising and desensitise the neurone. Self-synapsing neurones that form nearly closed loops may be highly sensitive to em field effects; and myelination of nerve fibres will increase their electrical excitability (Rattay, 1998). Finally, gap junctions connecting chains of cells focus the potential drop on the terminal (not electrotonically-coupled) cell membrane in the chain and thereby increases sensitivity of the entire cell ensemble to applied fields (Cooper, 1984).

To examine the influence that the firing of a single neurone will have on its neighbours, I estimate the volume (the *field volume*) wherein the induced field generated by neurone firing could modulate firing of 'receiver' neurones by

generating an induced membrane potential greater than the thermal noise level. Using Vigmond's model, a peak *intracellular voltage* of 2,600 V/m (thermal noise level) is induced in receiving cells that are located within a radius of 73–77 μm from the source cell (Edward J. Vigmond, Department of Biomedical Engineering, Tulane University, personal communication). Unfortunately, the resulting induced transmembrane voltage (TMV) cannot be calculated directly from the induced intracellular voltage, since the voltage drop will be distributed unevenly throughout the cell, depolarising some parts of the membrane and hyperpolarizing other regions. Nevertheless, in Vigmond's model, peak TMV's are almost an order of magnitude higher than intracellular potentials; therefore a distance of 73–77 μm is likely to be an underestimate of the field volume.

Considering only those cells in the plane of the source cell embedded in the human cerebral cortex (about 10^4 neurones/ mm^2), approximately 200 neighbouring cells will be within the field volume. The firing of a single neurone is thereby potentially capable of modulating the firing pattern of many neighbouring neurones through field effects. The strength of this 'field coupling' will depend on numerous factors including the cell geometry and electrical excitability. However, a major factor that will influence the strength of field coupling in the brain will be the synchronicity of nerve firing.

The superposition principle states that for overlapping fields, the total em field strength at any point is an algebraic sum of the component fields acting at that point. Like all wave phenomena, field modulations due to nerve firing will demonstrate constructive or destructive interference depending on the relative phase of the component fields. Temporally random nerve firing will generally generate incoherent field modulations leading to destructive interference and zero net field. In contrast, synchronous nerve firing will phase-lock the field modulations to generate a coherent field of magnitude that is the vector sum (the geometric sum — taking into account the direction of the field) of its components.

Synchronous nerve firing has been demonstrated in animal models and in humans. The number of cells involved in synchronous firing is thought to vary widely but in EEG, synchronisation of cortical beta and gamma rhythms can be detected between pairs of electrodes at inter-electrode distances of 40 mm, indicating that synchronisation may involve very many spatially-distributed neurones (Bullock *et al.*, 1995b; Lopes da Silva, 1998). So, whereas a single neurone may influence several hundred neighbouring neurones through field effects, synchronous (but not asynchronous) firing of clusters of neurones will generate perturbations of the brain's em field that will influence many millions of distributed neurones.

2. *Experimental evidence*

There is considerable evidence that neurones do indeed communicate through the em field (known as *field coupling*). *Ephaptic* nerve transmission describes the phenomenon whereby neurone firing is modulated by the firing of adjacent neurones and has been demonstrated *in vitro* when neurones are brought into

very close proximity under conditions that exclude synaptic transmission. Ephaptic transmission has been implicated in a number of pathological conditions such as tinnitus and peripheral neuropathy and is strongly suspected to be involved in the synchronisation of neurone firing that is seen in 'field bursts' within hippocampal slices maintained *in vitro* (Buzsaki *et al.*, 1992), and in epileptic seizures (Bawin *et al.*, 1986; Jefferys, 1981; Konnerth *et al.*, 1986; Richardson *et al.*, 1984; Snow and Dudek, 1984).

The role of the brain's endogenous em field in normal informational processing has not been fully considered. In humans, the strongest evidence for the sensitivity of the brain to relatively weak em fields comes from the therapeutic use of transcranial magnetic stimulation (TMS). In TMS, a current passing through a coil placed on the scalp of subjects is used to generate a time-varying magnetic field that penetrates the skull and induces an electrical field in neuronal tissue. The precise mechanism by which TMS modulates brain activity is currently unclear but is generally assumed to be through electrical induction of local currents in brain tissue that modulate nerve firing patterns. TMS has been shown to generate a range of cognitive disturbances in subjects including: modification of reaction time, induction of phosphenes, suppression of visual perception, speech arrest, disturbances of eye movements and mood changes (Hallett, 2000). Even single TMS pulses have been shown to induce spreading changes to the brain's electrical activity, that can be detected by EEG or MEG and persists for many milliseconds after stimulation (Ilmoniemi *et al.*, 1997; 1999), once again indicating that neuronal firing patterns have been modulated. The field induced in cortical tissue by TMS cannot be measured directly but may be estimated from modelling studies. The evoked field depends critically on the instrumentation, particularly the coil geometry and strength and frequency of the stimulating magnetic field. In one study where stimulation utilized a set of four coils, the induced electrical field was estimated to be in the range of 50–130 V/m (Epstein *et al.*, 1990). Another modelling study with a figure of eight coil estimated fields of 20–150 V/m (Ruohonen *et al.*, 2000). TMS voltages are thereby in the range of tens of volts per metre, values that are typical for the endogenous fields generated during normal and pathological brain activity (see above). Therefore, since TMS induced modulations of the brain's em field affect brain function and behaviour, it follows that the brain's endogenous field must similarly influence neuronal computation.

The issue of the sensitivity of the human brain to weaker voltage fluctuations is entangled with the powerline/mobile phone controversy, which, despite many studies, remains contradictory and unresolved. However, there is very solid *in vitro* evidence for very weak em fields modulating neuronal function. Fields as weak as 10–20 V/m have been shown to modulate neurone-firing patterns of Purkinje and stellate cells in the isolated turtle cerebellum *in vitro* (Chan and Nicholson, 1986) or the guinea-pig hippocampus (Jefferys, 1981). Electric field suppression of epileptiform activity in rat hippocampal slices has been demonstrated for fields as low as 5–10 V/m (Gluckman *et al.*, 1996) and modulation of hippocampal rhythmic slow activity in rats has been demonstrated *in vivo* by

weak extremely-low-frequency (ELF) magnetic fields (16.0 Hz; 28.9 T) associated with induced electrical fields of only 0.1 mV/m (Jenrow *et al.*, 1998). A mollusc neurone has been shown to be capable of responding to earth-strength (about 45 T) magnetic fields (Lohmann *et al.*, 1991), associated with induced electrical fields of just 0.26 mV/m.

The finding that fields that are weaker than electrical noise caused by thermal fluctuations are still capable of modulating neurone firing could be accounted for by a number of possible mechanisms. Stochastic resonance, whereby optimized random noise enhances the detection of weak signals in a noisy environment, has been proposed to be involved in neuronal signalling (Douglass *et al.*, 1993). Signal averaging by clusters of neurones may increase sensitivity of neurones to detect fields as weak as 0.1–100 mV/m (Astumian *et al.*, 1995; 1997; Weaver *et al.*, 1998; 1999). Finally, magnetically sensitive chemical reactions may be the sensors of weak field fluctuations (Weaver *et al.*, 2000).

By whatever mechanism, it is clear that very weak em field fluctuations are capable of modulating neurone-firing patterns. These exogenous fields are weaker than the perturbations in the brain's endogenous em field that are induced during normal neuronal activity. The conclusion is inescapable: the brain's endogenous em field must influence neuronal information processing in the brain.

C. The cemi field theory of consciousness

The brain's em field is as much a part of its activity as neuronal firing. Efforts to understand human consciousness have focussed on the informational processing performed by neurone firing and synaptic transmission, yet the brain's em field holds precisely the same information as neurone firing patterns and may be involved in transmission and processing of that information. The equivalence of matter and energy, apparent in Einstein's famous equation, implies that there is no *a priori* reason why consciousness should be associated with the matter of neurones rather than the em field activity within and between neurones. However, whereas information in neurones is digital, discrete and spatially localized, information in em fields is analogue, integrated and distributed. I note that these latter characteristics are those usually ascribed to the phenomenon of consciousness and are the properties of consciousness that are most difficult to account for in neural identity models of consciousness. I have earlier proposed (McFadden, 2000) that the seat of consciousness is the brain's em field and a similar proposal has recently been put forward by Susan Pockett (2000). I therefore examine the proposition that the brain's em field *is* consciousness and that information held in distributed neurones is integrated into a single conscious em field: the *cemi field*.

The cemi field theory makes a number of testable predictions:

- (1) Stimuli that reach conscious awareness will be associated with em field modulations that are strong enough to directly influence the firing of motor neurones.

- (2) Stimuli that do not reach conscious awareness will not be associated with em field modulations that affect motor neurone firing.
- (3) The cemi field theory claims that consciousness represents a stream of information passing through the brain's em field. Increased complexity of conscious thinking should therefore correlate with increased complexity of the brain's em field.
- (4) Agents that disrupt the interaction between the brain's em field and neurones will induce unconsciousness.
- (5) Arousal and alertness will correlate with conditions in which em field fluctuations are most likely to influence neurone firing; conversely, low arousal and unconsciousness will correlate with conditions when em fields are least likely to influence neurone firing.
- (6) The brain's em field should be relatively insulated to perturbation from exogenous em fields encountered in normal environments.
- (7) The evolution of consciousness in animals should correlate with an increasing level of electrical coupling between the brain's endogenous em field and (receiver) neurone firing.
- (8) Consciousness should demonstrate field-level dynamics.

D. Experimental evidence for cemi field predictions

Prediction 1. Sensory or motor information that is transmitted just by neurone firing will tend to scale arithmetically: the greater the stimulus or response, the more neurones are likely to be involved. However, because the em field is a wave-mechanical phenomenon the magnitude of its modulations will be proportional only to the number of those neurones that fire synchronously. The cemi field theory therefore predicts that conscious awareness will not correlate with neurone firing *per se* but with the synchrony of neurone firing.

As outlined in the Introduction, numerous studies have indeed indicated that whereas neurone-firing patterns alone do not correlate with awareness, their level of synchrony does. Studies using multiple microelectrodes implanted in the brain of experimental animals have demonstrated that clusters of neurones in their visual cortex fire in synchrony when animals perceive visual stimuli (Eckhorn *et al.*, 1988; 1993; Eckhorn, 1994; Engel *et al.*, 1991a,b; Fries *et al.*, 1997; Gray *et al.*, 1989; Kreiter and Singer, 1996). Disruption of synchronous firing by treatment with picrotoxin has been shown to reduce the ability of insects to discriminate between similar scents (Stopfer *et al.*, 1997), indicating that, at least in these animals, synchrony is not just an epiphenomenon, but plays a role in information processing. There is also indirect evidence that synchronous firing also correlates with awareness and attention in man. EEG (Miltner *et al.*, 1999; Rodriguez *et al.*, 1999) and MEG (Srinivasan *et al.*, 1999) studies indicate that synchronous firing in different regions of the human cortex correlates with awareness and attention. The existence of evoked potentials provides additional evidence for synchronous firing being involved in perception of stimuli and purposeful action, since although they are weak, they are much stronger than signals

that would be generated from the firing of single neurones and must be due to the synchronized firing of many neurones. Indeed, Fourier analysis on EEG segments recorded immediately after auditory stimuli demonstrated that stimuli do not change the amplitude of EEG, but instead shift their phase, to phase-lock the signal and generate the observed evoked potential (Sayers *et al.*, 1974). As outlined above, Walter Freeman's studies of rabbit olfaction (Freeman, 1991) demonstrated that sensory information is encoded within the spatial pattern of EEG activity and thereby the shape of the underlying em field. Interestingly, in Freeman's studies the em field contour maps were shown to correlate, not only with the identity of a particular odour, but with its meaning to the animal. When animals were trained to associate the odour with a particular reinforcement then the shape of the contour map would be altered. It therefore appears from these studies that modulations of the em field correlate with perception and meaning, rather than stimulus alone. All of these findings demonstrate that awareness and attention in man and animals, and thereby consciousness (at least in man), is associated with modulations to the brain's em field generated by synchronisation of neuronal firing patterns.

Prediction 2. Examining the second prediction, there is abundant evidence that the loss of awareness of repeated stimuli during habituation is associated with a reduction in amplitude of either EEG or MEG evoked potential signals (Coull, 1998; Hirano *et al.*, 1996) and thereby the synchronous neurone firing patterns that generate those signals. Loss of awareness therefore correlates with reduced disturbance to the brain's em field (Anninos *et al.*, 1987; Hulstijn, 1978; Leaton and Jordan, 1978; Rockstroh *et al.*, 1987). Indeed, a marked decline of EEG voltage is a key indicator of the onset of the preterminal state (Niedermeyer, 1998b). The cemi theory also predicts that em fields generated by neuronal activity in 'unconscious' areas of the brain — such as the retina or brain stem — or during preconscious information processing (as occurs in some areas of the visual cortex) should not impact on motor neurones. I know of no evidence regarding this prediction but it is testable. The theory also predicts that we would become conscious of this (previously unconscious) neuronal activity if conditions were modified to allow the induced fields to impact on motor neurones. Again I know of no direct evidence to confirm or deny this prediction but it is interesting to note that tinnitus is associated with ephatic nerve transmission (Eggermont, 1990) indicating that, in this condition, perception of what is normally unconscious neuronal activity is associated with field-level input into nerves.

Prediction 3. Analysis of the fractal dimension of EEG signal during various cognitive states has shown that dynamic complexity is increased during creative thinking but decreased during coma or deep sleep and raised during REM dreaming (Molle *et al.*, 1996), supporting the prediction that complexity in the brain's em field correlates with complexity in conscious thinking. Interestingly, the dynamic complexity of EEG is markedly affected (can be raised or lowered depending on the type of music and the musical sophistication of subjects) by listening to music, (Birbaumer *et al.*, 1996), indicating perhaps the route by which

music may influence the complexity of our conscious thought processes. Note however that widespread neuronal synchrony — such as experienced during an epileptic seizure — is likely to be pathological (with regard to our conscious state), since it contains very little information.

Prediction 4. Examining the third prediction, there is evidence that anaesthetics that decrease awareness of stimuli disrupt synchronous firing (Southan and Wann, 1989; Whittington *et al.*, 1998) and thereby reduce the influence of the em field on neurone firing. The onset of unconsciousness due to a variety of agents *e.g.* asphyxia or anaesthesia is associated with a reduction of amplitude of EEG signals (McPherson, 1998), indicating that loss of consciousness is associated with disruption to neuronal synchronization (Speckmann and Elger, 1998) and consequent weak endogenous em fields. As mentioned above, disruption of synchronous firing in insects by treatment with picrotoxin reduces their ability to discriminate between scents.

Prediction 5. The cemi field theory predicts that the increased levels of arousal (increasing conscious control of actions) should be associated with strong coupling between the brain's em field and neurones. There are two principle routes towards varying electrical coupling in the brain: modulating the amplitude of field disturbances, or shifting neuronal transmembrane potential to adjust electrical excitability. Local field amplitudes will be a product not only of the degree of synchronicity of neurone firing, but also the activity of glial cells that contribute (positively and negatively) to extracellular fields through their ability to take up potassium ions (Amzica and Steriade, 2000; De Giorgio *et al.*, 1993). In man, the amplitude of EEG-measured evoked potentials are depressed during deep sleep (Wesensten and Badia, 1988) and coma (De Giorgio *et al.*, 1993; Wesensten and Badia, 1988) and increased during arousal and selective attention (Coull, 1998; De Giorgio *et al.*, 1993; Naatanen, 1975). The amplitude of the P300 component of auditory evoked potentials is found to be inversely proportional to stimulus probability (*i.e.* P300 is elicited by unexpected stimuli or the absence of an expected stimulus) (Coull, 1998). Increased amplitude of visually-evoked potentials is also associated with short reactions times in monkeys (Chalupa *et al.*, 1976; De Giorgio *et al.*, 1993). The level of spatial coherence of EEG patterns — which is a reflection of the coherence of the underlying endogenous em fields — is also found to correlate with attention and awareness. For instance, in a recent study, the level of EEG spatial coherence was found to be related to the level of creativity needed to solve a problem (Jausovec and Jausovec, 2000). Spatial coherence was also found to increase during transcendental meditation (Travis and Wallace, 1999). Conversely, loss of EEG spatial coherence was found to correlate with increasing cognitive impairment in HIV patients (Fletcher *et al.*, 1997).

There is limited evidence that neuronal electrical excitability may be modulated by agents that impact on consciousness. The opiate agonist morphine increases electrical excitability and field potentials in hippocampal slices,

whereas the opiate antagonist, naloxone, is known to hyperpolarize neurones and thereby depress their electrical excitability (North and Tonini, 1977).

Prediction 6. The high conductivity of the cerebral fluid and fluid within the brain ventricles creates an effective ‘Faraday cage’ that insulates the brain from most natural exogenous electric fields. A constant external electric field will thereby induce almost no field at all in the brain (Adair, 1991). Alternating currents from technological devices (power lines, mobile phones, etc.) will generate an alternating induced field, but its magnitude will be very weak. For example, a 60 Hz electrical field of 1000 V/m (typical of a powerline) will generate a tissue field of only 40 μ V/m inside the head (Adair, 1991), clearly much weaker than either the endogenous em field or the field caused by thermal noise in cell membranes. Magnetic fields do penetrate tissue much more readily than electric fields but most naturally encountered magnetic fields, and also those experienced during nuclear magnetic resonance (NMR) scanning, are static (changing only the direction of moving charges) and are thereby unlikely to have physiological effects. Changing magnetic fields will penetrate the skull and induce electric currents in the brain. However, there is abundant evidence (from, e.g., TMS studies as outlined above) that these do modify brain activity. Indeed, repetitive TMS is subject to strict safety guidelines to prevent inducing seizures in normal subjects (Hallett, 2000) through field effects.

Prediction 7. It is generally agreed that although lower animals may possess some rudiments of consciousness (perhaps ‘awareness’), the involvement of conscious minds in decision making (‘free will’) is limited to animals with more complex nervous systems, such as the higher primates; and only in man has consciousness come to play a major role in modifying behaviour. The cemi theory predicts that conscious brains, such as man’s, should demonstrate a greater degree of electrical coupling, than unconscious (or *less conscious*) brains, such as a reptile’s. Though I know of no data relevant to this prediction, it is clearly amenable to experimental testing.

Prediction 8. The last prediction of the cemi theory — that consciousness should demonstrate field-level dynamics — is perhaps the most interesting, but also the most difficult to approach experimentally. In principle it should be possible to distinguish a wave-mechanical (em field) model of consciousness from a digital (neuronal) model. Although neurones and the fields generated by neurones hold the same information, the form of that information is not equivalent. For instance, although a complete description of neurone firing patterns would completely specify the associated field, the reverse is not true: a particular configuration of the brain’s em field could not be used to ‘reverse engineer’ the neurone firing patterns that generated that field. This is because any complex wave may be ‘decomposed’ into a superposition of many different component waves: a particular field configuration (state of consciousness) may be the product of many distinct neurone-firing patterns. The cemi field theory thereby predicts that if distinct neurone firing patterns generate the same net field then, at the level of

conscious experience, those firing patterns should be indistinguishable. In principle at least, this issue could be resolved experimentally.

Additional wave mechanical properties of em fields (e.g speed of light transmission and field-level processing of information, interference effects) may also be experimentally distinguishable from neuronal transmission. 'Interference effects' have been noted in studies of attention in animals (Barinaga, 1998), but it is generally assumed that the interference occurs at the level of synaptic modulation of nerve firing. Experiments could be designed to investigate whether wave-mechanical interference is a factor in conscious awareness. Field level informational processing may also endow consciousness with properties that are absent, or more complicated to emulate, in a digital system. For instance, wave-mechanical dynamics may allow Fourier-type (harmonic analysis) of information held in the conscious field, providing a possible mechanism for the ability of some individuals to hear pure tones in complex sound waves. MacLennan (1999) has recently argued that many mind processes may usefully be described as field-level computations.

Discussion

Many cognitive scientists have accepted T.H. Huxley's view that we are conscious automata (Huxley, 1874), with consciousness playing no more role in our lives than that of a 'steam whistle which accompanies the work of a locomotive [but which] is without influence upon its machinery' (i.e that consciousness is an epiphenomena of neuronal computation). However, William James countered that 'Taking a purely naturalistic view of the matter, it seems reasonable to suppose that, unless consciousness served some useful purpose, it would not have been superadded to life' (quoted in: Richards, 1987, p. 433). More recently, Popper and Eccles argued that the mind, including consciousness, should be considered to be analogous to a bodily organ and that is 'the product of evolution by natural selection' (Popper and Eccles, 1977, p. 72). Similarly, I would echo Dobzhansky's assertion that 'In Biology nothing makes sense except in the light of evolution' and therefore, in common with other biological structures, consciousness exists today because it provided some advantage to our ancestors that was harnessed by natural selection.

Neurones in a complex brain display a range of excitability and in the busy brain of our ancestral animals there would have been many neurones poised close to their threshold potential with voltage-gated ion channels sensitive to small changes in the surrounding em field. No less than electrochemical interactions, those field interactions would have been subject to natural selection. Wherever field effects provided a selective advantage to the host, natural selection would have acted to enhance neurone sensitivity (e.g. by maintaining neurones close to firing potential, increasing myelination or orientating neurones in the field). Possible advantages of field-level processing are: (i) ability to instantly integrate information from very many neurones and identify the most significant signals that are phase-locked by their response to a common stimulus; (ii) capability to

induce long-term potentiation and thereby learning in neural networks connected by Hebbian synapses (see below); (iii) rapid (at speed of light) parallel transmission of information with minimal energy loss or heat generation; (iv) field-level information processing such as the ability to perform Fourier transforms and wavelet transforms, linear superpositions or Laplacians. Note that information technology already exploits the advantages of em information transmission in optical fibre communication. Efforts to design optical computers through, for instance, the use of Vertical Cavity Surface Emitting Laser arrays (VCSEL) to interconnect circuit boards and thereby exploit field-level information transfer and processing is also ongoing (Miller, 1997). MacLennan (1999) has recently argued that many mind processes may usefully be described as field-level computations. Conversely, wherever field influences were detrimental to the host (e.g. providing an em field ‘feed-back’ or ‘cross-talk’ that interfered with neuronal-level informational processing), natural selection would have acted to decrease that sensitivity (e.g. by maintaining neurones at membrane voltages close to resting). Therefore, with just the information that the brain’s em field influences informational processing (as I have shown it must) and thereby contributes (positively and negatively) to host survival, the theory of natural selection predicts that over millions of years a complex brain will evolve into an em field-sensitive system and a parallel em field-insensitive system. I propose these systems correspond to our conscious and unconscious minds.

I have shown here that synchronous firing amplifies em field effects by phase-locking em field modulations generated by distributed neurones. Modulations of the brain’s em field are thereby correlates of awareness and attention and, by implication, consciousness. There are two possible interpretations. First, in what might be called the *weak interpretation*, the brain’s em field is considered to be either an epiphenomenon of consciousness (reflecting its underlying dynamics but the real action taking place elsewhere), or a necessary, but not sufficient, condition for consciousness. For instance, the em field might be a portal or conduit for neural influences to reach consciousness.

However, in what might be termed the *strong interpretation* of the correlation between modulations of the brain’s em field and consciousness, the brain’s em field is proposed to be the substrate of consciousness. In this view synchronous firing correlates with consciousness because it is the most efficient means of transmitting neuronal level information to the conscious mind.

Conscious electromagnetic information field (cemi field) theory: Digital information within neurones is pooled and integrated to form an electromagnetic information field in the brain. Consciousness is the component of the brain’s electromagnetic information field that is transmitted to motor neurones and is thereby capable of communicating its state to the outside world.

This cemi field theory expands and further explores the *cem field theory* outlined in my book *Quantum Evolution* (McFadden, 2000) but the role of information is highlighted in the current cemi field theory. The theory also has much in common with Susan Pockett’s electromagnetic theory of consciousness

(Pockett, 2000), but differs in increased emphasis on the informational aspect of the field and in identifying consciousness with only that component of the brain's em field that is capable of downloading its information to motor neurones. I also provide in this paper a more detailed discussion of the implications of a field theory for the phenomenal aspects of consciousness.

That complex information can be encoded in electromagnetic fields is of course familiar: electromagnetic waves are routinely used to transmit information that is decoded by television or radio receivers. I propose here that our thoughts are similarly electromagnetic representations of neuronal information in the brain, and that information is in turn decoded by neurones to generate what we experience as purposeful actions or free will. This circular exchange of information between the neurones and the surrounding em field provides the 'self-referring loop' that many cognitive scientists have argued to be an essential feature of consciousness.

Although synchronous firing may promote the transfer of information from neurones to the brain's em field, it is important to note that synchrony and the magnitude of consequent em field perturbations may not always correlate with consciousness. The key issue is not synchrony (or em field magnitude) *per se* but the informational transfer via synchronous firing. An excessive degree of synchrony — as occurs for instance during epileptic seizures — may influence neurone firing (e.g. inducing fits) but will decrease the informational content of the cemi field and thereby interfere with any information processing required for conscious thinking. Similarly, although regular EEG oscillations represent high amplitude perturbations to the brain's em field, they contain very little information and may thereby correlate negatively with attention and awareness. The informational content of the cemi field is likely to be at a maximum whenever multiple clusters of relatively small number of synchronised neurones generate the electromagnetic fluctuations. Thus, the dynamic complexity of EEG signal, rather than its amplitude, may be a better correlate of conscious thinking, as has been found in some studies (Molle *et al.*, 1996).

This strong interpretation of the correlation between consciousness and em field perturbations in the brain — the cemi theory — is favoured here because it provides solutions to many of the most intractable problems of consciousness, which will now be discussed.

1. The difference between conscious and unconscious information processing

The cemi theory provides a realistic physical model that accounts for the subjective difference between conscious and unconscious mental processing. Although many theories of consciousness propose that conscious neural processes differ from unconscious ones in being in some way 'higher level' (see, e.g., Searle, 1992), it is not clear how these higher level conscious activities differ from the lower level unconscious one. The example of driving along a familiar route has been explored by many authors. Whilst driving home from work our conscious minds may be busy reviewing the events of the day whilst at the same time, we

are watching traffic, changing gear, following the road but are unaware of any of these operations. Yet if we encounter a hazardous situation — such as a child in the road — we instantly become aware of the child, the road, the motor operations of driving, and thereafter slow down to drive more carefully under conscious control. Our conscious mind seems to ‘take over’ the control of our body in these situations. It is unclear how in a neural identity model of consciousness, the neural circuits involved in directing the motor coordination responsible for driving the car consciously are ‘higher’ than those that perform essentially the same task without awareness. However, in the cemi field theory, the neural circuits involved in conscious and unconscious actions are proposed to differ in their sensitivity to the brain’s em field. During *unconscious* driving, the sensory and motor activity responsible for the driving the car would have been performed by neurones with membrane potentials far from the critical threshold for firing (either positively or negatively) and thereby insensitive to the brain’s em field. When new or unusual stimuli reach the brain (presence of child on road) the consequent synchronous firing of neurones involved in processing that new information would transmit the information to the brain’s em field, allowing it to reach our conscious awareness. This additional sensory input may shift the membrane potential of some of the neurones involved to near the firing threshold and thereby make the whole neuronal pathway sensitive to augmentation by the brain’s em field. Our conscious mind — the cemi field — does indeed take over. In the cemi field theory, our conscious ‘will’ is our experience of this influence of the cemi field — our conscious minds — on motor neurones. It is our subjective experience that we are only forced to make ‘conscious decisions’ whenever our unconscious mind is unable to ‘make up its mind’ as to what to do next. It is precisely in these situations (e.g. driving in a hazardous situation) when we would expect motor neurones to be poised close to their firing potential and sensitive to the relatively weak influence of the brain’s em field and thereby receptive to its informational content.

The divergence of the brain into an em field-insensitive system (our unconscious mind) and an em field-sensitive system (consciousness) accounts for why much of the brain’s em field activity is not conscious. Although all neurones generate em fields, natural selection has optimised the neurone firing capability and information-processing activity of only that fraction of the brain’s em field that has contributed positively to host survival. Those em fields that have not contributed to host survival would have been invisible to natural selection and thereby remained unstructured and unlikely to influence motor neurone firing patterns. Such (unconnected) em fields are incapable of transmitting information to the outside world and thereby represent unconscious brain em activity. Similarly, not all phases of brain em modulations will be conscious. For instance, consciousness will be associated with only the later phases of evoked responses (+250 msec), when em field disturbances have reached sufficient amplitude to influence neurone firing. Once again, the key to consciousness is not the presence of em fields, but their ability to transmit information to motor neurones. This influence is, I propose, the role that natural selection has harnessed in the

evolution of human consciousness — a field-level information processing system that drives our ‘free will’. Curiously, William James’ description of the role of consciousness a century ago fits exactly with this model (as summarized and quoted in Richards, 1987, p. 431): ‘The delicately balanced cortex of these animals has, in James’s terms, a “hair-trigger”: the slightest jar or accident could set it firing erratically. . . . Yet, “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 & at the same time inhibit those that threaten to lead astray, why, consciousness will be of invaluable service”.’ This aspect of the cemi theory also makes a simple and testable prediction — that conscious and unconscious actions differ in their sensitivity to the brain’s em field.

The cemi field theory also provides a natural explanation for how, in the words of Bernard J. Baars (1993), ‘a serial, integrated and very limited stream of consciousness emerge from a nervous system that is mostly unconscious, distributed, parallel and of enormous capacity’. First, although, as described above, the brain’s em field represents a wave-mechanical representation of the entire informational content of the brain, only a small proportion of this field information (the cemi field) can be transmitted to the outside world through motor neurones. The range of potential difference across neural membranes spans more than 150 mV but neurones are only sensitive to their local field potential if their membranes are poised close to the firing threshold. Consequently, most neurones are insensitive to the brain’s em field and most neural pathways operate without field effects. Only the information represented by neurones that fire in synchrony is likely to generate sufficiently large perturbations of the brain’s em field to influence nerve firing in a few sensitive neurones and thereby modulate behaviour. This reportable ‘stream of consciousness’ represents only a trickle of information from the brain’s em information field to the outside world and is therefore of only very limited capacity compared to the underlying neural activity.

Similarly, the cemi field theory accounts for why consciousness appears to be a ‘serial’ system mounted on a parallel unconscious system. It is well established that many unconscious actions (e.g. driving a car whilst whistling a familiar tune) may be performed in parallel without interference whereas tasks requiring conscious attention suffer from the dual-task problem whereby multiple tasks suffer mutual interference (in the above driving example, one would generally cease whistling after spotting a child on the road). It should first be noted that although consciousness is serial in the sense that multiple conscious tasks must be performed sequentially, each task might be quite complex requiring the co-ordinated (parallel) operation of many neural pathways that are likely to be guided by information processing distributed throughout the entire cemi field. Consciousness *per se* is therefore not incompatible with the operation of parallel neural pathways; it appears rather that it is the goal-directed influence of consciousness on those pathways that is subject to the kind of interference that is characteristic for serial systems. Unlike digital (neural) addition, summation of two fields is never simple but generates a linear superposition that depends on the phase relationships between the individual waves involved. Interference is

therefore inevitable for multiple conscious tasks where each task is ‘fined tuned’ through the influence of the cemi field.

2. The role of consciousness in memory

It is well established that conscious awareness or attention appears to a prerequisite to laying down long-term memories and for learning complex tasks (although unconscious or subliminal learning may be possible for some tasks), but the mechanism remains obscure. However, in the cemi field theory, memory and learning are inevitable consequences of conscious attention. As described above, the influence of the cemi field in the brain (consciousness) may provide a fine control over motor tasks — a small push or pull on the probability of neurone firing. However, if the target neurones for em augmentation are connected by Hebbian synapses then the influence of the brain’s em field will tend to become hard-wired into either increased (long-term potentiation, LTP) or decreased (long-term depression, LTD) neural connectivity. After repeated augmentation by the brain’s em field, conscious motor actions will become increasingly independent of em field influences. The motor activity will be ‘learned’ and may thereafter be performed unconsciously, without the em influence on the neural networks involved. Similarly, in the absence of any motor output, the cemi field may be involved in strengthening synapses to ‘hard-wire’ neurones and thereby lay down long-term memories.

Although I know of no data that clearly demonstrates a role for em field input into natural learning and memory, Aronsson and Liljenström have recently demonstrated (Aronsson and Liljenstrom, 2001) that non-synaptic neuronal interactions (that includes both em fields and gap junctions) may enhance learning in a simulated neural network. Also, modulation of both LTP and LTD by em fields has been demonstrated *in vitro* for rat hippocampal slices (Bawin *et al.*, 1984). Additionally, the strongest data for significant biological effects of non-ionising em radiation has been in measurements of long-term potentiation (Stewart, 2000; Wang *et al.*, 1996) and it is perhaps significant that one of the few well-controlled studies of the effects of microwave radiation on cognitive function in man concluded that there was a small but significant effect on learning (Preece *et al.*, 1999) with a reduction in reaction times for repeated tests in subjects exposed to the radiation. The proposed role of the cemi field in learning and memory is consistent with these observations and clearly amenable to further experimental testing.

3. The nature of free will

In the cemi field theory, the phenomenon we call ‘free will’ is our subjective experience of the influence of the cemi field on motor neurones. This influence contrasts with our unconscious (or unwilled) actions that lack that influence. However, the influence of the cemi field is entirely causal: every fluctuation in the local cemi field capable of modulating the firing of a particular target motor neurone will have been generated by changing patterns of electrical activity

within the underlying neurones responsible for inducing that field. In this view, our will — the cemi field influence on neuronal firing — is not ‘free’ in the sense of being an action without a physical cause. It is entirely deterministic (although it is possible to speculate that quantum-level fluctuations of the field may sometimes influence neurone firing and thereby provide a non-deterministic component to our will, such an influence would not correspond to any kind of ‘free will’ in the traditional sense of that term). Therefore, whereas in agreement with most modern cognitive theory, the cemi theory views conscious will as a deterministic influence on our actions, in contrast to most cognitive theories it does at least provide a physically active role for ‘will’ in driving our conscious actions. In the cemi field theory, we are not simply automatons that happen to be aware of our actions. Our awareness (the global cemi field) plays a causal role in determining our conscious actions.

4. The nature of qualia

As Chalmers has emphasized (Chalmers, 1995b), the ‘hard problem of consciousness’ is to understand why a particular organisation of matter in the brain should give rise to the phenomenal aspect (qualia) of consciousness or awareness. In the standard psycho-physical identity theory, consciousness is solely a property of functional organization of the brain and could in principle be realized in any physical system with the same functional organisation. In this view, an electronic brain having the same functional organisation of the brain would be conscious. But as Block pointed out (Block, 1991), the functional organization of neurones in the brain involved in smelling a rose could equally well be implemented within the population of China, but it is absurd to conclude that such a system would possess ‘any mental states at all — especially whether it has what philosophers have variously called “qualitative states,” “raw feels,” or “immediate phenomenological qualities”.’ This so-called ‘Absent Qualia’ problem has been further explored by Chalmers (1995a) in his ‘Fading Qualia’ scenario in which neurones in the brain are gradually replaced by silicon chips. Chalmers argues that if Absent Qualia are possible for an entirely electronic system that performs the same functions as neurones in the brain then a gradual loss of awareness — Fading Qualia — must pertain to a system in which biological neurones are gradually replaced with electronic devices. The implausibility of Fading Qualia leads Chalmers to conclude that neither Fading Qualia nor Absent Qualia are indeed possible and therefore support the version of psycho-physical identity theory he terms ‘nonreductive functionalism’.

To consider the nature of qualia within the cemi field theory, it is first useful to clarify what is meant by ‘awareness’. Chalmers (1995b) has proposed a ‘double-aspect’ theory of information in which information has two aspects, a physical and a phenomenal aspect. In the cemi field theory information in the brain is represented both within the distributed matter of neurones and also within the unified electromagnetic field of the brain. As with any field, all components of the brain’s em field are causally related, therefore the information in the cemi field

has the same level of unity as information held by a single photon or a single electron (say, orbiting an atomic nucleus) in quantum field theory; each may be described as a single field. In contrast, the information encoded by (classical) matter within neurones is not unified and in quantum mechanics would be described by independent wave functions. It is therefore only within the cemi field of the brain that information is physically unified (see also argument below concerning the binding problem) in a way that corresponds to the unity of awareness. I therefore propose that awareness corresponds to information held within the brain's em field. To put it another way, awareness is *what it is like* (Nagel, 1974) to integrate complex information into a physically unified field. In this view, awareness will be a property of any system in which information is integrated into an information field that is complex enough to encode representations of real objects in the outside world (such as a face). Awareness in this sense has much in common with what Ned Block terms 'phenomenal consciousness' (Block, 1995).

However, awareness *per se*, without any causal influence on the world, cannot have any scientific meaning since it cannot be the cause of any observable effects. In the cemi field theory, consciousness — the cemi field — is distinct from mere awareness in having a causal influence on the world by virtue of its ability to 'download' its informational content into motor neurones. It therefore corresponds quite closely to what Ned Block terms (Block, 1995) 'access consciousness'. How far animals or inanimate informational systems are conscious will depend on whether they possess complex information fields that are capable of having a causal influence on the world. This may well be amenable to experimental testing.

Since, in the cemi field theory, a conscious being is *aware* of the information contained within the cemi field, qualia — the subjective *feel* of particular mind states — must correspond to particular configurations of the cemi field. The qualia for the colour red will thereby correspond to the em field perturbations that are generated whenever our neurones are responding to red light in our visual field. However, since at the level of the brain's em field, sensory information may be combined with neuronal information acquired through learning, the ensuing field modulations would be expected to correlate not with the sensory stimuli alone, but with the *meaning* of particular stimuli. This was indeed what Freeman discovered in his classic experiments on rabbit olfaction (Freeman, 1991).

The integration of information into higher level perceptions within the cemi field is, I would argue, central to consciousness. A face is far more than a collection of features and, in a conscious mind, is perceived and handled — at the field level — as an integrated whole rather than a collection of parts. Nearly all qualia — the sound of C minor, the meaning of the number seven, the image of a triangle, the concept of a motor car, the feeling of anger, etc. — are similarly complex and their existence as conscious states is conditional upon our ability to integrate parallel information streams to form a model that is both complex and physically unified within the cemi field.

Fading Qualia are therefore possible in the cemi field theory. If neurones were to be gradually replaced by mechanical devices that perform the same neural-level information processing but do not generate any field-level integration of that information, then qualia would indeed fade as information is gradually lost from the cemi field. It follows that absent qualia are also possible in a system — a robot — in which the neural-level processing has been completely replaced by mechanical devices that exclude a field-level representation of that information. However, in contrast to Chalmers (1995a) I would argue that such a robot would not behave the same as a conscious person because it would lack the influence of the cemi field upon motor output — its brain would not be functionally equivalent to a human brain. All of the robot's actions would be unconscious — it would be an automaton without a conscious 'will' (as defined above). Since it is our conscious actions that make us characteristically human, such a robot, I would argue, would be clearly distinguishable from a person.

The cemi theory does however predict that artificial consciousness could be realized within a system in which an integrated information field was capable of driving motor actions. A robotic brain could therefore be constructed that is functionally equivalent to a human brain that would experience subjective qualia, if it incorporated a cemi field. It will however have a very different informational processing architecture than current electronic computers that are constructed to minimise field effects.

Similarly, the cemi field theory predicts an absence of qualia for the population of China (as in Ned Block's argument) if it were persuaded to simulate the functional organisation of the brain. In fact it can be argued that China's population already simulate that organisation. Each Chinese person exchanges information with many hundreds or thousands of other Chinese via vibrations in air (speech) together with messages encoded on paper, electronically and visually. The entire population of China is therefore engaged in processing huge amounts of information concerning the 'body' of China and its environment, that is functionally similar (if not equivalent) to that performed within a human brain. Yet there is of course no evidence of any 'higher-level consciousness' for the population of China and it would be preposterous to propose that there are any qualia associated with the entire Chinese nation. In the cemi field theory the absence of qualia is entirely explained because the information that is being exchanged within the Chinese population is discrete and scattered amongst the many carriers of information. There is no higher-level field representation where information is integrated to generate awareness.

5. The binding problem

As Valerie Hardcastle (1994) put it, 'given what we know about the segregated nature of the brain and the relative absence of multi-modal association areas in the cortex, how [do] conscious percepts become unified into single perceptual units?' Considering, as an example, the experience of a visualizing a complex scene. Information from the retina is processed by independent groups of

neurones in the retina and visual cortex specialised to detect, colour, orientation, movement, texture, shape, etc. These groups of neurones are located in distinct areas of the cortex so that the information describing each item is smeared over a large area of the visual cortex. As described above, there is considerable evidence that the neurones that recognize aspects of a single object that is the subject of selective attention, such as an apple, fire synchronously. At a neuronal level, the information representing the apple will therefore be represented as a particular pattern, or assembly, of (synchronous) neurone firing. The problem is to understand how the (simultaneous firing) of a cluster of physically separated neurones could give rise to the single unified sensation of seeing an apple. John Searle (1980) noted that neuronal-level information could be realized by ‘a sequence of water pipes, or a set of wind-machines’ and questioned whether the unity of perception could be maintained within a system connected by water or airflow. If not, what is special about electrochemical fluctuation travelling at 100 metres per second between neurones that is able to maintain that unity?

To illustrate the problem, consider two entirely independent neural networks (either biological or artificial): the first is able to recognize green objects, and the second is able to identify round objects. If an apple is presented to both networks then, in a neural identity theory of consciousness, each network would (if sufficiently complex) experience their own particular qualia for roundness or greenness. But now we add a wire (or neurone) that connects the two networks so that the combined assembly is able to recognize objects that are both round and green. A neural identity theory would then predict that the enlarged network should experience qualia in which roundness and greenness are somehow bound together in a way analogous to our own conscious perception of an apple. Yet the only additional input that either network would have received is a single binary digit travelling down the connecting wire from the adjacent network. Neither ‘roundness’ nor ‘greenness’ could be fully described by a single binary digit. To account for the existence of unified qualia that includes the information coming from both networks, the neural identity theory must propose some overarching reality that connects and unifies the two networks. But no such overarching reality exists — at least at the level of matter. Each network is composed of discrete lumps of matter (atoms and molecules) that are isolated within each network (except for their em field interactions). The vast majority of the matter within one network cannot possibly be even ‘aware’ (possess information) of the existence of the other network.

But in the human brain, there is an overarching reality that connects neural networks: the brain’s electromagnetic field. At the field level, and in contrast to the neuronal level, all aspects of the information representing the apple (colour, shape, texture etc.) are physically linked to generate a single physically unified and coherent modulation of cemi field that represents conscious perception.

At the neuronal level, information in the brain is scattered both in space and time; but at the level of the em field information is physically unified with zero time between all the components of that information. The cemi field thereby corresponds to our subjective experience of being aware of all items in our

conscious minds at the same instant of time — there appears to be zero time between all of the contents of consciousness. The cemi field therefore provides a natural solution to the binding problem of consciousness.

The cemi field theory is compatible with many contemporary theories of consciousness. The cemi field can be considered to be a global workspace (Baars, 1988) that distributes information to the huge number of parallel unconscious neural processors that form the rest of the brain. Similarly, the brain's em field may be considered to be the substrate for Dennett's multiple drafts model (Dennett, 1991) since its informational content will be continually updated by neuronal input until a field configuration is reached that is capable of generating 'output' that is downloaded as motor actions or the laying down of memories. The theory also has much in common with quantum models of consciousness (Penrose, 1995) since both propose a field-level description of consciousness. However in contrast to quantum consciousness models that must propose a physically unrealistic level of quantum coherence between neurones or microtubules within neurones, the cemi field theory has no such requirement. The wave-mechanical properties of the cemi field are entirely consistent with conventional physics and our current knowledge of neurophysiology.

The cemi field theory therefore provides an elegant solution to many of the most intractable problems of consciousness and places consciousness within a secure physical framework that is amenable to experimental testing. The proposed interaction between the cemi field and neuronal pathways restores to the mind a measure of dualism, but it is a dualism rooted in the real physical distinction between matter and energy, rather than the metaphysical (Cartesian) distinction between matter and soul. Although the cemi field *will* is deterministic, it does at least retain a crucial role for our conscious minds in directing purposeful actions. Consciousness is not a steam whistle. As a wave-mechanical driver of *free* will, it may be the key evolutionary capability that was acquired by the human mind.

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Paper received January 2001, revised January 2002