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Are Virtual Photons the Elementary Carriers of Consciousness?

Abstract: *Based on neurobiological data, modern concepts of self-organization and a careful rationale, the hypothesis is put forward that the fleeting, highly ordered patterns of electric and/or magnetic fields, generated by assemblies of dendritic trees of specialized neuronal networks, should be thought of as the end-product of chaotic, dynamically governed self-organization. Such patterns encode for subjective (conscious) experiences such as pain and pleasure, or perceiving colours. Because by quantum mechanical definition virtual photons are the theoretical constituents of electric and magnetic fields, the former hypothesis can be re-formulated as follows: it is the highly ordered patterns of virtual photons that encode for subjective (conscious) experiences. Arguments are then given that consciousness did not emerge during evolution only after neuronal networks had been formed able to generate electric and/or magnetic fields of sufficient complexity but, rather, that subjectivity already existed in a very elementary form as a fundamental property of the omnipresent virtual photons, i.e., of matter. The contribution of neuronal networks to consciousness was to generate highly ordered patterns of germs of subjectivity (virtual photons), so allowing complex subjective (conscious) experiences. Due to the omnipresence of virtual photons, it follows finally that the whole universe must be imbued with subjectivity. An experimental strategy is proposed to test the hypothesis.*

key words: consciousness, brain, electric fields, magnetic fields, virtual photons.

I: Introduction

One of the main targets of cognitive neurobiology is to reveal those processes in the brain that can be denoted as the ultimate material substrate underlying psychic functioning. This raises the question as to which part of the patterned electro-chemical activity of the twenty billion nerve cells in our cerebral cortex elicits subjective (conscious) experiences such as pleasure, pain, fear, hearing

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sounds or seeing colors. Or put differently, what is the ultimate material substrate that most strictly correlates with subjective (conscious) experience and, as Searle states (Searle 2000), is both causally necessary and sufficient? To answer this question, I will start by giving my definition of a subjective (conscious) experience, followed by an analysis of relevant information on neurobiology and physics. On this basis a working hypothesis will be formulated.

Experimental evidence from electroencephalography (EEG) and modern scanning techniques, such as positron emission tomography (PET), functional magnetic resonance imaging (fMRI) and magnetoencephalography (MEG), has demonstrated the existence of a close correlation between the functioning of nerve cells in our cerebral cortex, on the one hand, and the corresponding subjective experiences on the other (Raichle, 1998; Schacter et al., 1998; Frith et al. 1999). An everyday example is dream sleep. Its objective features are, as a result of underlying neuronal activity, a characteristic EEG pattern accompanied by rapid-eye-movements, whereas its subjective features are quasi-hallucinatory in nature. The objective features can be studied in an *objective-instrumental* way in a controlled laboratory setting, whereas this is impossible for the subjective features. A subjective feature is a private experience which can only be studied in a *subjective-introspective* way by the individual him/herself or, indirectly, by interviewing a volunteer about his or her experience or interpreting his or her behavior in the light of a tacit assumption that others are like oneself. Put differently, subjective features have a first-person ontology whereas objective features have a third-person ontology.

Based on a careful comparison of the various features of objectivity versus subjectivity (Romijn, 1997), I have taken the view that: (i) subjective experiences are, for the person who has them, just as real as the corresponding objective properties (e.g. the recorded electro-chemical activities) are for the external investigator; (ii) subjective experiences and the corresponding objective properties are two fundamentally different manifestations of one and the same underlying, physically not yet understood, deeper reality; they cannot be reduced to each other nor interact with each other. I would like to reserve the term consciousness for those subjective experiences that, as a result of attention, have expanded to a certain degree of complexity such that they contain an aspect of time (when?), space (where?), and/or self (it is me who is aware of) (see for arguments (Romijn, 1997).

II: Neurobiological Data

1. *Synaptic transmission*

In the following sections, I will give a brief account of the main neurobiological processes typically found in a functioning neuronal network and evidently correlated with conscious experience. This information will provide a basis for deciding which neurobiological processes can be denoted as the ultimate material substrate underlying subjective (conscious) experience.

Almost all of our bodily cells have an electrical potential across their cell membrane which roughly varies between 20-80 mV (inside negative). This so-called resting potential is mainly due to the activity of a metabolic Na^+/K^+ pump in combination with different membrane permeabilities for different ions. During evolution, nerve cells chose the membrane potential as a crucial element in the development of a unique system for the transport and integration of information (Fig. 1). Generally stated, transport of information is realized by means of short-term depolarizations of the membrane potential (action potentials) generated at the beginning of a long axon and subsequently propagated with a *constant* amplitude along that axon to other nerve cells upon which the axon makes synaptic contacts. Integration of information occurs along the dendritic tree of a nerve cell upon which hundreds of axons, derived from other neurons, make synaptic contacts. If an action potential arrives at a dendritic synapse this results, depending the chemical nature of the synapse, in a local depolarization or hyperpolarization of the resting membrane potential. As a result of such a local synaptic depolarization

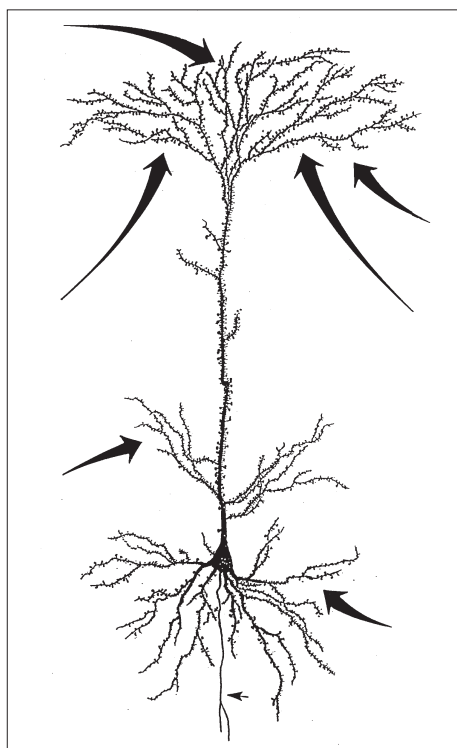


Figure 1. Schematic drawing of a Golgi-stained cortical pyramidal neuron. Observe the short branched basal dendrite (on the lower side) and the long upward-coursing apical dendrite mainly branching at its terminal region (on the upper side). Almost all dendrites are studded with spines. A relatively thin downward-coursing axon leaves the cell body at the bottom (short arrow). The thick curved arrows symbolize the afferent axons making many hundreds to thousands of synaptic contacts on the shaft and spines of the dendritic arbor.

(excitatory postsynaptic potential) or hyperpolarization (inhibitory postsynaptic potential), a transient electric field emerges between the de- or hyperpolarized membrane patch and the remaining dendrite, both on the in- and outside of the membrane where the intra- and extracellular fluid has a relatively low electrical resistance (Fig. 2). Generally speaking, a synaptic de- or hyperpolarization spreads in a passive, *decremental* way in both directions over a dendrite and splits at bifurcations. The latter implies that a synaptic signal is, to a greater or lesser extent, noticed everywhere on the dendritic tree. However, proportionally a greater part of the electric field will flow towards the thicker proximal parts of the dendritic tree (including the neuronal cell body) than towards the thinner distal parts, because the thicker the dendrite the lower its inner electrical resistance. Thus, the cell body and the axon hillock normally 'suck' a good deal of the current away. Moreover, excitable ion channels may be present along the dendrite

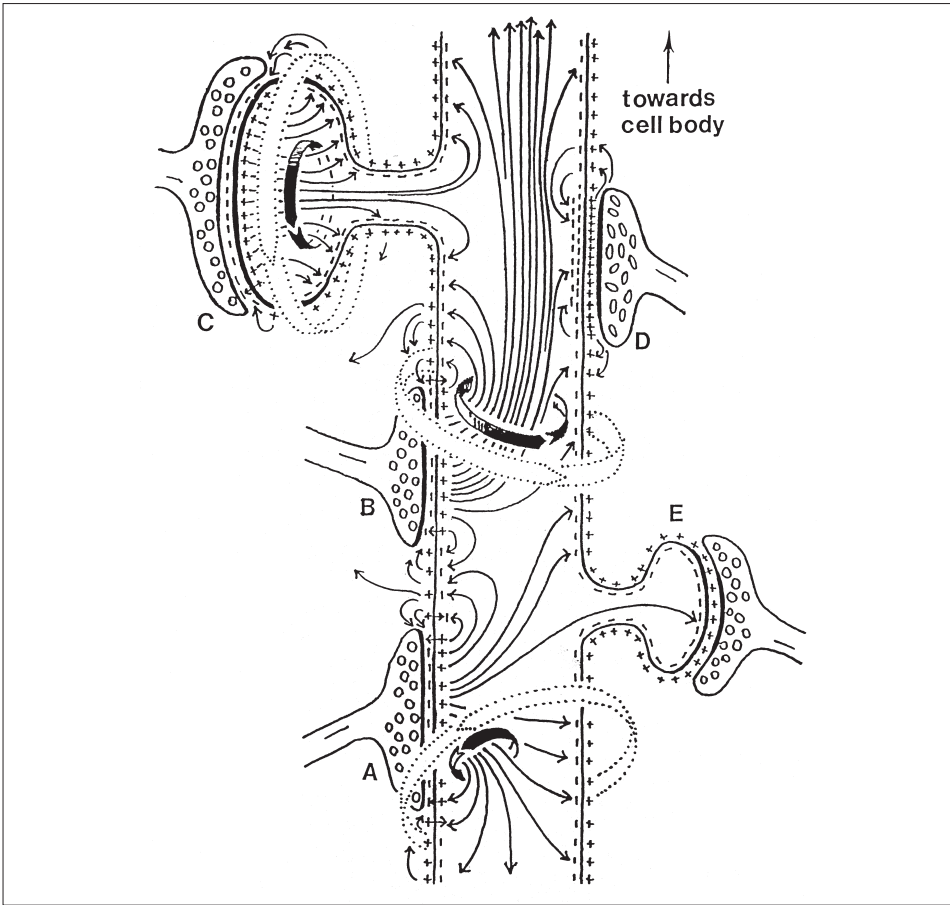


Figure 2. Schematic picture of charge distribution and the concomitant electric fields (depicted by lines of force) within a small part of a dendrite with two active excitatory shaft synapses (A and B), one active excitatory spine synapse (C), one active inhibitory shaft synapse (D) and one non-active spine-synapse (E). Because the cell membrane has a thickness of about 9–10 nm and its transmembrane resting potential is about -70 mV (which corresponds with $-70,000$ V/cm), it forms a dielectric causing an accumulation of negatively charged ions adjacent to its inside and positively charged ions adjacent to its outside. This 'triple layer' therefore possesses a certain electrical capacitance in addition to an electrical resistance.

Observe that part of the electric field emanating from (A) is repulsed by that from (B), while another part is sucked away by spine (E). As a consequence, the electric field emanating from (A) will not reach the cell body and the initial axon segment but, on the other hand, pushes the greater part of the electric field arising from (B) into that direction. Note, moreover, that only a small part of the electric field from (C) leaves the spine stem. The thick circular arrows indicate the direction of the lines of force of the *magnetic fields* at two arbitrarily chosen spots on the inside of the dendrite and in the active spine synapse (C). These magnetic fields are generated as a result of the changing electric fields and the movements of ions (ionic fluxes) in the cytoplasm. They are able to pass the polarized dendritic membrane (as indicated by the dotted circular arrows). No example is given of magnetic fields generated within the thin dendritic membranes or on their outside since these fields disappear for the greater part by dispersion and mutual cancellation. Bear in mind that this scheme is very simplified: the real pattern is much more complex and, moreover, continuously varies on a (sub)millisecond time-scale under the bombardment of synaptic activity. (For the sake of clarity, in a permanent electric field the magnetic aspects of the virtual photons mutually cancel each other out, thus only leaving the electric aspects; the magnetic aspects are merely revealed by a *change* of the electric field. The same principle holds for a permanent magnetic field.)

causing synaptic depolarizations to be actively propagated, hence with minimal decrement, towards the cell body. In this manner, hundreds of synaptic de- and hyperpolarizations per second are continually generated along the dendritic arbor of a neuron to give rise to a confluent merger of electric fields. And it is this composite electric field that, in its turn, will occasionally depolarize the membrane potential at the axon hillock of the nerve cell body to such an extent that one or more action potentials are generated and sent off to other nerve cells (Dowling, 1992; Lopes da Silva, 1996).

2. *Electric and magnetic fields*

Synaptic de- and hyperpolarizations along the dendritic tree not only entail the generation of transient *electric fields* but also of transient *magnetic fields* (Fig. 2). These transient magnetic fields are generated in two ways. First, a changing electric field generates a changing magnetic field, the magnetic lines of force of which stand perpendicular to the lines of force of the electric field. Second, a changing electric field makes the hydrated ions present in the intra- and extracellular space (Na^+ , K^+ , Cl^- , Ca^{++} , HCO_3^- and HPO_4^-) move along its lines of force and this movement (flux) of electrically charged particles (ion currents) subsequently causes the generation of a magnetic field too. Because the lines of force of both magnetic fields point in the same direction, they coincide. It has been calculated, furthermore, that the contribution of ion currents and changing electric fields in the extracellular space and across the dendritic membrane to the formation of measurable extracellular magnetic fields is negligible due to processes such as dispersion and mutual cancellation (Romani, 1989; Wikswo, 1989). Thus, what is finally measured at the outside of the skull by MEG are mainly magnetic fields generated *inside* of synchronously activated dendrites, situated along the inner regions of the cortical sulci, and which have passed through the cytoplasm and polarized membranes of surrounding glial and nerve cells (Hämäläinen et al., 1993). In contrast, polarized dendritic and glial membranes show a substantially lower permeability to electric fields, which implies that the electric fields generated on the in- and outside of dendrites will be largely confined to their compartments of origin, i.e., the capriciously shaped intracellular and extracellular space, respectively. In humans, therefore, the EEG can be considered to reflect electric fields generated mainly on the *outside* of synchronously activated dendrites situated along the outer regions of the cortical gyri just under the skull (Williamson & Kaufman, 1990; Näätänen et al., 1994; Lopes da Silva, 1996; Hari & Salmelin, 1997). Basically, two different groups of *virtual* photons make up these electric and magnetic fields: one group predominantly showing its electric aspect while the other reveals mainly its magnetic one. These electric and magnetic fields must be distinguished from the self-propagating *electro-magnetic waves* which are formed by *real* photons equally showing their electric and magnetic aspect and, as such, are carriers of, e.g., light, radio and TV signals (for more details see a special section on virtual photons further on).

3. Mechanisms of dendritic integration

Experimental research has shown that the dendritic tree of a neuron uses several mechanisms to modulate and process the different streams of information which continually enter its branches in the form of synaptic de- and hyperpolarizations. At the level of the synapse, for example, most, if not all, nerve endings contain two or more different neurotransmitters which can be differentially released depending on the frequency pattern of action potentials arriving at the ending (Salter & De Koninck, 1999). At the postsynaptic membrane, numerous receptor subtypes, differentially sensitive to one single neurotransmitter and directly or indirectly coupled to ion-channels, have been found clustered into complex spatial patterns. Some of these receptors have a short-term action over a time course of a few milliseconds (subserving the transmission of high-frequency, time-coded information), others exert long-term-effects over periods of seconds or minutes. The time a transmitter can exert its task in the synaptic cleft is modulated by catabolic enzymes, by transmitter-specific re-uptake mechanisms present in the pre- and postsynaptic membrane, and by diffusion out of the cleft. Via so-called allosteric interaction, receptors can modulate each other's efficacy. Outside the synaptic cleft, the extracellular fluid contains slowly fluctuating, relatively low concentrations of ions, neurotransmitters, hormones and other messengers which presumably exert subtle, tonic effects on large groups of neurons and glial cells. This so-called *volume transmission* would enhance interneuronal connectivity and probably exert a synchronizing effect on neuronal activities (Zoli et al., 1998). Such a synchronizing effect can also be brought about by *compound* electric and magnetic fields propagating across the neuronal network (Griffin, 1994). Experimental and computational studies have demonstrated, furthermore, that the dendritic tree possesses mechanisms to detect on a millisecond scale, the correlation (coincidence) of individual discharges of spatially separate synapses (Softky, 1994; König et al., 1996; Markram et al., 1997). Mechanisms for amplifying the signal-to-noise ratio have also been found. Long-term potentiation and depression of synaptic transmission are special forms of such a fine-tuning, which are based on alterations at the level of receptors, transmitter release, reuptake mechanisms and/or ion-channels (for a review, see Maren & Baudry, 1995).

4. Spines

A special function is fulfilled by spines (Fig. 1 and 2), the tiny protrusions of the dendritic membrane which form the postsynaptic contact sites for more than 80% of all excitatory synapses in the cortex (Andersen & Figenschou Soleng, 1999). Because the extracellular space of a neural network amounts to about 20% of its total volume (Zoli et al., 1998), spines have sufficient space to change their shape on a (milli)second time-base, resulting in a rapidly decreased or increased conductance of inflowing information to the underlying dendrite (Rusakov et al., 1996; Fischer et al., 1998; Andersen & Figenschou Soleng, 1999; Smith, 1999). Spines are therefore considered to act as key-units of dendritic integration.

2.5. *Feed back and mutual interaction*

Protein molecules making up ion-channels, receptors and enzymes, bear several electrically charged groups which are held together by intramolecular polar bonds, intermolecular dipole-dipole interactions and Van der Waals forces. Since these binding forces are electrostatic in nature, they play an important role in determining the tertiary structure and, therefore, the physico-chemical properties of these conglomerates. The consequence is that the functional state of ion channels, receptors and enzymes distributed along a dendrite incessantly fluctuates as a result of the continually changing merger of electric fields generated by synaptic activity along that dendrite (Fröhlich, 1975; Azanza & Del Moral, 1994; Blank, 1995; Goodman et al., 1995; Hong, 1995). In addition dendritic properties are affected by the firing of the neuron itself since action potentials, generated at the axon hillock, are to a greater or lesser extent actively (via excitable ion channels) back-propagated as a decremental wave into the dendritic arborization (Stuart et al., 1997).

Furthermore experimental indications have been obtained that, by lateral electrodiffusion within the dendritic membrane (cell membranes are not rigid but rather fluid), the spatial distribution pattern of postsynaptic receptors and ion-channels continually changes (clustering vs. dispersion) in a non-linear way due to the synaptically induced electric fields (Savtchenko et al., 2000). Finally, the electro-chemical properties of a dendrite will also be affected, albeit to a much lesser extent, by electric and magnetic fields radiating from neighboring (bundles of) dendrites (Griffin, 1994). As a result of these feedback mechanisms and mutual interaction, the processing of an individual synaptic signal by a dendrite is strongly dependent on the electrochemical state of that dendrite (and surrounding dendrites) at that particular moment. Thus, the electro-chemical properties of dendrites, on the one hand, and the generated electric and magnetic fields, on the other, form *an integrated whole*, which means that dendrites are very complex units of integration (Koch, 1997; Frégnac, 1998; Galarreta & Hestrin, 1998; Segev & Rall, 1998; Magee, 2000).

I hope that this brief survey has made clear that the dendritic tree possesses an almost infinite spectrum of possibilities to *rapidly and optimally tune its integrative properties to the varying character of inflowing information* that continuously arrives on its surface via hundreds of synaptic de- and hyperpolarizations per second. Integration of these information streams finally results in a profile of highly ordered electric and magnetic fields, characterized by thousands of rapidly changing 'sinks' and 'sources' that spread over the inside and outside of the dendritic arbor. One should realize that the pattern of lines of force of such a composite of electric and magnetic fields is very complex and that such a pattern continuously changes its three-dimensional structure, expanding and contracting, intensifying and attenuating, closely attuned to the ever changing stream of information entering the dendritic tree. And all this happens on a time-space scale of milliseconds and micrometers, respectively.

III: Which Brain Process Underlies Subjective Experiences?

We now arrive at the key-question posed at the beginning of this article: Which part of the patterned electro-chemical activity of the many billions of nerve cells in our brain, particularly those in the cerebral cortex, can be denoted as the ultimate material substrate underlying subjective (conscious) experience? To answer this question we will analyze five relevant processes in the functioning brain: (i) the frequency- and interval-coded trains of action potentials actively propagated with a constant amplitude along afferent axons, (ii) the transient accumulations of synaptically released transmitter molecules from axon endings into the synaptic clefts of synapses situated along the dendritic trees of neurons, (iii) the transient shifts of ions via special ion-channels situated in the postsynaptic membrane patches of the dendritic tree resulting in local depolarizations and hyperpolarizations of the resting membrane potential, (iv) the electric and magnetic fields generated by these local de- and hyperpolarizations along the inside and outside of the capriciously branched dendritic trees, (v) the frequency- and interval-coded train of action potentials along efferent axons conveying the final outcome of previous dendritic integration processes to other nerve cells.

If we consider each of these processes in relation to the probability that they underlie subjective (conscious) experience, it is self-evident that the processes mentioned under (i) and (v) cannot be serious candidates. The pattern of action potentials generated at the axon hillock of spatially separated neuronal cell bodies (the firing pattern) is but a very meager and distorted derivative of all integrative processes that take place along the upstream dendritic tree and remains so after the action potentials have been sent off along the axons. Moreover, since the function of axons is only to transport information from one neuronal cell body to another, individual axons in axon bundles are largely mutually isolated to minimize cross-talk and, thus, integration (Dowling, 1992).

The processes mentioned under (ii) and (iii) are improbable candidates too, because of the following three arguments. First, it is hardly conceivable that local accumulations of synaptically released transmitter molecules, shifts of ions or subsequent de- and hyperpolarizations, all separated in time and space, can give rise to *holistic subjective* experiences, particularly when the arbitrary nature of the type of neurotransmitters and ions involved is taken into account. Second, there exists a great deal of individual variability with respect to the anatomy and histology of our brain, the profile of neurotransmitter levels, the pattern of blood-vessels traversing the neural network etc. whereas most people still perceive, think and move in more or less the same way. This becomes particularly obvious when, as a result of compensatory reactions to local brain damage before birth, the function of an affected cortical region has been taken over more or less by other cortical regions (Lewin, 1980). Thus, there is little accord between the high variability of cortical 'hardware' between individuals, on the one hand, and the high similarity of basic psychic functioning, on the other. Third, it has been found that synaptic transmission of a frequency- or interval-coded message via a

synaptic contact on a dendrite is far from accurate. Each time an action potential arrives at a nerve ending, it is a matter of probability (roughly ranging between 30 and 80 %, depending on the type of synapse) as to whether a synaptic vesicle will be released, a receptor-linked ion-channel opened, and a de- or hyperpolarization of the postsynaptic membrane induced (Auger et al., 1998; Shadlen & Newsome, 1998). This inaccuracy is known to be solved by the nervous system by applying the principle of averaging, i.e., by using more than one axon and concomitant synaptic contacts to transmit the same message onto the same dendrite, as well as by using assemblies of neurons doing the same job (Dowling, 1992). However, averaging makes sense only if the end-product of such an averaging process, the mean, is somehow *actualized*. It is self-evident that such an averaging process can not be achieved by the individual synaptic processes as mentioned under (ii) and (iii). Taken together with both former arguments, it is unlikely that these processes are the ultimate material substrate of psychic functioning.

The above-mentioned objections are absent with the last candidate (iv): the patterns of electric and magnetic fields generated along the inside and outside of the dendritic tree. At this level, the different streams of information, arriving as discrete trains of action potentials at the hundreds of separate synaptic contacts along the dendrite, become converted to a confluent pattern of electric and magnetic fields. It can readily be understood now how, during this conversion process, the dendrite tree with the aid of its wide spectrum of integrative capabilities (see before), is able to largely eliminate the *individual variation* of dendritic hardware, to smooth out the *fragmented* character of inflowing information, and to average out the *inaccuracies* of synaptic transmission. With other words, electric and magnetic fields could be formed which are, to a certain extend, *invariant* with respect to these three constrains. Because of the relatively small size and extremely short half-life of their constituents, i.e., virtual photons, electric and magnetic fields form an optimal material substrate to be flexibly sculptured to highly ordered, continually changing 4-dimensional (space and time) patterns of 'sources and sinks' accurately reflecting synaptically driven de- and hyperpolarizations caused by inflowing information. The above rationale thus points to the *electric and/or magnetic fields as the most plausible candidate out of a number of options to function as the ultimate material substrate underlying subjective (conscious) experiences*.

The following data lend extra support to the above-mentioned option. By means of EEG analysis during various forms of mental activity, Lehmann and co-workers (Lehmann et al., 1998) arrived at the conclusion that changes in the spatial configuration of EEG fields across the cortex are discontinuous. The near-stable field configurations, which differ depending on the nature of mental activity - e.g., visual imagery vs. abstract thinking -, last about 120 msec, which is the minimum time apparently required for a unitary conscious experience (the mean duration of 120 msec of such a microstate is within the time range of 100 msec postulated by Newell (1992), but shorter than the 500 msec reported by Libet (1985)). The researchers concluded that the stream of consciousness

actually consists of a sequence of discernible microstates of the electric fields (see also Zeki and Bartels, 1998). Thus, a certain electric field configuration in the cerebral cortex would have to remain more or less stable for some minimal time in order to become experienced subjectively. This may also explain why a visual stimulus of too short a duration (Velmans, 1991) or too low an intensity (Roelfsema et al., 1998; Gulyás, 1999) only leads to unconscious (subliminal) perception. (N.B. In view of the close relationship between electric and magnetic fields, semi-stable field configurations can also be expected to exist for the MEG). These experimental findings lend extra support to my above-mentioned option that the electric and/or magnetic fields function as the ultimate material substrate of cognitive functioning.

In summary, it is not so much the number of neurons, the precise shape of dendritic trees or the accurate position of synapses, nor the firing of individual neurons or functioning of local synapses that is crucial, but rather whether the derivative, i.e., the fleeting electric and/or magnetic fields generated along the dendritic trees are shaped as optimally as possible to short-lasting, meaningful patterns. Thus, (human) brains can be metaphorically viewed as orchestras of different composition and size trying to perform in a comparable manner the same symphony of Beethoven.

IV: Self-organization

Self-organization can be thought of as a key property of matter by which individual material elements in an assembly spontaneously start to interact with each other and behave in a coherent and cooperative way to finally result in the formation of larger and more complex, stable structures which show emergent properties not possessed by the individual elements. This process is based on the electro-chemical properties of the individual elements and some environmental conditions, such as temperature and energy supply, while the process is governed by deterministic chaotic, non-linear dynamics (Mainzer, 1994; Kauffman, 1995; Kelso, 1995; Gaspard et al., 1998). The complex structures that are formed can be thought of as *meta-stable, oscillating, low-energy preference patterns* to which the dynamic system is attracted. Such systems are very sensitive to influences (information) from outside, which has the consequence that their oscillating patterns easily adapt to a greater or lesser extent to any environmental change, returning again to the original state as soon as the stimulus has disappeared. However, if one or more of the environmental influences pushes the system beyond a critical level, it can jump to a different meta-stable preference pattern. Such phase-transitions can occur repeatedly.

Self-organization is ubiquitous in non-living and living nature. It is even proposed that self-organization characterizes the universe on every scale, from the cosmos as a whole through to the smallest component structure (Smolin, 1997). Examples are the formation of whirlpools in a river, the Belousov-Zhabotinsky reaction, which shows the formation of oscillating, colored ring-shaped structures in a relatively simple, inorganic chemical mixture (Field, 1972), and, of

course, all living systems. It is not surprising, therefore, that the formation and functioning of neuronal networks in the cerebral cortex also comes about by self-organization and that the time-spatial patterns of the electric and magnetic fields as detected by EEG and MEG analysis are characterized by non-linear, chaotic dynamics (Kowalik & Elbert, 1994; Freeman, 1995; Hoshino et al., 1996; Lopes da Silva, 1996; Wright & Liley, 1996; Accardo et al., 1997; Rabinovich & Abarbanel, 1998; Anokhin et al., 1999; Mölle et al., 1999). This finding is crucial because the EEG and MEG are, indeed, a direct reflection of the electric and magnetic fields generated by balanced excitatory and inhibitory activity along bundles of dendrites in the cerebral cortex. Although generated by millions of individual dendritic trees, the process of self-organization causes the formation of ever larger and more complex composites via resonance and nesting.

Because of their highly volatile character and extreme sensitivity to minute influences, these electric and magnetic fields can rapidly take an almost infinite number of different, meta-stable configurations as a result of the fluctuating input from the inside (memory) and outside (sensory stimuli) and, thus, give rise to the almost infinitely varying stream of feelings and thoughts (Sakai & Miyashita, 1994; Tononi et al., 1994). Thus, also considered from the perspective of chaotic dynamics, the dendritic electric and magnetic fields are plausible candidates to function as the ultimate material substrate underlying the fleeting stream of thoughts and feelings during psychic functioning. Since the same conclusion was already drawn on the basis of more conventional neurobiological arguments (former section), the following hypothesis can be put forward:

Hypothesis (1a): *The fleeting, highly ordered 4-dimensional (space and time) patterns of the electric and/or magnetic fields generated by assemblies of information processing dendritic trees of a specialized (e.g., cortical) neuronal network, should be thought of as the final product of chaotic, dynamically governed self-organization. These patterned electric and/or magnetic fields encode for subjective (conscious) experiences such as pain and pleasure, or seeing the colors red, yellow and blue etc.*

One should keep in mind that, as a consequence of evolutionary specialization, not only did dendritic networks develop that generated the electric and magnetic fields underlying subjective experiences, but also networks fulfilling quite different functions entailing minimal subjectivity, if any at all. For example, sensory information, before coming to conscious experience in the cerebral cortex, has to be processed in subcortical dendritic networks where consciousness is generally assumed to be absent. Sometimes an adequate motor reaction can even be elicited (reflex) before the stimulus in question is consciously sensed. And in the opposite direction, a conscious cortical command leading, for example, to a coordinated movement of our hand has first to be processed at a subcortical and spinal level before it can eventually stimulate in a balanced way the appropriate muscles. Likewise unconscious information processing plays an important role

in speaking and reading, or if one tries to remember something. It also forms the basis of our unconscious mental life (Romijn, 1997).

Actually, conscious experience is only possible if, neurophysiologically, two conditions are fulfilled. First of all, the basic activity level of the cerebral cortex has to be brought to a *wakeful* state by several ascending activating processes mainly originating in the brain stem, as was originally discovered by Moruzzi and Magoun in the forties. During such a wakeful state, the cortical EEG predominantly shows beta-activity (minimally synchronized neuronal activity leading to fast, low-voltage activity of >12 Hz), which reflects the processing of information originating from the external and internal world. In the second place, cortical activity is consciously experienced only if it is selected to be the focus of *attention*, i.e. is intensified, synchronized and modulated so that its pattern attains the level of consciousness. It is still a matter of debate, however, whether the latter process is caused by a special circuit (locus) in each hemisphere, functioning like a 'searchlight' (Crick, 1984; Crick 1999 in Bogen, 2000; Bogen, 2000) or by a self-reinforcing process raising part of ongoing cortical activity to a sufficiently high level of complexity (Tononi & Edelman, 1998). Additionally, there is no agreement yet as to whether or not a person has to be already conscious before a certain experience can pop up. In the first case, a conscious experience should be considered then as a modification of an already present unified conscious field in the person's cerebral cortex. In the opposite case, a certain conscious experience is believed to be made up of various small building blocks (colors, shapes, sounds etc.) which are individually brought to consciousness, whereafter these 'micro-consciousnesses' are subsequently unified by a binding process to one coherent conscious field (see for an elaborate discussion Searle, 2000). Whatever the mechanism, it is certain that only a tiny part of ongoing unconscious information processing is continually 'boosted up' to special activity patterns in the cerebral cortex to form the stream of conscious experience.

During a state of dreamless sleep, in contrast, the cortical EEG is characterized by slow-wave activity (strongly synchronized neuronal activity leading to slow, high-voltage oscillations of <4 Hz) assumed not to support information processing but instead the metabolic recovery processes of the neuronal network. In summary, it is not the electric and/or magnetic fields as such but the special *patterns* of the electric and/or magnetic fields generated by assemblies of information processing dendritic trees (in mammals mainly in the cerebral cortex) which give rise to conscious experience (for more data see Kinney and Samuels, 1994; Romijn, 1997).

It is plausible, moreover, that in higher non-mammalian species which lack a distinct cerebral cortex, other brain parts (such as the hypothalamus, striatum, and/or amygdala, assigned as subcortical in mammals) function as a substratum underlying subjective experience. During evolution various functions (such as hearing and seeing) largely 'moved' to the developing cerebral cortex but this hardly happened, if at all, with respect to such basic feelings as pain, pleasure, hunger, thirst, and emotions. It is not unlikely, therefore, that some lower brain parts in mammals, including humans, still generate some basic subjective

experiences which just expand then to full-blown conscious experiences after having been passed on to the cerebral cortex (see e.g. Damasio, 1994, and also a special section on evolution further on).

V: Which Part of the Electric and/or Magnetic Fields?

As to the question whether it is the electric or the magnetic field, or both together, which carry the code for subjective (conscious) experiences, no answer can yet be given because of the lack of pertinent data. Only two remarks will be made here. First, in contrast to electric fields, magnetic fields easily penetrate the polarized membranes of surrounding tissue. This will lead to mutual interaction (repellence or attraction) between individual magnetic fields of (bundles of) activated dendrites and, thus, to the formation of complex patterns of ‘cross talk’ which might well be a critical feature for subjective experience. Second, the further an electric or magnetic field extends from its dendrite of origin, the more will its detailed 4-dimensional (space and time) configuration — which can initially be considered to accurately reflect local, synaptically driven de- and hyper-polarizations — smooth away in detail and field force. This effect is particularly extreme at the outside of the skull and logically triggers the question as to whether the extracranial portion of the electric and/or magnetic fields (underlying the EEG and MEG) would still make any contribution to subjective (conscious) experience. Experimental analysis of cortical dendritic fields by means of multi-electrode recording techniques combined with (non)linear data analysis could lift a corner of the veil surrounding this challenging question.

VI: Virtual Photons

If we return now to the aim of this study as formulated in the Introduction, viz, what is the ultimate material substrate underlying subjective (conscious) experience, the question then arises as to what can be said about the building blocks of electric and magnetic fields. To answer this question we should first look at electromagnetic radiation which can be considered as oscillating, self-propagating fields carrying light, radio and TV signals. From the perspective of quantum mechanics, the constituent of electromagnetic radiation is the photon. A photon can be thought of as a wave packet with a certain amount of energy directly proportional to the frequency of that wave. Photons have no mass, move in space with the highest permissible speed (i.e. 300,000 km per second in vacuum), have in principle an unlimited life-time and range, possess an electric and a magnetic aspect. Photons can be generated by various kinds of processes. Apart from these, also called, *real* photons, so-called *virtual* photons can be distinguished.

The term virtual photon is used in quantum mechanics as a metaphor for the mathematical description of electric and magnetic fields. Thus, metaphorically speaking, virtual photons are continually emitted by electrically charged particles such as protons, electrons, and quarks (the constituents of protons and neutron). The magnetic aspect of virtual photons associated with randomly moving

electric charges is mutually self-cancelling, so that they can only reveal themselves as an electric field. When virtual photons are emitted by electrically charged particles moving in the same direction, as is, for instance, the case for an ion-flux in a fluid or for electrons moving in a permanent magnet or in a copper wire (electric current), their electric aspect is mutually canceled out and they manifest as a magnetic field. The trajectories of the virtual photons are classically described as lines of force which never cross each other. If two electrically charged particles or two permanent magnets exchange virtual photons, this has the effect of attraction or repulsion depending whether both particles or magnets have the same or opposite sign. Virtual photons, per definition, receive insufficient energy to start an independent life as real photons, i.e., as electromagnetic radiation, as a consequence of which they are extremely ephemeral. It is Heisenberg's uncertainty principle which allows virtual photons to temporarily elude the law of conservation of mass and energy, thus enabling them to temporarily exist according to the relationship: the lower their energy (wave frequency) the longer their life-time, and consequently the distance that can be covered (Zukav, 1979; Hawkin, 1988). Based on these data, my hypothesis can be reformulated as follows:

Hypothesis (1b): *The fleeting, highly ordered 4-dimensional (space and time) patterns of virtual photons (electric and/or magnetic fields), generated by assemblies of dendritic trees of a specialized (e.g., cortical) neuronal network, should be thought of as the final product of chaotic, dynamically governed self-organization; such patterns encode for subjective (conscious) experiences.*

Such patterns of virtual photons, thus, have to be distinguished from patterns of real photons (self-propagating electromagnetic fields) generated by radio and television transmitters which function as carriers of *objective* information.

VII: The Mind-brain Relationship in the Light of Evolution

As stated in the previous section, all matter (protons, electrons, quarks) constantly emits and reabsorbs virtual photons. This means that virtual photons must be continually present everywhere in the universe. Additionally, the virtual constituents of electromagnetic, gravitational and both nuclear force fields — thus also virtual photons — are continuously created as quantum fluctuations within the energy and time limits of the uncertainty principle of Heisenberg everywhere in space, even in the deepest, isolated vacuum cooled down to absolute zero. They spontaneously wink in and out of appearance from a deeper reality (see Lamoreaux, 1997). Thus virtual photons are always omnipresent in the universe although their concentration in space varies.

If the principle of simplicity (Ockham's razor) is now applied to the mind-brain relationship, a logical corollary of the above is that subjectivity *per se* did not suddenly emerge during evolution at a point when neuronal networks had been formed which were able to generate 4-dimensional patterns of virtual photons (electric and/or magnetic fields) of sufficient complexity. Instead,

subjectivity must already existed as a fundamental property of the omnipresent virtual photons, i.e. of matter, from the very beginning, the ‘big bang’. Indeed, during organic evolution, self-organization gave rise to the formation of all kinds of living structures with organs specialized to fulfil specific tasks, e.g., the ears, the nose, and the eyes. These formed sounds, odours, and visual images from the already omnipresent waves of air vibrations, air-borne molecules, and streams of real photons in the environment. Likewise, in the course of evolution, nerve cells and neuronal networks developed, specialized to generate clouds of virtual photons (elementary germs of subjectivity) and to arrange them in complex configurations underlying complex subjective experiences. Similar to the fact that any material object (e.g. a piano, bicycle, or aeroplane) with its characteristic (emergent) properties is composed of the same elementary *material constituents*, i.e. atoms, molecules etc., so is any subjective experience (e.g. a special sense perception, thought or emotion) with its characteristic (emergent) properties composed of the same elementary *subjective constituents*, i.e. virtual photons. Thus, subjectivity did not suddenly emerge as a weird phenomenon out of a material structure but, rather, must always have been there! Put differently, matter is always animated and because of self-organizing processes we see then (a) the emergence of complex material, objective structures as well as (b) the emergence of complex mental, subjective activities but never the emergence of (b) from (a).

Support for this view is provided by the fact that all serious attempts so far to explain the mind-brain problem on the basis of (i) interaction between a non-material mind and a material brain (even if the uncertainty principle of quantum mechanics is taken into account), or (ii) the emergence of a non-material mind from a neural network at a certain stage of complexity, have recently been demonstrated to be in serious conflict with basic physical laws (Burns, 1999; Wilson, 1999; Seife, 2000; Tegmark, 2000). My view, on the contrary, lacks this flaw and, thus, offers a simple and plausible solution to the mind-brain problem, viz, why consciousness and other sorts of mental phenomena, generally accepted to be caused by neurobiological processes in the brain, cannot be causally reduced to them (see e.g. Gold and Stoljar, 1999; Searle 2000). If the above-mentioned reasoning is true, my hypothesis can be reformulated again:

Hypothesis (1c): *The fleeting, highly ordered 4-dimensional (space and time) patterns of germs of subjectivity (virtual photons), generated by assemblies of dendritic trees of a specialized (e.g., cortical) neuronal network, should be thought of as the final product of chaotic, dynamically governed self-organization; such patterns encode for — that is to say **they experience themselves as** — subjective (conscious) experience.*

From an evolutionary point of view I predict, moreover, that any characteristic configuration of electric and magnetic fields underlying a specific subjective (conscious) experience, should have the same basic 4-dimensional (space and time) code, irrespective of whether it is evoked in a human, rat, fish or snail brain; once developed during evolution, the code is probably universal, like the DNA code.

If the rationale leading to the contention that virtual photons are the elementary carriers of subjectivity is correct, their omnipresence implies that the *whole universe must be imbued with subjectivity*.

The question, finally, as to whether real photons, like virtual photons, also possess subjectivity cannot be answered as yet.

VII: Panpsychism

The question then arises whether plants and trees which lack nerve cells are nevertheless endowed with some form of *structured* subjectivity rising above the basal level formed by the omnipresent virtual photons. It can be speculated that by the process of self-organization, which in all living creatures incessantly binds the millions of elementary constituents into coherent, ever larger and more complex composites which are nested in each other (atoms, molecules, cells, tissues, organs through a complete individual) and interrelated by resonance, the millions of virtual photons emitted by the atoms of these composite structures will be correspondingly patterned (see e.g. Ho, 1996). This implies that any cell, organ or complete individual, such as a plant, animal, or human being, has its own relatively simple level of subjective experience. The latter, of course, will substantially differ from the amplified, highly structured states of subjectivity (consciousness) generated by specialized neuronal networks with at the top of the evolutionary complexity the human cerebral cortex. This panpsychistic view is in harmony with that of some philosophers such as Spinoza, see Boyle (1989), Bergson (1907), Driesch (1928), Haldane (1932) and Teilhard de Chardin (1947). The last once phrased poetically: *The mind sleeps in the mineral kingdom, breathes in the vegetable kingdom, dreams in the animal kingdom, and awakes in man.*

IX: Submanifest Levels

One may conclude from the above that it is the patterned fields of virtual photons per se which experience themselves as a violent pain, a sound or a color. This implies that, by further exploring these fields, the essence of subjectivity will eventually be found. However, it is not unlikely that these fields of virtual photons with their objective and hypothesized subjective properties derive from a deeper, fine-material level which perhaps may stem from a still deeper level, thus forming a whole sequence of ever deeper levels of order which are not (yet) accessible to currently available physical measuring instruments (Davis, 1983; Fischer, 1997; Romijn, 1997; Greene, 1999; Wilson, 1999). Considering the history of physics, it would be a highly unlikely coincidence if the depth to which modern physics has so far penetrated matter (from our daily, macroscopic objects via light microscopic structures, molecules, atoms, subatomic particles through quarks) is precisely the ultimate border of reality, and that there is nothing more beyond. Matter is certainly no less mysterious than mind. The fact, moreover, that modern physics is still far from giving an satisfactory explanation of what

matter actually is, makes it all the more likely that deeper, more fundamental levels exist than that they do not. One should not forget that what we observe is not nature as such but nature exposed to our sensory perception, instruments and thinking. Even quantum mechanics mainly furnish a mathematical description of certain properties of matter without really explaining them.

A typical example is the weird, but experimentally proven phenomenon of *non-local quantum mechanical interconnectedness*, which, if one searches for an explanation, almost axiomatically refers to the existence of a submanifest order of being in which the ostensibly separate parts of the universe are closely entangled (Bohm, 1980; Romijn, 1997). Likewise the ‘string theory’ with its ten or twenty-six dimensions, refers to such a deeper level of order (Greene, 1999). Thus, to postulate the existence of deeper levels of ordered energy is a plausible hypothetical extension of the current empirical scope of natural sciences. Such a submanifest level of energy was recently postulated to function as the repository of our unconscious mental life as well as of the billions of declarative memories which each of us bears in one’s mind (for arguments see Romijn, 1997).

And last but not least, is the plain phenomenon that the functioning cerebral cortex can see (experience), for example, a yellow banana while, objectively considered, there is actually neither yellow light nor a real banana present anywhere in the brain. Taken together, subjective (conscious) experience implies a not yet understood transformation within the cortex: *from some objective phenomena (action potentials, synaptic activities, electric and magnetic fields) to the subjective experience of a yellow banana* which, since present-day physics totally lacks the fundamental concepts needed for an explanation, presumably occurs at a deeper physical level; one which is governed by as yet undiscovered physical principles. Put differently, subjectivity (consciousness) may find its origin somewhere in the submanifest depth-of-being to manifest itself in our material world in the shape of (patterned fields of) virtual photons.

X: Can the Current Hypothesis Be Empirically Tested?

Doing experiments in the field of consciousness studies is essentially different than in the conventional sciences. In contrast to the material brain, which can be studied in a normal objective-instrumental way, consciousness can only be studied in a subjective-introspective way and, thus, eludes measuring instruments (see also the Introduction). Conscious experience is by definition a private matter. Only by interviewing a volunteer or by interpreting the behaviour of a volunteer or an animal, one can obtain indirectly information about conscious experience while one tacitly assumes that others are like oneself (see e.g. Goldman, 2000). Therefore, it is difficult to delineate objective experiments that decisively confirm or falsify the present hypothesis.

Nevertheless I propose the following experimental strategy, which could support the current hypothesis, at least as formulated under 1a and 1b, and might confirm it. With the aid of intracortical multi-electrode measurements or refined EEG and EMG analysis, one could search for those characteristic elements in the

(sub)cortical electric and magnetic fields that most strictly correlate with, and according to the hypothesis thus encode for, a certain mental experience, e.g., seeing the colour red versus green, or a typical figure such as a line, cross or square, or hearing tones of a different pitch, as well as experiencing such basic feelings like pain (by applying small pinpricks). And as was already said at the end of section 7, I predict that such a ‘language’, once developed during evolution, should be universal and, thus, contain the same feature-specific, 4-dimensional (space and time) code irrespective as to whether it is evoked in the a human, rat, fish or snail brain. Thus, comparative electrophysiological studies should be carried out to decipher the ‘language’ hidden within the electric and/or magnetic field patterns. Once unravelled, one can simply substitute ‘electric and magnetic field patterns’ by ‘virtual photon patterns’ since virtual photons are by definition the theoretical constituents of these fields. Although such studies have already been going on for years (e.g. the pioneering experiments of Walter Freeman on the processing of olfactory stimuli, Freeman 1995; see also Zeki & Bartels, 1998; Lehman et al. 1989; Iwaki et al, 1999), current techniques are not adequate to crack the code at present, though they can certainly be expected to do so in the future.

With respect to the hypothesis as formulated under 1c, the situation is more complicated. It is questionable whether it will be ever possible to experimentally prove that virtual photons are the elementary carriers of subjectivity. Indeed, as has already been described, subjectivity escapes objective analysis by whatever instrument. Subjectivity, by definition, is a private matter that can only be studied in an indirect way by interviewing a volunteer or by interpreting the behaviour of a volunteer or an animal. I am afraid, therefore, that the proposal that virtual photons are the elementary carriers of subjectivity can never be proven *experimentally*; conclusions about the validity of hypothesis 1c will be reached only via *a theoretical, deductive* approach.

At this moment, the hypothesis derives its value from (i) a careful, data-based rationale which leads to a new view on the mind-brain relationship and which can be verified step-by-step regarding logic and flaws and (ii) new scientific arguments supporting panspsychism.

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References

- Accardo, A., Affinito, M., Carrozzi, M. and Bouquet, F. (1997), 'Use of the fractal dimension for the analysis of electroencephalographic time series', *Biol Cybern.* **77**, pp. 339–50.
- Andersen, P. and Figenschou Soleng, A. (1999), 'A thorny question: How does activity maintain dendritic spines?', *Nature Neurosci.*, **2**, pp. 5–7.
- Anokhin, A.P., Lutzenberger, W. and Birbaumer, N. (1999), 'Spatiotemporal organization of brain dynamics and intelligence: An EEG study in adolescents', *Int. J. Psychophysiol.*, **33**, pp. 259–73.
- Auger, C., Kondo, S. and Marty, A. (1998), 'Multivesicular release at single functional synaptic sites in cerebral stellate and basket cells', *J. Neurosci.*, **18**, pp. 4532–47.
- Azanza, M.J. and Del Moral, A. (1994), 'Cell membrane biochemistry and neurobiological approach to biomagnetism', *Progr. Neurobiol.*, **44**, pp. 517–601.
- Bergson, H. (1907), *L'évolution créatrice* (Paris).
- Blank, M. (1995), 'Electric and magnetic field signal transduction in the membrane N^+/K^+ -adenosinetriphosphatase', in *Electromagnetic Fields, Biological Interactions and Mechanisms*, ed. M. Blank, Advances in Chemistry Series 250, pp. 339–48.
- Bogen, J.E. (2000), 'Split-brain basics: Relevance for the concept of one's other mind', *J. Amer. Acad. Psychoanal.*, **28** (2), pp. 341–69.
- Bohm, D. (1980), *Wholeness of the Implicate Order* (London: Routledge and Kegan Paul).
- Boyle, A. and Parkinson, G.H.R. (1989), *Spinoza/Ethics* (London: Everyman's Library).
- Burns, J.E. (1999), 'Volition and physical laws', *J. Consciousness Stud.* **6** (8–9), pp. 27–47.
- Crick, F. (1984), 'Function of the thalamic reticular complex: The searchlight hypothesis', *Proc. Nat. Acad. Sci. USA*, **81**, pp. 4586–90.
- Damasio, A.R. (1994), *Descartes' Error: Emotion, Reason and the Human Brain* (New York: Avon Books).
- Davis, P. (1983), *God and the New Physics* [chapter 10] New York: Simon & Schuster, Inc.).
- Dowling, J.E. (1992), *Neurons and Networks. An Introduction to Neurosciences* (Cambridge, MA and London: The Belknap Press of Harvard University Press).
- Driesch, H. (1928), *The Science and Philosophy of the Organism* (New York).
- Field, R.J. (1972), 'A reaction periodic in time and space', *J. Chem. Education*, **49**, pp. 308–11.
- Fischer, L. (1997), 'In the realm of intangibles', *New Scientist*, Dec. 75, pp. 20–27.
- Fischer, M., Kaech, S., Knutti, D. and Matus, A. (1998), 'Rapid actin-based plasticity in dendritic spines', *Neuron*, **20**, pp. 847–54.
- Freeman, W.J. (1995), 'Chaos in the brain: Possible roles in biological intelligence'. *Int. J. Intelligent Systems*, **10**, pp. 71–81.
- Frégnac, Y. (1998), 'Homeostasis or synaptic plasticity?', *Nature*, **39**, pp. 845–6.
- Frith, C., Perry, R. and Lumer, E. (1999), 'The neural correlates of conscious experience: An experimental framework', *Trends Cognit. Sci.*, **3**, pp. 105–14.
- Fröhlich, H. (1975), 'The extraordinary dielectric properties of biological materials and the action of enzymes', *Proc. Natl. Acad. Sci.*, **72**, pp. 4211–15.
- Galarreta, M. and Hestrin, S. (1998), 'Frequency-dependent synaptic depression and the balance of excitation and inhibition in the neocortex', *Nature Neurosci.*, **1**, pp. 587–94.
- Gaspard, P., Briggs, M.E., Francis, M.K., Sengers, J.V., Gammon, R.W., Dorfman, J.R. and Calabrese, R.V. (1998), 'Experimental evidence for microscopic chaos', *Nature*, **394**, pp. 865–8.
- Gold, I. & Stoljar, D. (1999), 'A neuron doctrine in the philosophy of neuroscience', *Behav. Brain Sci.*, **22**, pp. 809–69.
- Goldman, A.I. (2000), 'Can science know when you're conscious?', *J. Consciousness Stud.*, **7** (5), pp. 3–22.
- Goodman, E.M., Greenebaum, B. and Marron, M.T. (1995), 'Effects of electromagnetic fields on molecules and cells', *Int. Rev. Cytol.*, **158**, pp. 279–339.
- Greene, B. (1999), *The Elegant Universe: Superstrings, Hidden Dimensions, and the Quest for the Ultimate Theory* (New York and London: Norton & Co.).
- Griffin, L.D. (1994), 'The intrinsic geometry of the cerebral cortex', *J. Theoret. Biol.*, **166**, pp. 261–73.
- Gulyás, B. (1999), *Neuroreport*, **10**, i–ii.
- Haldane, J.B.S. (1937), *The Inequality of Man* (first pub. 1932; Harmondsworth: Penguin Books).

- Hämäläinen, M., Hari, R., Ilmoniemi, R., Knuutila, J. and Lounasmaa, O.V. (1993), 'Magnetencephalography: Theory, instrumentation, and application to non-invasive studies of signal processing in the human brain', *Rev. Mod. Phys.*, **65**, pp. 413–97.
- Hari, R. and Salmelin, R. (1997), 'Human cortical oscillations: a neuromagnetic view through the skull', *Trends Neurosci.*, **20**, pp. 44–9.
- Hawkin, S. (1988), *A Brief History of Time: From the Big Bang to Black Holes* (Toronto: Bantam Books).
- Ho, M.W. (1996), 'The biology of free will', *J. Consciousness Stud.*, **3**(3), pp. 231–44.
- Hong, F.T. (1995), 'Magnetic field effects on biomolecules, cells, and living organisms', *BioSystems*, **36**, pp. 187–229.
- Hoshino, O., Kashimori, Y. and Kambara, T. (1996), 'Self-organized phase transitions in neuronal networks as a neural mechanism of information processing', *Proc. Natl. Acad. Sci.*, **93**, pp. 3303–7.
- Iwaki, S., Ueno, S., Imada, T. and Tonoike, M. (1999), 'Dynamic cortical activation in mental image processing revealed by biomagnetic measurement', *Neuroreport*, **10** (8), pp. 1793–7.
- Kauffman, S. (1995), *At Home in the Universe: The Search for Laws of Self-Organization and Complexity* (Oxford: Oxford University Press).
- Kelso, J.A.S. (1995), *Dynamic Patterns: The Self-Organization of Brain and Behavior* (Cambridge, MA: MIT Press).
- Kinney, H.C. and Samuels, M.A. (1994), 'Neuropathology of the persistent vegetative state: A review', *J. Neuropathol. Exp. Neurol.*, **53**, pp. 548–58.
- Koch, C. (1997), 'Computation and the single neuron', *Nature*, **385**, pp. 207–10.
- König, P., Engel, A.K. and Singer, W. (1996), 'Integrator or coincidence detector? The role of the cortical neuron revisited', *Trends Neurosci.*, **19**, pp. 130–7.
- Kowalik, Z.J. and Elbert, T. (1994), 'Changes of chaoticness in spontaneous EEG/MEG', *Integr. Physiol. Behav. Sci.*, **29**, pp. 270–82.
- Lamoreaux, S.K. (1997), 'Demonstration of the Casimir force in the 0.6 to 6 mm range', *Phys. Rev. Lett.*, **78**, pp. 5–8.
- Lehmann, D., Strik, W.K., Henggler, B., Koenig, T. and Koukkou, M. (1998), 'Brain electric microstates and momentary conscious mind states as building blocks of spontaneous thinking: I. Visual imagery and abstracts thoughts', *Int. J. Psychophysiol.*, **29**, pp. 1–11.
- Lewin, R. (1980), 'Is your brain really necessary?', *Science*, **210**, pp. 1232–4.
- Libet, B. (1985), 'Unconscious cerebral initiative and the role of conscious will in voluntary action', *Behav. Brain Sci.*, **8**, pp. 529–66.
- Lopes da Silva, F.H. (1996), 'The generation of electric and magnetic signals of the brain by local networks', in *Comprehensive Human Physiology*. vol.1, ed. R. Greger and U. Windhorst (Heidelberg and Berlin: Springer Verlag).
- Magee, J.C. (2000), 'Dendrite integration of excitatory synaptic input', *Nature Reviews (Neuroscience)*, **1**, pp. 181–90.
- Mainzer, K. (1994), *Thinking In Complexity, the Complex Dynamics of Matter, Mind, and Mankind* (Berlin: Springer Verlag).
- Maren, S. and Baudry, M. (1995), 'Properties and mechanisms of long-term synaptic plasticity in the mammalian brain: relationships to learning and memory', *Neurobiol. Learning Memory*, **63**, pp. 1–18.
- Markram, H., Lübke, J., Frotscher, M. and Sakmann, B. (1997), 'Regulation of synaptic efficacy by coincidence of postsynaptic APs and EPSPs', *Science*, **275**, pp. 213–15.
- Mölle, M., Marshall, L., Wolf, B., Fehm, H.L. and Born, J. (1999), 'EEG complexity and performance measures of creative thinking', *Psychophysiol.*, **36**, pp. 95–104.
- Näätänen, R., Ilmoniemi, R.J. and Alho, K. (1994), 'Magnetoencephalography in studies of human cognitive brain function', *Trends Neurosci.*, **17**, 389–95.
- Newell, A. (1992), 'Precis of unified theories of cognition', *Behav. Brain Sci.*, **15**, pp. 425–92.
- Penrose, R. (1989), *The Emperor's New Mind* (New York: Oxford University Press).
- Rabinovich, M.I. and Abarbanel, H.D.I. (1998), 'The role of chaos in neural systems', *Neurosci.*, **87**, pp. 5–14.
- Raichle, M.E. (1998), 'The neural correlates of consciousness: an analysis of cognitive skill learning', *Phil. Trans. R. Soc. Lond. B.*, **353**, pp. 1889–901.
- Roelfsema, P.R., Lamme, V.A.F. and Spekreijse, H. (1998), 'Object-based attention in the primary visual cortex of the monkey', *Nature*, **395**, pp. 376–81.

- Romani, G.L. (1989), 'Fundamentals on neuromagnetism', in *Advances in Biomagnetism*, ed. S.J. Williamson (New York: Plenum Press).
- Romijn, H. (1997), 'About the origin of consciousness: A new, multidisciplinary perspective on the relationship between brain and mind', *Proc. Kon. Akad. v. Wetensch.*, **100**, pp. 181–267.
- Rusakov, D.A., Stewart, M.G. and Korogod, S.M. (1996), 'Branching of active dendritic spines as a mechanism for controlling synaptic efficacy', *Neuroscience*, **75**, pp. 315–23.
- Sakai, K. and Miyashita, Y. (1994), 'Visual imagery: An interaction between memory retrieval and focal attention', *Trends Neurosci.*, **17**, pp. 287–9.
- Salter, M. and De Koninck, Y. (1999), 'An ambiguous fast synapse: a new twist in the tale of two transmitters', *Nature Neurosci.*, **2**, pp. 199–200.
- Savtchenko, L.P., Korogod, S.M. and Rusakov, D. (2000), 'Electrodifusion of synaptic receptors: a mechanism to modify synaptic efficacy?', *Synapse*, **35**, pp. 26–38.
- Schacter, D.L., Buckner, R.L. and Koutstraal, W. (1998), 'Memory, consciousness and neuroimaging', *Phil. Trans. R. Soc. Lond.*, **353**, pp. 1861–78.
- Searle, J.R. (2000), 'Consciousness', *Ann. Rev. Neurosci.*, **23**, pp. 557–8.
- Segev, I. and Rall, W. (1998), 'Excitable dendrites and spines: earlier theoretical insights elucidate recent direct observations', *Trends Neurosci.*, **21**, pp. 453–60.
- Seife, Ch. (2000), 'Cold numbers unmake the quantum mind', *Science*, **287**, p. 791.
- Shadlen, M.N. and Newsome, W.T. (1998), 'The variable discharge of cortical neurons: implications for connectivity, computation, and information coding', *J. Neurosci.*, **18**, pp. 3870–96.
- Smith, S.J. (1999), 'Dissecting dendritic dynamics', *Science*, **283**, pp. 1860–1.
- Smolin, L. (1997), *The Life of the Cosmos* (Oxford: Oxford University Press).
- Softky, W. (1994), 'Sub-millisecond coincidence detection in active dendritic trees', *Neuroscience*, **58**, pp. 13–41.
- Stuart, G., Schiller, J. and Sakman, B. (1997), 'Action potential initiation and propagation in rat neocortical pyramidal neurons', *J. Physiol. (Lond.)*, **505**, pp. 617–32.
- Teilhard de Chardin, P. (1947), *Le phénomène humain* (Paris).
- Tegmark, M. (2000), 'Importance of quantum decoherence in brain processes', *Physical Rev. E.*, **61**, pp. 4194–206.
- Tononi, G. and Edelman, G.M. (1998), 'Consciousness and complexity', *Science*, **282**, pp. 1846–51.
- Tononi, G., Sporns, O. and Edelman, G.M. (1994), 'A measure for brain complexity: relating functional segregation and integration in the nervous system', *Proc. Natl. Acad. Sci.*, **91**, pp. 5033–7.
- Velmans, M. (1991), 'Is human information processing conscious?', *Behav. Brain. Sci.*, **14**, pp. 651–726.
- Wikswo, J.P. (1989), 'Biomagnetic sources and their models', in *Advances in Biomagnetism*, ed. S.J. Williamson, M. Hoke, G. Stroink, M. Kotani (New York: Plenum Press).
- Williamson, S.J. and Kaufman, L. (1990), 'Theory of neuroelectric and neuromagnetic fields', in *Auditory Evoked Magnetic Fields and Electric Potentials*, ed. F. Grandori, M. Hoke, G.L. Roman (Basel: Karger).
- Wilson, D.L. (1999), 'Mind-brain interaction and violation of physical laws', *J. Consciousness Stud.*, **6** (8–9), pp. 185–200.
- Wright, J.J. and Liley, D.T. (1996), 'Dynamics of the brain at global and microscopic scales: neural networks and the EEG', *Behav. Brain Sci.*, **19**, pp. 285–320.
- Zeki, S. and Bartels, A. (1998), 'The asynchrony of consciousness', *Proc. R. Soc. Lond. B.*, **265**, pp. 1583–5.
- Zoli, M., Torri, C., Ferrari, R., Jansson, A., Zini, I., Fuxe, K. and Agnati, L.F. (1998), 'The emergence of the volume transmission concept', *Brain Res. Rev.*, **26**, pp. 136–47.
- Zukav, G. (1979), *The Dancing Wu-li Masters* (New York: William Morrow and Co.).

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