Quantum Processes in the Brain:
A Scientific Basis of Consciousness

Friedrich Beck & John C. Eccles (deceased)

The question whether neural activities in the brain can be correlated with conscious action is as old as brain research itself. Even in view of the remarkable progress of neuroscience in recent years, the question is far from being settled. The difficulties arise from the fact that the qualia of consciousness connected with thoughts, emotions, free decisions, can hardly be reconciled with the concept of a causal, computer-like neural net. A new and intriguing view of the relation between brain and consciousness arises, however, if quantum processes play a decisive role in brain activity. The quantum state reduction, or selection of amplitudes, offers a doorway for a new logic, the quantum logic, with its unpredictability for a single event. Brain activity consists of a constant firing of neural cells, regulated by synaptic switches which establish the connections between neurons. Conscious action, e.g. intention, is a dynamical process which forms temporal patterns in some areas of the brain. We discuss how synaptic activity in the form of exocytosis of transmitter molecules can be regulated effectively by a quantum trigger based on an electron transfer process in the synaptic membrane. Conscious action is hereby essentially related to quantum state reduction.

Keywords: brain dynamics, quantum state reduction, synaptic transmission, quantum trigger model

Introduction

Since the earliest testimony of mankind we can observe a deeply mysterious feeling about the invisible soul, as contrasted to the material body. Originally, the soul was conceived as material, as air, or as finest matter penetrating the body. Later on, in the Greek philosophy of Plato and Aristotle the soul was conceived as a non-material entity that interacts with the body. This dualistic concept raised no problem with Greek natural philosophy which had rather abstract and primitive ideas about cause and effect.

This article was prepared by, and reviews work of, both authors on quantum aspects of brain activity. Since Sir John Eccles passed away during preparation, responsibility for text is due to first author, Friedrich Beck (Institut für Kernphysik, Technical University Darmstadt).

At the same time the first great physician, Hippocrates, stated that in movement the brain is the interpreter of consciousness, it tells the limbs how to act, and it is also the messenger to consciousness, expressing dualism and interactionism.

There was not much change to these ideas until philosophy turned to rationalism at the end of the Renaissance period. It was the great French philosopher and mathematician René Descartes (1644) who presented his well-known explanation of mind-body interaction. 'cogito ergo sum' was the shortest possible rational expression of mind-body entity, realized by interaction of a non-material mind, res cogitans, with a material brain, res extensa. Descartes unfortunately combined this abstract rationalism with the inadequate postulate that the pineal body was the
organ immediately moved by push from the human soul. This brought the Descartes’ dualism into heavy criticism, even among contemporaries like Leibniz and Spinoza.

Descartes’ dualism cam into even heavier waters with the triumph of modern science. At the end of 19th century classical physics in the form of Newton’s mechanics and Maxwell’s electrodynamics was regarded as a complete, closed and causal description of the world, leaving no room for any kind of freedom. This is best expressed in the form of Laplace’s daemon: Giving a super-mind the momentary initial conditions of the whole world, he can calculate all its future unambiguously. The world runs like a clock!

There was then not much room left for a dualistic picture of mind-brain interaction, and materialism prevailed, as has been expressed rather drastically by Charles Darwin: ‘Why is thought being a secretion of the brain, more wonderful than gravity a property of matter?’ (Gruber, 1974).

Materialism was, however, not accepted by everybody. Too strong was the believe, based on personal experience, that self-consciousness governs our actions in the world, and that this requires the ability for free, not pre-determined, decisions. Natural scientists were quite aware that such a non-materialistic view caused an unsurpassable conflict with the laws of nature to which our bodies, including the brain, underlie as material biological objects. The frustration could not be better expressed than in an address of the neurophysiologist and science philosopher Emil Du Bois-Reymond (1916), which he presented earlier, in 1872 at the German natural scientists and physicians meeting: ‘There occurs at a certain point of evolution of life in the world, which we do not know and whose determination is of no importance in this connection, something new and hitherto incommensurable. Something which is, like the nature of matter and force and like the first motion, mysterious (…) This new mystery is consciousness. I shall now, as I believe in an unambiguous manner, outline that not only by our present day knowledge consciousness can not be explained out of its material conditions, what apparently everybody would admit, but that by its own nature, it will be never explainable from these conditions.’ (transl. by author). He ended his talk with the apodictic prognosis ‘ignorabimus’.

The situation has not changed much since then. There is still a vivid debate between “monists” and “dualists”, and about the notions of real or apparent free will and determinism. A critical evaluation of the different positions, as represented by some leading neuroscientists and psychologists, has been given by one of the authors (Eccles, 1994). Recently, however, quite a new aspect has entered the discussions. It is the question if quantum processes play a decisive role in brain activities, and if so, do they open a new pathway towards a science of consciousness (Margenau, 1984; Penrose, 1984; Squires, 1988; Eccles, 1990; Donald, 1990; Stapp, 1991). It should be emphasized, however, that such a discussion has two aspects which should be clearly separated. One resides on the epistemological level of quantum logic, which, in turn, is related to the interpretation of quantum mechanics, or even to the need for an essential extension of the present theory (Penrose, 1994). The other aspect is the search for a better understanding of synaptic and neural actions, and their relation to microscopic, and eventually large scale coherent action, where quantum processes work in a decisive manner on the basis of present-day theory. This is certainly open to experimental and theoretical research in contemporary brain physiology. Only very few realistics attempts have been made, however, to contribute to the latter question, and to locate a quantal process in the functional microsites of the neocortex (Beck & Eccles, 1992; Hameroff & Penrose, 1995).

In this article we discuss briefly the role of quantum logic, as contrasted to the deterministic logic of classical physics, and, in the main part, give a resume of our work on the microsite
hypothesis, and its relation to synaptic emission. We then introduce the quantum trigger model based on electron transfer in the biological reaction center of the synaptic membrane. Finally we discuss consequences for regulating the coherence patterns of groups of neurons, as has been observed in the visual cortex, or in positron emission tomography (PET) studies (Singer, 1990; Pardo & Raichle, 1991).

**The Epistemological Question: Why are Quantum Processes Interesting?**

The dualistic concept of mind-brain interaction, even in its modern version as, e.g., presented by Popper (1972), involves the assumption that the immaterial mind acts upon the material brain. This would either require some kind of a force (Popper et al., 1993; Lindahl and Århem, 1994; Beck, 1996a), and this implies the mind to be not really immaterial, or one is forced to give up at least one of the global conservation laws of physics, based on strict space-time symmetries. The latter is not acceptable from a purely scientific standpoint. It should, however, be emphasized that the apparent contradiction between dualism and identity theory ("the mind is the brain") is itself deeply rooted in the logic of a world view based on classical physics. We are so used to our daily experience of macroscopic events surrounding us, and which are well described by classical physics, that we can hardly appreciate a world in which determinism is not the rule of the game. 'If—then' lies deeply in our conscious experience. Yet the quantum world, governing microphysical events, has a different logic.

The basic difference between classical and quantum dynamics can be made clear in a simple diagram, without entering into the subtleties of the theory. The generation of a physical process consists of preparing an input (the initial condition) followed by a more or less complicated process, and a possible output (the result) which can be observed. For simplicity, we restrict the
distinguishable outcomes to only two states (Figure 1). In classical dynamics the output is unique (strict determinism), which means we have either state I or state II: excluding states (Figure 1 A). The essence of a quantum process is, contrary to this, that the output is not unique (no strict determinism), we have neither state I nor state II but a coherent superposition of both states: interfering states (Figure 1 B).

In both cases the time development of the system is given by partial differential equations of first order in the time variable (Newton’s or Maxwell’s equations in the classical case, Schrödinger’s equation in the quantum case) which describe the dynamics in a strictly causal way: the initial conditions determine uniquely the output. The non-causal element in the quantum case enters through the famous von Neumann state collapse which occurs if one tries to realize the output state, either by a measurement, or by letting the output state undergo a successive process. Then the coherent superposition

$$\alpha \cdot |\text{state I} \rangle + \beta \cdot |\text{state II} \rangle$$

collapses into

- either $|\alpha|^2$ with probability $|\alpha|^2$,
- or $|\text{state II} \rangle$ with probability $|\beta|^2$,

and $|\alpha|^2 + |\beta|^2 = 1$.

For the single event — and it has to be emphasized that quantum mechanics is a theory for the single event, and not, as is sometimes claimed, an ensemble theory — the outcome is completely unpredictable (provided that not all but one of the probabilities are zero, which would imply the one left is equal to one). This constitutes the non-computable character of quantum events (Penrose, 1994). It is evident that the deterministic logic underlying Cartesian dualism, which runs so heavily into conflict with the material world of classical physics, no longer applies if elementary quantum processes play a decisive role in brain dynamics.

Figure 2 (A) Three dimensional construct by Szentagothai (1978) showing cortical neurons of various types.

(B) detailed structure of a spine (sp) synapse on a dendrite (den); st, axon terminating in synaptic bouton or presynaptic terminal (pre); sv, synaptic vesicles; c, presynaptic vesicular grid (PVG in text); d, synaptic cleft; e, postsynaptic membrane; a, spine apparatus; b, spine stalk; m, mitochondrion (Gray, 1982).

Neocortical Activity

Figure 2 A illustrates the universally accepted six laminae of the neocortex (Szentagothai, 1978) with two large pyramidal cells in lamina V, three in lamina III, and two in lamina II. The pyramidal apical dendrites finish in a tuft-like branching in lamina I (Figure 3A). There is agree-
Figure 3  (A) Drawing of a lamina V pyramidal cell with its apical dendrite showing the side branches and the terminal tuft, all studded with spine synapses (not all shown). The soma with its basal dendrites has an axon with axon collateral before leaving the cortex. (B) Drawing of the six laminae of the cerebral cortex with the apical dendrites of pyramidal cells of laminae II, III and V, showing the manner in which they bunch in ascending to lamina I, where they end in tafts (A. Peters, personal communication).

Figure 4  (A) Axon terminal, or bouton, showing dense projections (dp) projecting from the active site with cross linkages forming the PVG, which is drawn in the Inset with dimensions (Pfenninger et al., 1969). cv, small vesicle; dv, big vesicle. (B,C) Tangential section through the presynaptic area. A section of the patterns of dense projections and synaptic vesicles, triangular and hexagonal, of the PVG is clearly represented. (Bar = 0.1 μm). [Reprinted from Akert et al., 1975 with permission.] (D-E) Active zone (AZ) of mammalian central synapse showing geometrical design (Gray, 1982). SV, synaptic vesicle; VAS, vesicle attachment site; PA presynaptic area. (F) Synaptic vesicle in apposition. (G) Exocytosis (Kelly et al., 1979).

ment by Fleischhauer, Peters and their associates (Schmolke & Fleischhauer, 1984; Peters & Kara, 1987) that the apical bundles, diagrammatically shown in Figure 3 B, are the basic anatomical units of the neocortex. They are observed in all areas of the cortex that have been investigated in all mammals, including humans. It has been proposed that these bundles are the cortical units for reception (Eccles, 1990), which would give them a preeminent role. Since they are composed essentially of dendrites, the name dendron was adopted.

Figure 2 B illustrates a typical spine synapse
that makes an intimate contact with an apical dendrite of a pyramidal cell. The ultrastructure of such a synapse has been intensively studied by Akert and his associates (Pfenninger et al., 1969; Akert et al., 1975). The inner surface of a bouton confronting the synaptic cleft (d in Fig 2 B, the active site in Figure 4 A) forms the presynaptic vesicular grid (PVG) (Figure 4 A-E). Fig 4 B is a photomicrograph of a tangential section of a PVG, showing the dense projections in triangular array, and with the faint synaptic vesicles fitting snugly in hexagonal array. The spherical synaptic vesicles, 50–60 Å in diameter, with their content of transmitter molecules, can be seen in the idealized drawings of the PVG (Figure 4 C and D). They arrange themselves in a hexagonal array on the active zone (Pfenninger et al., 1969; Akert et al., 1975).

A nerve impulse propagating into a bouton causes a process called exocytosis. At most a nerve impulse evokes a single exocytosis from a PVG (Figure 4 F and G, Figure 5). Exocytosis is the basic unitary activity of the cerebral cortex. Each all-or-nothing exocytosis of synaptic transmitter results in a brief excitatory postsynaptic depolarization (EPSP). Summation by electrotonic transmission of many hundreds of these milli-EPSPs is required for an EPSP large enough (10–20 mV) to generate the discharge of an impulse by a pyramidal cell (Figure 6). This impulse will travel along its axon to make effective excitation at its many synapses. This is the conventional macro-operation of a pyramidal cell of the neocortex, and it can be satisfactorily described by conventional neuroscience, even in the most complex design of neural network theory and neuronal group selection (Szentagothai, 1978; Mountcastle, 1978; Edelman, 1989).

Exocytosis has been intensively studied in the mammalian central nervous system, where it is meanwhile possible to refine the study by utilizing a single excitatory impulse to generate EPSPs in single neurons that are being studied by intracellular recordings. The initial studies were on the monosynaptic action on motoneurons by single impulses in the large Ia afferent fibres from muscle (Jack et al., 1981). More recently it was found that the signal-to-noise ratio was much
better for the neurons projecting up the dorsospino-cerebellar tract (DSCT) to the cerebellum.

This successful quantal resolution for DSCT neurons and motoneurons gives confidence in the much more difficult analysis of neurons of the cerebral cortex, which provide the key structures of neural events which relate to consciousness. The signal-to-noise ratio was so low in the studies of CA1 neurons of the hippocampus that so far only three quantal anlyses have been reliable in the complex deconvolution procedure by fluctuation analysis. In the most reliable case, a single axon of a CA3 hippocampal pyramidal cell set up an EPSP of quantal size 278μV (mean value) in a single CA1 hippocampal pyramidal cell with approximately equal probabilities of release at each active site (n = 5) of 0.27 (Sayer et al., 1990). In the alternative procedure the single CA3 impulse projecting to a CA1 pyramidal cell was directly stimulated in the stratum radiatum. The EPSPs delivered by the deconvolution analysis of the two CA1 pyramidal cells were of quantal sizes 224μV and 193μV with probabilities (n = 3) of 0.24 and (n = 6) of 0.16, respectively (Sayer et al., 1989). For a systematic review, see Redman (1990). Key result of these observations is the fact that exocytosis occurs with probabilities much smaller than one per each impulse reaching the synapse.

**Quantum Versus Classical Brain Dynamics**

In the brain there exists an interplay between micro- and macrostructures. The latter consist of pyramidal cells, dendrites and their bundles (dendrons), electrochemical transitions, while microstructures involve synaptic membranes and microtubules. Nerve impulses, propagating along nerve cells are, independent of external stimuli or internal brain activity, always present and constitute a stochastic background in the brain. Recent investigations suggest that the neural net stays close to instability, and in this way can be switched by minute action between different states (Freeman, 1996). In order to control such a system, a stable regulator has to be present which generates a coherent pattern in the active cortical unit. According to the cortical ultrastructure, as outlined in the previous section, synaptic action qualifies as this regulator. This has also been demonstrated in various biochemical studies of the influence of drugs and anesthesia on the ion channel properties of the synaptic membrane (Flohr, 1996; Hameroff, 1997). We argue in the following that because of the stochastic thermal background quantum ac-
tion could only be effective in brain dynamics if it establishes itself as a ‘quantum switch’ within the microstructures.

The all important regulatory function of spine synapses results from the fact that exocytosis, the release of transmitter molecules across the presynaptic membrane, occurs only with probabilities much smaller than one upon each incoming nerve impulse (Redman, 1990). We therefore regard exocytosis as a candidate for quantum processes to enter the network, and thus regulating its performance (Beck and Eccles, 1992)\(^1\).

Micro- and macrostructures in the brain are clearly separated by time-, or correspondingly, energy scales. The macrostructure is typically characterized by the fact that the brain lives in hot and wet surroundings of \( T \approx 300^\circ \text{K} \). This raises immediately the question of quantum coherence vs. thermal fluctuations. As is well known, as soon as thermal energies surpass quantal energies classical thermal statistics prevails.

To answer this question, two characteristic energies can be defined:

(i) the thermal energy per degree of freedom \( E_{th} = \frac{1}{2} k_b T \)

with \( k_b \): Boltzmann’s constant.

(ii) the quantal energy, defined as zero point energy of a quasiparticle of mass \( M \) which is localized over a distance \( \Delta q \).

From Heisenberg’s uncertainty relation \( \Delta p \cdot \Delta q \geq \frac{2\hbar}{\pi} \) it follows

\[
E_{qu} = \frac{(\Delta p)^2}{2M} \approx \left( \frac{2\hbar}{\Delta q} \right)^2 \frac{1}{2M}
\]

with \( \hbar \): Planck’s constant.

These relations define two energy regimes

\[
E_{qu} \gg E_{th} : \text{the quantal regime}
\]

\[
E_{th} \gg E_{qu} : \text{the thermal regime}
\]

An estimate with typical numbers: \( T = 300^\circ \text{K} \), localization distance \( \Delta q \approx 1 \text{\AA} \), and a critical separation, \( E_c \), between the two regimes, following from \( E_{qu} = E_{th} = E_c \approx 1.3 \cdot 10^{-2} \text{eV} \), results in a critical quasiparticle mass

\[
M_c \approx 6M_H
\]

with \( M_H \): mass of a hydrogen atom

This indicates that the dynamical mass of a quantum transition, if robust against thermal fluctuations, has to be of the order of the hydrogen atomic mass, or less. Biomolecules whose mass is in the range of kD, do not qualify as a whole.

We can also derive a critical frequency, \( \hbar \omega_c = E_c \), and a signal time, \( \tau = 2\pi/\omega_c \),

\[
\omega_c \approx 2 \cdot 10^{13} \text{s}^{-1}; \tau \approx 30 \text{ps}
\]

These results show unambiguously that quantum processes at room temperature involve frequencies smaller than the picosecond scale. This, in turn, means they correspond to electronic transitions, like electron transfer or changes in molecular bonds (breaking of a hydrogen bridge, e.g.).

Our analysis leads to the consequence that in brain dynamics two well separated regions with different time scales exist:

(i) The macroscopic, or cellular, dynamics with time scales in the milli-, and down to the nanosecond range.

(ii) The microscopic, or quantal, dynamics with time scales in the pico- to femtosecond range.

The large difference in time scales makes it possible to deal with quantum processes in the individual microsites, and decoupled from the neural net. On the other hand, it explains why the usual biochemical and biophysical studies do not show the need for introducing quantum considerations. To uncover them one has to employ ultra-short time spectroscopy (Vos et al., 1993).

\(^1\) An alternative regulating process by tubulin molecules comprising the cylindrical walls of microtubules has been proposed by Hameroff & Penrose (1996). We would like to emphasize that the basic quantal event postulated by them, a two state conformational transition in the tubulin molecule, is rather similar to the synaptic quantum trigger model presented here. We do not follow, however, these authors in their postulate of a macroscopic coherent quantum state along the microtubules, nor in their quantum gravitational arguing for ‘orchestrated (state) reduction’ (OR).
The Quantum Trigger Model

Experimental analysis of transmitter release by spine synapses of hippocampal pyramidal cells has revealed a remarkably low exocytosis probability per excitatory impulse. This means that there exists an activation barrier against opening of an ion channel in the PVG. Activation can either occur purely stochastically by thermal fluctuations, or by stimulation of a trigger process. Here we propose a two-state quantum trigger which is realized by quasi-particle tunneling. This is motivated by the predominant role of exocytosis as the synaptic regulator of cortical activity which is certainly not completely at random. On the other hand, primary electron transfer processes play a decisive role in membrane transport phenomena (Vos et al., 1993).

Exocytosis as a whole certainly involves macro-molecular dynamics (Figure 5). We propose, however, that it is initiated by a quantum trigger mechanism: An incoming nerve impulse excites some electronic configuration to a metastable level, separated energetically by a potential barrier $V(q)$ from the state which leads in a unidirectional process to exocytosis. Here, $q$ denotes a collective coordinate representing the path along the coupled electronic and molecular motions between two states. The motion along this path is described by a quasiparticle of mass $M$ which is able to tunnel through the barrier quantum-mechanically. As has been shown in the previous section, $M$ can be at most of the order of a hydrogen atom mass to survive thermal fluctuations. This implies that ion channel dynamics as a whole does not qualify for significant quantum processes in the brain.

The quasiparticle assumption allows the treatment of the complicated molecular transition as an effective one-body problem whose solution follows from the time dependent Schrödinger equation

$$\frac{i\hbar}{\partial t} \Psi(q; t) = -\frac{\hbar^2}{2M} \frac{\partial^2}{\partial q^2} \Psi(q; t) + V(q) \cdot \Psi(q; t).$$

Figure 7 (A) The initial state ($t = 0$) of the quasiparticle in the potential $V(q)$. The wave function is localized to the left of the barrier. $E_0$ is the energy of the activated state which starts to tunnel through the barrier. (B) After time $t_1$ the wave function has components on both sides of the barrier. $a$, $b$: classical turning points of the motion inside and outside the barrier (Beck & Eccles, 1992).

Figure 7 shows schematically the initial state at $t = 0$ (after activation by the incoming impulse), and at the end of the activation period, $t = t_1$. Here it is assumed that the activated state of the presynaptic cell lasts for a finite time $t_1$ only before it recombines. $t_1$, however, is of the macroscopic time scale (micro to nanosecond), as discussed in the previous paragraph. At $t = t_1$ the state has evolved into a part still sitting to the left of the barrier in region I, while the part in region III has tunneled through the barrier.

We can now separate the total wave function
at time $t_1$ into two components, representing left and right parts:

$$\Psi(q; t_1) = \Psi_{\text{left}}(q; t_1) + \Psi_{\text{right}}(q; t_1),$$

and this constitutes the two interfering amplitudes for the alternative results of the same process as discussed in 2nd section: either exocytosis has happened ($\Psi_{\text{left}}$), or exocytosis has not happened ($\Psi_{\text{right}}$) (inhibition).

State collapse transforms this into

exocytosis: probability $p_{\text{ex}}(t_1) = \int |\Psi_{\text{right}}|^2 \, dq$

inhibition: probability $p_{\text{in}}(t_1) = \int |\Psi_{\text{left}}|^2 \, dq$

Using the WKB approximation (cf, e.g., Messiah, 1961) for the solution of the tunneling problem, we can once more evaluate the process with characteristic numbers:

**input**

- mass of quasiparticle: $^2) M \approx 500 \times$ electron mass
- spatial extension: $\Delta q \approx 1 \text{Å}$
- effective barrier height: $V - E \approx 0.5 \text{ eV}$
- effective barrier width: $b - a \approx 1 \text{Å}$
- activation time: $t_1 \approx 10 \text{ ns}$

**result**

- energy of tunneling state: $E_0 = 0.3 \text{ eV}$
- barrier penetration coefficient: $T \approx 10^{-7}$
- exocytosis probability: $p_{\text{ex}}(t_1) \approx 0.5$

The numerical estimate with realistic numerical input leads to meaningful results for the quantum trigger which regulates exocytosis!

As a consequence we can describe brain dynamics by two time scales:

microscopic scale

(femtosecond): quantum synaptic dynamics

macroscopic scale

(nanosecond): (coherent) cell dynamics

coupling: microtubular structure

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$^2)$ The estimate for the quasiparticle mass respects the fact that the coupling of the electron transition to the molecular motion increases its effective mass considerably.

As a possible realization we can consider electron transfer (ET) between biomolecules (Beck, 1996b). In biological reaction centers such processes lead to charge transfer across biological membranes (Vos et al., 1993). The quasiparticle describes the electron coupled to nuclear motion according to the Franck-Condon principle. The theory has been worked out by Marcus (1956), and was later put into quantum mechanical version by Jortner (1976). The initializing step of ET is excitation of donor D, usually a dye molecule, with subsequent transport of an electron to acceptor A, producing the polar system D$^+$$A^-$. This is accompanied by rearrangement of the molecular coordinates leading to unidirectional charge separation and, over several further electronic transitions with increasing time constants, to the creation of an action potential across the membrane. The energetics is shown in Figure 8. Figure 8A shows the potential energy curves separately for electrons and nuclear conformations, Figure 8 B gives the combined potential in the quasiparticle picture (Marcus & Sutin, 1985). This latter form resembles closely the effective potential assumed in our quantum trigger model presented earlier in this section.

**Neural Coherence**

Neural activity in processes of perception or intention is characterized by coherent action of specific areas in the brain (Singer, 1990; Pardo et al., 1991; Eccles, 1994). Activated areas are characterized by an increase in regional cerebral blood flow, as demonstrated in radio-xenon technology (Roland, 1981), or more recently by positron emission tomography (PET, Posner et al., 1985; Corbetta et al., 1990; Raichle et al., 1991). Activation generates most complex spatio-temporal patterns which characterize the specific perception (visual, audible, taste or touch) or intention (silent thinking, moves). These patterns are intimately related to memory and the learned inventory of pyramidal cells (Kandel & Schwartz, 1982). Since in the neural bundles ("dendrons")
which comprise the active area, there are thousands of modifiable synapses which have to act cooperatively to generate the increased action potential needed to bring out the observed activity (Figure 6). Since the synapses can only mod-

ify (increase or decrease) their exocytosis probability upon incoming nerve impulses, there has to be a constant background activity which will be modulated coherently by a large number of synapses.

Long range coherence in biological systems at room temperature can either be established by self-organization in classical nonlinear dynamics, or by macroscopic quantum states ("Fröhlich coherence", Fröhlich, 1968). The necessary ingredients for macroscopic quantum states at room temperature are dissipation and energy supply ("pumping"). Pumping stabilizes against thermal fluctuations, and phase synchronization is achieved by self organization. The latter is mediated by nonlinear couplings to classical fields (electromagnetic, phonons, molecular) which implies that the quantal spectrum becomes quasi-continuous. Quantum state interference and subsequent state reduction, however, need a few well separated discrete states (like the two states in the synaptic trigger model), and consequently are not possible with macroscopic quantum states at room temperature.

From empirical evidence (Freeman, 1996,
Spitzer & Neumann, 1996), and from successful modeling (Haken, 1996), we would rather attribute long range cooperative action in the active zones of the brain to nonlinear dynamics of a driven open system. Such a system is far from thermal equilibrium and close to instability, and it can organize itself by external stimuli in a variety of synchronous activity patterns (Gray et al., 1989). Synaptic exocytosis in such a system serves as a regulator, and the cooperation of the many synapses in the dendrons (active area) produce the spatio-temporal patterns above noise. Quantum action and subsequent state reduction in the individual synapse produce the non-algorithmic binding in cortical units. Figure 9 presents a schematic sketch of three bundles of pyramidal cells (dendrons) surrounded by their spatial pattern which are produced temporarily by cooperation within the individual cells. Since these patterns are activated by perception, intention as well as in ideation (Ingvar, 1989) they represent the basic units of consciousness. To give them a name which expresses their outstanding importance, we may call them psychons (Eccles, 1990). The physiological mechanism of pattern formation and signal transduction in the brain are not yet fully understood. Recent rapid progress in understanding many facets of nonlinear dynamics in biological systems (Goldbeter, 1996) gives, nevertheless, hope to proceed substantially in understanding large scale brain dynamics in the near future. The important role of quantum events does, however, not depend on the exact nature of this large scale structure, but it relies on the concept of state superposition in microscopic molecular transitions.

Finally, a word concerning the qualia of consciousness may be added. Science can not, by its very nature, present any answer to the philosophical, ethical or religious questions related to the mind. It can, however, and it does, provide the openness which is essential to make discussions beyond the limitations of science possible. Thus the ‘ignorabimus’ of du Bois-Reymond (cf. Introduction) has been turned into ‘non ignorabimus’ by quantum- and non-linear physics!

Conclusions

Quantum state collapse is the decisive process which distinguishes quantum mechanics from classical physics. In a single event it is unpredictable. By this it qualifies for the indecisive and non-computable nature of brain functioning. It is emphasized that this introduces a new logical concept, different from classical determinism, underlying the struggle between dualism, identity theory, and the call for ‘free will’. The interpretation of quantum mechanics as a succession of single events produces in a natural way the fundamental difference between past and future, in so far as the past is known (by events having manifestly occurred) while the future is not known (by the unpredictability of state reduction). One could, however, object against this interpretation by arguing that the Schrödinger equation is causal, and consequently describes the time evolution of the probability amplitudes unambiguously. Thus, the probabilities for future events are completely determined. This, however, relates to ensemble averages, for a large number of identical systems under identical initial conditions. Such ensembles can be realized in the material world of microscopic atomic systems but they are never realized in the world of complex objects such as the brain. Each new event finds itself borne in a new initial state. For these the non-predictability for single events prevails.

In view of these new and important concepts for elevating consciousness finally up to a scientific basis, we present evidence for a realistic implementation of quantum events into brain dynamics. It is based on our present knowledge of cortical structure and the synaptic regulation of neural impulses. Basic assumptions and results are:

- Quantum processes in the wet and hot surroundings of the brain are only possible at the microscopic level of (electron) transitions
in the pico- to femtosecond time scale.

- Spine synapses are important regulators in brain activity, filtering the ever present firings of nerve impulses.

- Exocytosis, the release of transmitter substance across the presynaptic membrane, is an all-or-nothing event which occurs with probabilities much smaller than one.

- A model, based on electron transfer, relates exocytosis with a two-state quantum trigger, leading by quantum tunneling to the superposition of these two states, followed by state reduction (collapse into one definite final state).

- The coherent coupling of synapses via microtubular connections is still an open problem. Quantum coherence ('macroscopic quantum state') is not needed to couple microsites, which exhibit quantum transitions with their definite phase relations, to produce spatiotemporal patterns. The quantum trigger can however initialize transitions between different macroscopic modes (stochastic limit cycles, Grifoni and Hänggi, 1996).

- The quantum trigger opens a doorway for a better understanding of the relations between brain dynamics and consciousness.

References


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**Sir John Eccles** (1903-1997)

Born in Australia, John C. Eccles worked with Sir Charles Sherrington in Oxford. After his return to Australia in 1937 he became Professor of Physiology at the Australian National University in Canberra. He devoted his interest to virtually all aspects of neuroscience, and his pioneering work on synaptic transmission was honoured with the Nobel Prize in 1963. In 1966 he moved to the United States, and worked there at the State University of New York in Buffalo. In 1975 he retired to Switzerland where he lived near Locarno. Here most of his numerous articles and books on the mind-brain problem where written.

【注】

この論文は、昨年9月の「認知科学」第4巻3号、「意識：脳と心の認知科学」特集の一編として掲載されるべきものでしたか、同号の編集後記にもあるように、著者の一人であるEccles氏の死去により間に合わなかったものです。特集と合わせてお読みいただけるようお願いいたします。

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