Article

The Central Enigma of Consciousness

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ABSTRACT

The nature and physical basis of consciousness remains the central enigma of the scientific description of reality in the third millennium. This paper seeks to examine the phenomenal nature of consciousness and elucidate a possible biophysical basis for its existence, in terms of a form of quantum anticipation based on entangled states driven by chaotic sensitivity of global brain states during decision-making processes.

Key Words: consciousness, central enigma, reality, biophysical basis, quantum anticipation, entangled state, chaotic sensitivity, global brain state, decision-making process.

1. The Enigmatic Theatre of Conscious Experience

The term consciousness itself is enigmatic. Both ‘mind’ and ‘consciousness’ present a varied array of associated words and concepts, which we need to clarify, to even begin to close in on the central enigma, which the terms present to us. Mind conjures up a plethora of concepts from minding i.e. emotional caring, or objecting, through the rational mind of thought and language based reasoning, mindfulness or focused concentration, to absent-, clear- or small- mindedness to the mindless blunders many of us consciously make, despite ourselves. Consciousness can mean everything from the root capacity to have subjective experiences at all, through awake alertness, as opposed to the slumber, or coma, of unconsciousness, through the fuzzy boundary between subconscious or unconscious processing that accompanies conscious cognition, to the restrictive idea of self-consciousness, as knowing that you know - “a conscious state is one which has a higher-order accompanying thought which is *about* the state in question” [i].

Wikipedia [ii, iii] has the following introductory descriptions, chosen because they are a product of a social process of consensual agreement as to their meaning and content:

> *“Mind collectively refers to the aspects of intellect and consciousness manifested as combinations of thought, perception, memory, emotion, will and imagination; mind is the stream of consciousness. It includes all of the brain's conscious processes. This denotation sometimes includes, in certain contexts, the working of the human unconscious or the conscious thoughts of animals. "Mind" is often used to refer especially to the thought processes of reason.”*
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> *“Consciousness has been defined loosely as a constellation of attributes of mind such as subjectivity, self-awareness, sentience, and the ability to perceive a relationship between oneself and one's environment. It has been defined from a more biological and causal perspective as the act of autonomously modulating attentional and computational effort, usually with the goal of obtaining, retaining, or maximizing specific parameters (food, a safe environment, family, mates). Consciousness may involve thoughts, sensations, perceptions,*

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> *moods, emotions, dreams, and an awareness of self, although not necessarily any particular one or combination of these."*

Although these contain a constellation of meanings, in which mind is sometimes focused on the attributes of reasoned, or even language-based thought, and consciousness is sometimes given the more restrictive meaning of self-awareness, both contain a central arena of subjectivity and sentience, while conceding that the boundaries between consciousness and the sub- or unconscious may be fuzzy, both in varied brain states, from waking thought to sleep and coma, and in complex autonomous processes, which go on below the level of immediate awareness, during activities like driving a car.

The central enigma we are referring to is not self-consciousness, but subjective consciousness – the capacity of a conscious sentient being to have a subjective experience of the existential condition, both of the everyday world, and of dream, memory and reflection [iv], hallucination, psychedelic reverie, and other forms of internal subjective experience, not necessarily correlated with the immediate events of the physical world.

In the face of the apparent causality of the Laplacian universe, many 20th century philosophers assigned to consciousness the orphan status of an epiphenomenon, a mere reflection of physical reality which could have no influence upon it. Some, such as Gilbert Ryle [v], who coined the term 'the ghost in the machine', went further, attempting to deconstruct the dualistic notion of mind altogether, as a form of false reasoning, claiming "that the idea of Mind as an independent entity, inhabiting and governing the body, should be rejected as a redundant piece of literalism carried over from the era before the biological sciences became established. The proper function of Mind-body language, he suggests, is to describe how higher organisms such as humans demonstrate resourcefulness, strategy, the ability to abstract and hypothesize and so on from the evidences of their behaviour" [vi].

Derived from the dualistic cosmology of Rene Descartes, this subjective arena is frequently referred to as the "Cartesian theatre", sometimes constructively, as in Barrs [vii, viii], who describes the theatre of the conscious in terms of working memory and its associated backdrops, but other times in somewhat disparaging terms as in Dennett [ix], who, rather than explaining consciousness, as he claims, replaces it with a 'multiple drafts model', more representative of the publishing industry, than either the conscious mind, or the sentient brain.

Some of these criticisms arise from the practical difficulties of defining the borders of consciousness and the difficulty of finding the actual mechanisms for generating the 'internal model of subjective reality' in terms of brain centers and their electrochemical dynamics, in the absence of clear evidence characterizing which brain states other than general focused global activity are responsible for consciousness, and as a result of the binding problem - how and where the disparate components of brain processing are all brought together in the hypothetical 'Cartesian theatre' of the mind. Some of these problems are misplaced because they are falsely identifying brain and mind states. For example, the 'binding problem' of brain dynamics may be resolved in practical terms through the phase coherence of excitations that are related, to form resonant neural circuits, differentiating them from the incoherent noise of the background, even though there is no specific brain centre as such where consciousness is generated.

At issue is a fundamental frame of subjective reference, and a confusion on the part of brain researchers and philosophers alike, between the physical world, and our representation of it in the so-called ‘internal model of reality’, which tends to become finessed in the dialectics of discourse on the problem.

The veridical reality is that from birth to death each of us is a subjective conscious observer of the existential condition. All our experiences of the physical universe are without exception subjective conscious impressions, which only we as individual subjective observers have access to. Ultimately all data and scientific observations of the universe likewise achieve validation through the subjective conscious experience of the researchers and those who read their papers and witness their results.

Far from being the fundamental components of veridical reality, the physical universe and all the constructs applied to it, from wave-particles through atoms and molecules, to complex biological systems such as the sentient brain and all our experiences of the everyday world around us are entirely, and without exception, purely and completely, abstract models of subjective conscious impressions, knitted together by a consensual agreement between subjective perceivers - that the table before us is solid and made of wood, plastic, or metal, as the case may be, and that our impressions of the world, from the lemon, or coffee cup on the table, to the horizon upon which we gaze, from a lonely hill top, looking out to sea, or the stars and galaxies we perceive in the sky, and entertain the humbling specters of an eventual demise in the heat death or big crunch, according to cosmological theories of the time.

Subjective consciousness is thus the primary veridical conduit of existential reality, and the phenomena of the objective world, for all the convincing lessons that we are biological organisms which bleed if we are cut, and lose consciousness if we slumber, or are concussed, are consensual stabilities of our subjective consciousness. This remains true, notwithstanding our obvious dependence on our brain states, and the fact that some of the most bizarre and interesting states of altered consciousness arise from psychoactive molecules, which mimic neurotransmitters, or transport processes affecting synapses and thus radically altering brain states.

However, based on the consistency of the scientific description of the physical universe and our part in it, as biological organisms dependent on our functioning brains to survive, this veridical logic has tended to become reversed, on the basis of the inaccessibility of subjective experiences to objective experimental testing and replication, so that consciousness has either been relegated to an epiphenomenon, merely reflecting, but not influencing, physical processes, e.g. in the brain, or banished to the wilderness, as ‘naïve or imaginary’ concepts not well founded in the domain of philosophical or scientific discourse.

Put in its completion, the relationship between consciousness and physical reality, rather than being either an epiphenomenon, or mere identity, or a fully divided Cartesian duality has characteristics more of the complementarity we see between the wave and particle aspects of the quantum world, in which a quantum can manifest wave, or particle natures, but not both at the same time, and in which the two aspects are also qualitatively symmetry-broken, one being discrete and the other continuous. It is this type of complementarity that Lao Tsu called a Tao or ‘way’ of nature, and subjective consciousness and the objective physical universe clearly have just such a qualitative complementarity existentially.

The nature of this complementarity and its fundamentality in the light of attempts on the part of functionalists to finesse consciousness to be merely an aspect of the attention process, or certain classes of excitation, such as those in the gamma range of the eeg (30-60 Hz), have been highlighted in David Chalmers’ [x] enunciation of the so-called “Hard Problem” in consciousness research, -

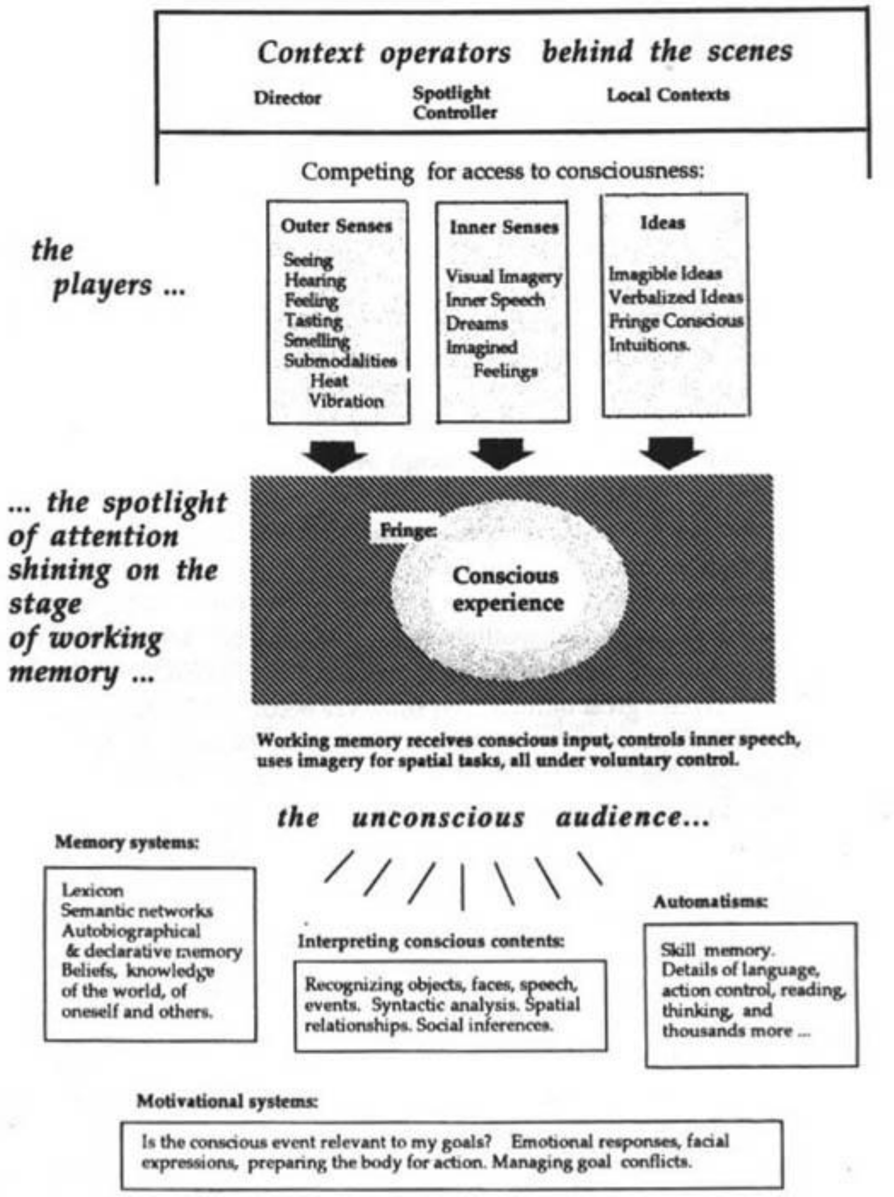

Fig 1: Baars' description of the Cartesian Theatre of consciousness and its 'players' in terms of functional working memory processes.

"explaining why we have qualitative phenomenal experiences. It is contrasted with the "easy problems" of explaining the ability to discriminate, integrate information, report mental states, focus attention, etc. Easy problems are easy because all that is required for their solution is to specify a mechanism that can perform the function" [xi]. For example Crick and Koch [xii] identify conscious states accompanying attentive processes with higher frequency electroencephalogram (eeg) signals in the gamma range. Defining consciousness as a functional process associated with attention and/or working memory is addressing an 'easy' problem in consciousness research. The dilemma of the 'hard' problem implies that no purely objective mechanism can suffice to explain subjective consciousness as a phenomenon in its own right.

Baars' approach suggests that consciousness is associated with the whole brain in integrated correlated activity and is thus a property of the brain as a whole functioning entity rather than a product of some specific area, or system, such as the supplementary motor cortex [xiii, xiv, xv]. Furthermore, the approach rather neatly identifies the distinction between unconscious processing and conscious experience in terms of whether the dynamic is confined to local or regional activity or is part of an integrated coherent global response. It is also consistent with there being broadly only one dominant stream of conscious thought and experience at a given time, as diverse forms of local processing gives way to an integrated global response. A series of experiments, many by teams working with Stanislas Dehaene, involving perceptual masking of brief stimuli to inhibit their entry into conscious perception [xvi, xvii, xviii, xix, xx, xxi, xxii], studies of pathological conditions such as multiple sclerosis [xxiii, xxiv], and brief episodes in which direct cortical electrodes are being used during operations for intractable epilepsy [xxv] have recently tended to confirm the overall features of Baars' model of consciousness founded on the global work space [xxvi, xxvii, xxviii].

This couples again rather nicely with a recently 'discovered' system called the 'default network' [xxix], which was unearthed when background readings discarded from many brain scan studies were found to have common dynamical features. It has been proposed that the default network is an active brain process we drift into when not preoccupied in more essential tasks dominating our attention, and that it may have adaptive value in rehearsing strategic situations important for our survival. One can loosely identify the default network with the process of daydreaming, reminiscence, worrying and idle thought, but in these terms it looks clearly like a manifestation of global work space in action and hence provides another view on the global mechanisms being brought into play in conscious experience [xxx].

However, while this integrates the notion of conscious experience neatly in with the coordinated activity of the whole brain, it still doesn't explain how the brain generates subjective conscious experience, or indeed what the subjective aspect provides that has led to it being selected by evolutionary change.

Completing the enigma of consciousness is the thorny spectre of 'free-will', upon which all concepts of law and personal accountability hinge, as well as the assumptions of virtually every religious tradition. Although it is possible to couch questions of personal accountability in purely behavioural terms of social conditioning, the problem of free-will remains a shibboleth for the effectiveness of the scientific description. While many scientifically-trained people consider that they may in principle be a chemical machine driven by their brain states, the notion that subjective consciousness decision-making has no capacity whatever to influence the physical circumstances around leads to catatonic stasis. Everyone who gets up in the morning and does something so predictable as pouring a cup of coffee is making a direct investment in the notion that they are in some sense in control of their personal decisions and that their feeling of subjective autonomy is a valid expression of their condition. We act in the world on this assumption and upon this investment.

Like subjective consciousness, free-will has become an orphan of the scientific description, seemingly inconsistent with the hypothesis that the behavior of the organism is purely a function of its brain reacting as an electrochemical machine, albeit a very complex one to the physical conditions of the organism's environment. However, from the outset of the quantum era, scientific researchers have noted that, since the quantum description of reality is not deterministic, the apparently stochastic nature of quantum uncertainty could provide a loophole for free-will, since the universe is no longer in-principle a Laplacian mechanism [xxxi]. Arthur Eddington [xxxii], for example noted that the uncertainty of position of a synaptic vesicle was large enough to correspond to the thickness of the cell membrane, giving a possible basis for a change in neurodynamics arising from quantum uncertainty. Concluding that intentional volition might then be inconsistent with the chance probability-based calculations of particle statistic, Eddington then effectively suggested a form of hidden correlation in sub-quantum dynamics: a correlated behaviour of the individual particles of matter, which he assumed to occur for matter in liaison with mind.

This 'loophole' has led to a continuing tradition of physicists, mathematicians and brain researchers, speculating on various models by which the quantum world might interpenetrate with the sort of brain dynamics associated with conscious decision-making. We will look at these in detail, once we have examined the brain dynamics associated with conscious states.

2. A Dynamic View of the Conscious Brain

Unlike the digital computer which is a serial digital device based on a discrete logic of 0s and 1s, the brain is a massively parallel dynamic organ. Although the action potential of long neuronal axons is a pulse coded firing rate proportional to membrane depolarization, many neurons and indeed those forming the organizing centre of many processes have continuously graded potentials. Thus although some individual neuron outputs may be pulsed action potentials, the electrical activity of the human brain, as expressed in the eeg consists of broad spectrum excitations indicative of chaos [xxxiii], rather than the discrete resonances of ordered states. While some aspects of the eeg, such as the alpha rhythms of visual relaxation, may be housekeeping activities, as noted, oscillations in the gamma band have been associated with specific conscious thought processes. The basis of the eeg appears to lie in dynamic feedback between excitatory and coupled inhibitory neurons which set up mutual oscillations through a phase-delayed feedback loop, which implicates it as a major dynamical feature of cerebral processing.

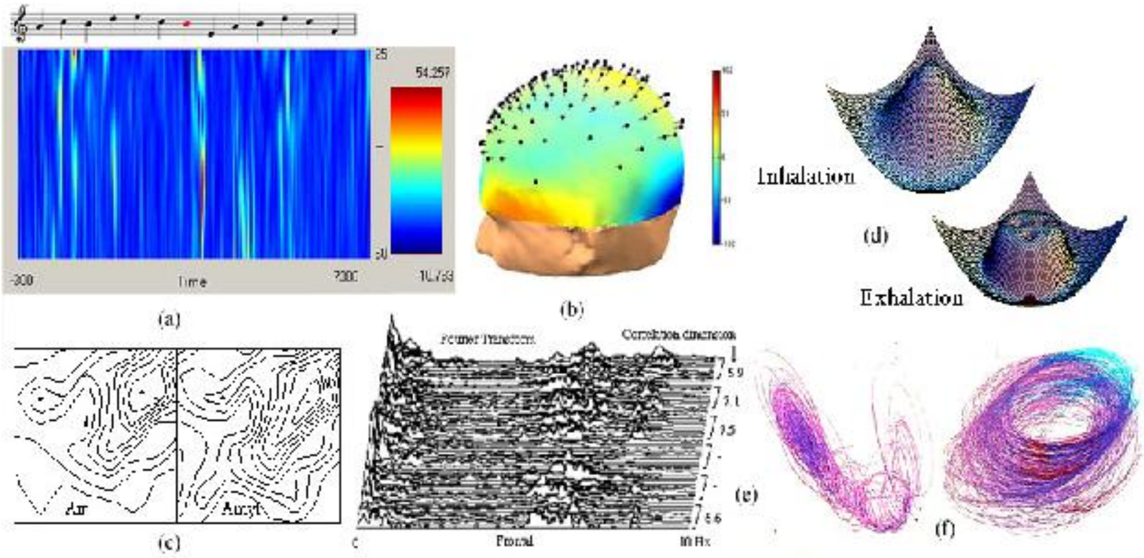

Fig 2: Evidence for both dynamical chaos and phase wave-front 'holographic' processing. (a) Wavelet (morlet) transform, showing time evolution of amplitudes with a peak in the gamma band accompanying recognition of an anomalous note is consistent with phase-front processing. Broad-spectrum excitation (extended vertical distribution of frequencies) is also consistent with chaotic dynamics in the time domain. (b) Coherent distribution of electroencephalogram over the cortex, is consistent with globally coupled excitation. (c) Extended spatial distribution of cortical activation accompanying recognition of an odour. (d) Freeman's [xxxiv] [xxxv] model of olfactory recognition involves a transition from high-energy chaos on inhalation to enter a new or existing strange attractor basin as the energy is lowered on exhalation. Although this is a transition from chaos to an ordered outcome, the attractor may be a strange attractor, still supporting chaos locally within the basin. (e) Fourier transforms of electroencephalogram, showing broad-spectrum excitation and

correlations dimensions consistent with global chaotic dynamics. (f) Putative strange attractors in the electroencephalogram.

While it might seem a contradiction that a brain state leading to any form of strategic decision could be chaotic, this is not actually the case. Ordered dynamical systems are inexorably drawn towards existing equilibria or resonant attractors making them insensitive to their surroundings. A key characteristic of chaotic dynamics is the ‘butterfly effect’ – their arbitrary sensitivity on their initial, or boundary conditions – which in the words of Lorenz [xxxvi] enable fluctuations as small as those of a butterfly’s wings to become amplified onto a tropical cyclone.

The dynamical brain needs to be arbitrarily sensitive to its external conditions to respond effectively to the sometimes very subtle clues from the world around us that are absolutely essential for survival. A second key characteristic particularly of high-energy chaos is that it tends to explore the entire space of available states, sometimes called the ‘phase space’, pseudo-randomly, so that it can appear anywhere, without prejudicing the outcome or missing an angle. Thus a fundamental theme, which has proved very useful in exploring brain dynamics, is a transition from chaos to order, in which an unstable high-energy chaotic exploration falls into an ordered attracting state, corresponding to recognition of a smell, or the ‘aha’ of eureka that replaces the confusion of a problem with the flash of inspiration of an insight that appears to pop out of nowhere.

While these excitations may be chaotic in the time domain, the dynamics accompanying perceptual recognition shows spatially correlated excitations similar to a hologram, in which the recognition process arises from populations of neurons firing together in a resonant phase-coherent manner, which distinguishes the recognized stimulus from the random ground swell of unrelated excitations. In this respect Karl Pribram [xxxvii, xxxviii] has noted that such processes are analogous, if not identical to, quantum measurement based on constructive phase-dependent wave interference.

Phase coherence is consistent with chaotic dynamics in the time domain because mode-locked resonances between oscillators are a feature of non-linear systems. For example the heart beat, although approximately periodic, has dynamics comparable to a chaotic sinusoidally kicked rotator [xxxix], which enables it to maintain mode-locked non-linear resonance with heart pacemaker cells which in turn are under central nervous system influence.

By contrast with a digital computer which relies on gigahertz speed to perform discrete serial computations, the brain is a massively parallel organ, using wave-front processing, containing between 10^{10} and 10^{11} neurons each of which can have up to 10^4 excitatory and inhibitory synapses using a variety of chemical neurotransmitters to modulate electrochemical transfer. The extreme parallel-distributed basis of this processing is emphasized by the fact that there may only be around 10 serial synaptic junctions between sensory input and motor output. By contrast, a digital computer needs to make as many serial iterations as the computation requires before coming up with an answer, and the latest PCs allow for only up to 4 parallel units and even the largest super-computers have no more than a few thousand, principally used in a restricted form of matrix calculation, such as weather prediction, where each unit is essentially carrying out a similar computation on differing initial conditions.

As shown in figure 3, the cerebral cortex of the mammalian (and thus human) brain consists of a large convoluted sheet about 1 m^2 consisting of up to six layers of neurons, organized into functional columns on a scale of around 1 mm^2 and mini-columns of 28–40 µm performing unique processing in a modular manner on aspects of sensory and cognitive processing, from lines of a given orientation, through sounds of a given pitch to more abstract features, such as recognition of specific faces, or facial expressions, to associating the sound of a word with its semantic meaning. The cortex is broadly divided between frontal areas responsible for action and its abstraction in terms of plans and goals and perception and its abstractions in terms of spatial orientation (parietal), semantic meaning (temporal) and other creative, expressive, and classificatory skills.

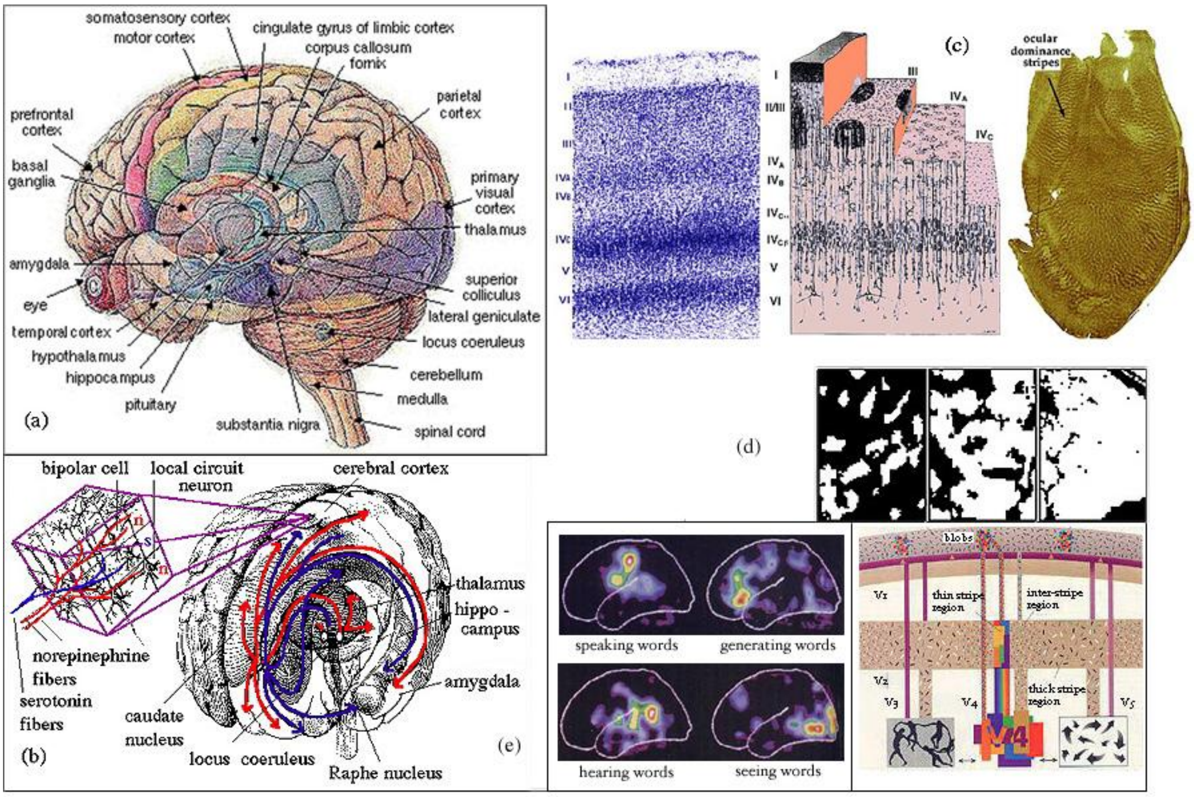

Fig 3: Structual outlines of the brain as a dynamical organ. (a) Major anatomical features including the cerebral cortex, its underlying driving centres in the thalamus, and surrounding limbic regions involving emotion and memory, including the *cingulate* cortex, *hippocampus* and *amygdala*. (b) Conscious activity of the cortex is maintained through the activity of ascending pathways from the thalamus and brain stem, including the reticular activating system and serotonin and nor-adrenaline pathways involved in light and dreaming sleep. (c) Processing in the cortex consists of up to six layers of neurons, forming modular processing columns around 1 mm in size, illustrated in cortex stained for ocular dominance (right). (d) Such modularity is dynamic as shown by changes on ocular dominance as a result of covering one eye during development. (e) Modular cortical processing illustrated in pet scans of cortical activity during language processing and the parallel processing of movement and colour in the visual cortex.

The organization of these modular columns is dynamic to the extent that covering one eye will dynamically alter the balance of binocular dominance, and in a blind person even use visual areas for spatial orientation based on sound rather than vision. Many aspects of sensory processing occur in a parallel modular manner, for example, separate local regions process colour and movement, so that pathological conditions can result in loss of colour, or motion perception, independently of the other.

The electrical activity of the cortex is driven by centres in the underlying nuclei in the *thalamus*, which have reciprocal connections with corresponding areas of the cortex. In isolation, cortical tissues tend to be electrochemically quiescent, which emphasizes that to a certain extent the cortex represents complex boundary conditions, modulating underlying thalamic excitations. Moreover the entire span of cortical activity accompanying waking consciousness is dependent on a general level of excitatory activity welling up from the brain stem centres of the reticular activating system and major modes of dynamical brain activity modulation, such as light and dreaming sleep are likewise modulated through ascending nor-epinephrine, dopamine and serotonin pathways passing from the brain stem upwards to permeate specific layers of the whole cortex.

Active cognition is believed to involve an interplay of so-called ‘working memory’ in which frontal regions modulating the goals and direction of the thought process, are interacting with parietal and temporal areas providing the spatial and semantic information involved. There are actually two cortices, left and right, connected by large parallel tracts of nerve fibres, the *corpus callosum*. The left and right cortices are lateralized to varying degrees, particularly in men, so that language articulacy and other more structured forms of cognitive processing are predominantly in the left cortex and more generalized diffuse types of processing occurs in the right cortex.

Consistent with edge of chaos processing involving a transition to order from chaos, studies of the kind of insight process that leads to phenomena such as Archimedes’ “Eureka!” [xl] appear to stem from the right anterior *superior temporal gyrus*, when distracting structured ‘thinking’ activities of the left hemisphere have been replaced by the relatively ‘contemplative’ relaxation of alpha activity.

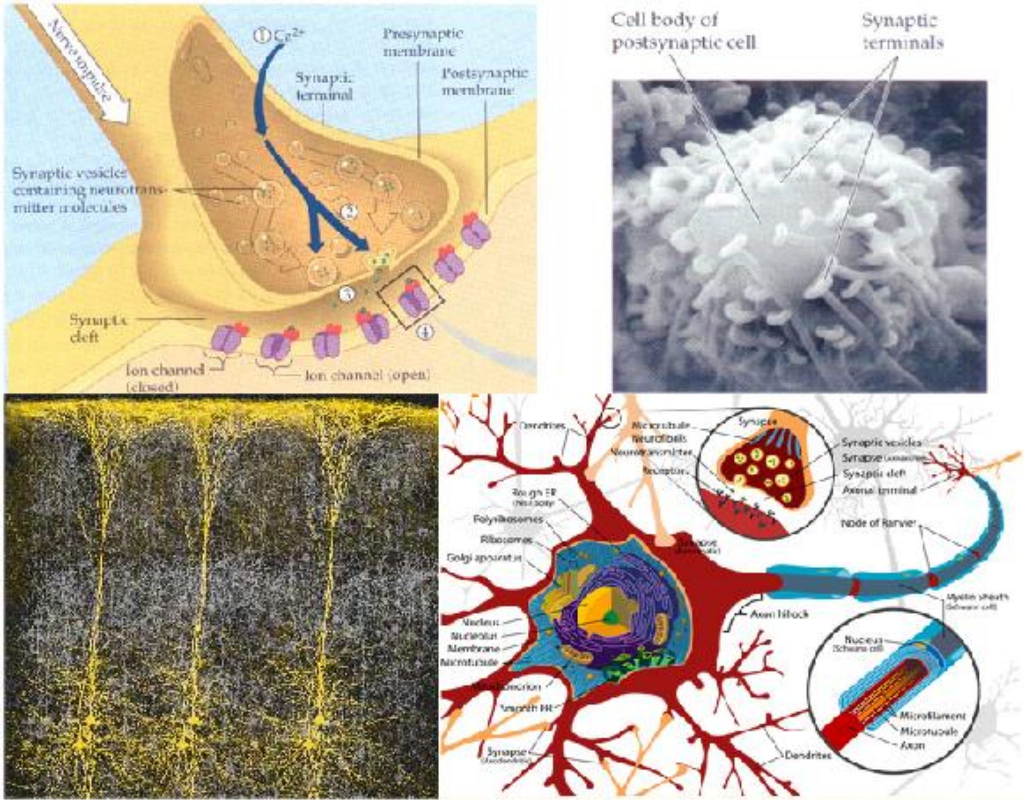

Fig 4: Quantum fractality differs from classical fractality in that it becomes discrete at the quantum level. Fractal scale transformations emerge from quantum non-linearities forming the chemical bond, in emergent stages through tertiary and quaternary molecular structures, to cellular organelles, cells, tissues and finally the whole organism, with its successive bifurcations of development to form the tissue layers and later, interactive migrations of specific cell types. Nervous system organization is thus fractal, running from the molecular level of ion-channels, to neurotransmitter vesicles and synaptic junctions (upper), then to neurons (lower right), then to neuronal complexes such as mini-columns (lower left) and finally to whole brain activation.

In addition, feedback systems involving emotional recognition, flight and fight reactions and the establishment of long-term sequential memory surround the periphery of the cortex in the so-called limbic system, comprising the *cingulate cortex*, *fornix*, *hippocampus*, *amygdala* and associated structures. The semantic significance of the temporal cortex appears also to be able to combine with the intense emotional significance of the closely associated *amygdala* to create mystical and other symphonic experiences in temporal lobe epilepsy, a region coined by Ramachandran [xli, xlii] as "the God Spot" for this mix of emotional significance and ultimate meaning. This association may have a genetic basis in religiosity [xliii] as an evolutionary adaptation enabling larger, more dominant societies [xliv].

3. Edge of Chaos, Self-organized Criticality and Fractal Sensitivity

Between the global level, the cellular level and the molecular level are a fractal cascade of central nervous processes, which in combination, make it theoretically possible for a quantum fluctuation to become amplified into a change of global brain state. The neuron is itself a fractal with multiply branching dendrites and axonal terminals, which are essential to provide the many-to-many synaptic connections between neurons, which make adaptation possible. Furthermore, like all tissues, biological organization is achieved through non-linear interactions which begin at the molecular level and pass upward in a series of scale transformations through supra-molecular complexes such as ion channels and the membrane, through organelles such as synaptic junctions, to neurons and then to neuronal comp-lexes such as cortical mini-columns and finally to global processes.

At the molecular level, the ion channel is activated by one, or two, neurotransmitter molecules. Because neurons tend to tune to their threshold with a sigmoidal activation function, which has maximum slope at threshold, they are capable of becoming critically poised at their activation threshold. It is thus possible in principle for a single ion channel, suitably situation on the receptor neuron, e.g. at the cell body where an activation potential begins to act as the trigger for activation.
The lessons of the butterfly catastrophe combined with evidence for transitions from chaos in perceptual recognition therefore suggest that if a brain state is in a transition at the edge of chaos or is in a state of self organized criticality, in which the system tunes to a critical state such as a sand pile where there are fractal 'avalanches' of activity global instabilities, which are encoding for the unresolved perceptual or conceptual context may be 'resolved' through amplification of a local fluctuation at the neuronal, synaptic or ion-channel level.

Although neuroscientists have tended to discount the idea that micro-instabilities could lead to global changes in brain dynamics, on the basis that mass action will overwhelm such small effects, a variety of lines of evidence have demonstrated that fluctuations in single cells can lead to a change of brain state.

In addition to the issue of sensitive dependence in chaotic systems, two further lines of evidence suggest changes in ion channels and/or single cells can influence global brain states.

The first of these phenomena is stochastic resonance [xlv], in which the occurrence of noise, somewhat paradoxically, leads to the capacity of ion channels to sensitively excite hippocampal cells and in turn to cause a change in global brain state. In this sense noise is playing a similar role to the ergodic properties of dynamical chaos, which likewise distribute the dynamic pseudo-randomly and so prevent the dynamic getting stuck into the rut of a given ordered attractor and it is thus able to fully explore its 'phase' or dynamical space. Thermodynamic 'annealing' is likewise used in classical artificial neural nets to avoid them becoming locked in sub-optimal local minima.

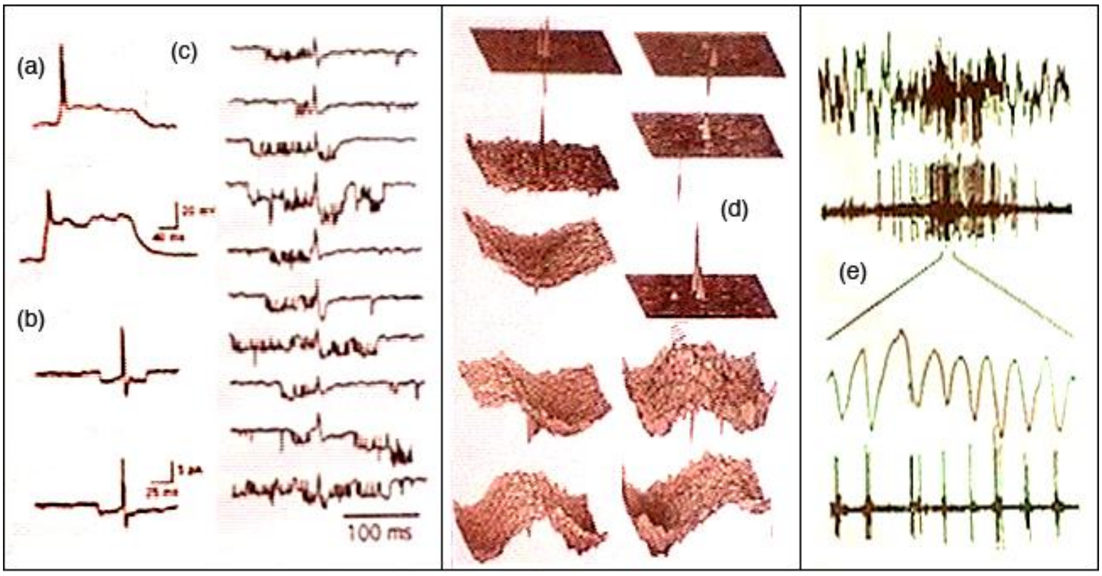

Fig 5: Evidence for complex system coupling between the molecular and global levels. Stochastic activation of single ion channels in hippocampal cells (a) leads to activation of the cells (c). Activation of such individual cells can in turn lead to formation of global excitations as a result of stochastic resonance (d). Individuals cells are also capable of issuing action potentials in synchronization with peaks in the eeg (e).

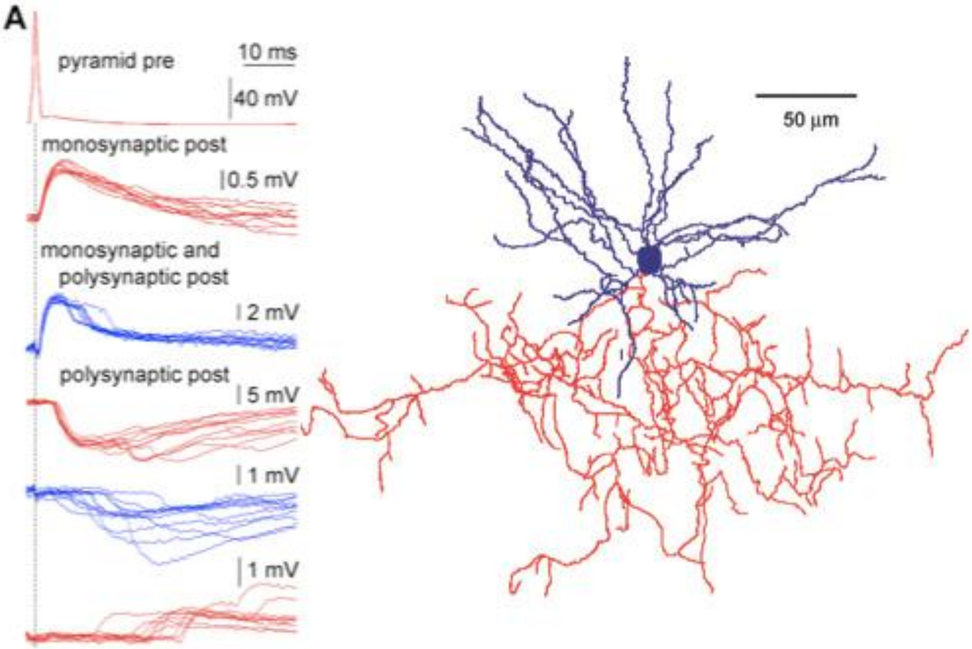

Fig 6: Left: Single pre-synaptic pyramidal action potential leads to multiple post-synaptic excitations. Right: Structure of chandelier or axon-axonal cells with dendrites (blue) and axons (red).

More recently it has been discovered that a specific class of cortical neuron, the chandelier cell is capable of changing the patterns of excitation between the pyramidal neurons that drive active output to other cortical regions and to the peripheral nervous system, in such a way that single action potentials of human neurons are sufficient to recruit Hebbian-like neuronal assemblies that are proposed to participate in cognitive processes. Chandelier cells, which were only discovered in the 1970s, and are more common in humans than other mammals such as the mouse, and were originally thought to be purely inhibitory, are axon-axonal cells, which can result in specific poly-synaptic activation of pyramidal cells [xlvi, xlvii].

The research paper and review note:

The increased signal-to-noise ratio in the network provided by hyperpolarizing GABAergic synapses is further amplified by the coincident action of chandelier cells, resulting in a sparse and potentially task-selective activation of pyramidal neurons. Thus, the human microcircuit appears to be tuned for unitary-EPSP–activated Hebbian-like functional cell assemblies that were proposed as building blocks of higher-order cortical operations and could contribute to single cortical cell–initiated movements and behavioral responses.

This reveals an extremely efficacious means of activity propagation in the cortical network. Although earlier work had shown polysynaptic activations following a single chandelier spike, the current study demonstrates much longer responses. Moreover, one of the most interesting results relates to the temporal structure of the activity patterns elicited after stimulation of a single neuron. While most of them appear to propagate through the circuit with increasing disorganization, occasionally the authors were able to trigger an amazingly precise temporal pattern. This implies that the microcircuit is capable under some circumstances of generating patterns of activation with low jitter and high temporal precision.

Given the potential for fluctuations at the molecular, ion-channel, synaptic or neuronal level to become the organizing centre resolving instabilities in global brain dynamic, it becomes possible to form an edge-of-chaos model for resolving situations of cognition involving intuition, insight and the ‘eureka’ attributed to Archimedes’ sudden discovery of his principle. In this model, the dynamic of the ‘problem’ remains unresolved and thus contains instabilities, which in turn become sensitive to perturbation on descending fractal scales leading to the molecular and quantum level.

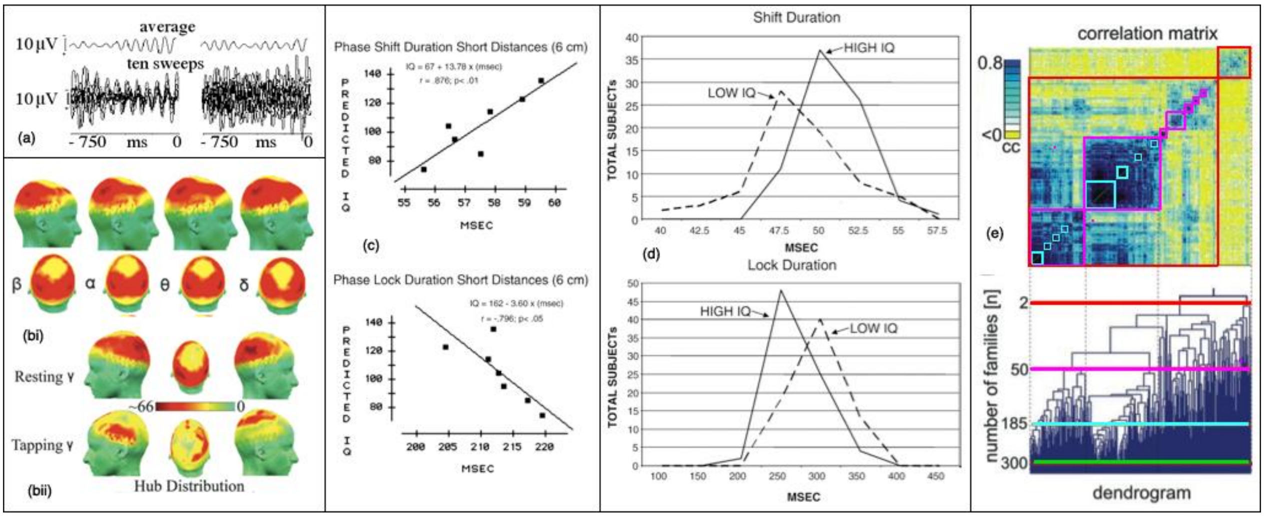

Fig 7: (a) EEG sweeps are coherent when anticipating a regular tone but decoherent when the tone becomes erratic in its timing [l]. (bi) Neural connection hubs are scale independent in terms of frequency forming a small world network consistent with self-organized criticality, (bii) Hubs compared in resting and tapping. (c),(d) Intelligence measures correlate positively with phase shift duration and negatively with phase lock duration [li]. (e) Evidence for self organized criticality. Sorted correlation matrix and dendrogram of avalanches in a cortical slice [liii, liv].

Such an unstable dynamic is tending to a transition from higher-energy chaos to order by developing a new attractor, out of the fractal diversity of repelling attractors in the chaotic dynamic. In terms of an active brain state, this would be likely to correspond to a global excitation, say in the gamma range containing several uncorrelated phase components representing features of the problem that cannot be put into coherent relationship. Hence the essential instability at the fractal level would consist of a transition from multiple uncorrelated phases to the emergence of a correlated ‘organizing center’ resolving the global instability.

A recent growth area of research consistent with, but not limited to the edge of chaos concept, is the development of models based on self-organized criticality, the tuning of processes from sand piles to earthquakes towards a critical state in which fractal avalanches maintain the process in a critical state. In the case of a sand pile, as in an hour-glass, if the angle is too steep, massive avalanches return it to the critical angle. Likewise, if it is too shallow more sand will pile up with few or on avalanches until the critical angle is reached. Edge of chaos processes share this tuning towards the critical state at the boundary, but the reasoning also extends to stochastic systems such as the Ising model [xlviii] of magnetization.

Karl Pribram’s concept of the holographic brain [xlix] has drawn attention to the deep analogy, and possible physical correspondence, between phase coherence in brain dynamics and the wave phase basis of all quantum measurements. Phase coherence provides a basis for distinguishing the processes the brain is paying attention to from the decoherent groundswell of background noise. Key experimental investigations [l, li] have repeatedly confirmed a relationship between phase coherence in central nervous electrodynamics and recognized, or anticipated, stimuli.

More recently a variety of key experimental research results [lii] have shown a close correspondence between self-organized criticality and brain dynamics in processing real perceptual and cognitive tasks. These are reflected in several different forms of analysis. Study of avalanches is isolated neuronal circuits [liii] [liv] shows the avalanches are tuned to a critical threshold where a given avalanche is like to elicit only one further one, consistent with self-organized criticality in neural circuits.

The fractal power law dynamics of active brains states has been found to correspond closely with self-organized criticality related to computational simulations of the Ising model [lv]. Brain processing states have also been found to reflect a small-world network architecture consistent with self-organized criticality [lvi, lvii] across all frequency scales used in electroencephalogram studies. Small-world networks lie between regular networks, where each node is connected to its nearest neighbours, and random networks, with no regular structure but many long-distance connections between nodes at opposite sides of the network. A small-world network enables communication between any two locations of the network through just a few nodes - the "six degrees of separation" reputed to link any two people in the world. In the brain, the number is closer to 13.

In an intriguing 2008 study [lviii], high intelligence, as measured on IQ scores, was found to consistently correlate with longer times of phase decoherence, between phase-locked coherent states, and shorter phase-locked episodes. The idea behind this is that longer decoherence times corresponds to bringing larger systems of neurocircuits into play, in cognitively analyzing a given situation and that shorter phase-locked episodes corresponds to not getting stuck in a non-adaptive so called ‘fixed position’.

By contrast with the earlier work on chaos in brain dynamics which tended to deal predominantly with house-keeping states, rather than active cognition, these studies involve intelligence and thought processes. They are consistent both with a stochastic approach to criticality and with edge of chaos dynamics in the active brain.

4. Sensory Transduction and Subjective Experience

The occurrence of putative sensory transduction genes in the central nervous system is consistent with a novel biophysical model supporting subjective consciousness (King [lix]) - that the distributed functioning of the central nervous system provides an 'internal sensory system' which can generate abstracted sensory experiences of reality forming an 'internal model of reality' using the same physical principles as are involved in sensory transduction in a bi-directional manner, enabling coherent generation and reception of biophysical excitations, particularly those associated with vision and audition. Olfaction has a fundamentally different basis, both in brain architecture and in the fact that it involves specific molecular receptors, which cannot regenerate their stimuli by reverse transduction, although there is evidence for olfactory synesthesia. Some forms of synesthesia, such as responding with feeling to seeing another person's finger touched, may also involve specific interactive circuitry, including mirror neurons.

Recent research in whole genome mapping of the mouse brain has made it possible to investigate the potential central nervous function of genes that might otherwise be associated primarily with peripheral sensory transduction. At the same time, the actual molecules involved in sense transduction, in vision, hearing and touch are being characterized. The first putative transduction molecule for mammalian touch, stomatin-like protein 3 (SLP3, or Stoml3) was reported this year in Nature, and putative molecules in the auditory transduction pathway, epsin, and cadherin 23 (otocadherin) have only been reported in the last five years and otoferlin in 2006. Research into the genetic evolution of the visual system has also unearthed provocative new findings about vision, which became the trigger for this hypothesis. In parallel with the usual cilia-based photo-transducer molecule c-opsin are retinal ganglion cells, which use melanopsin, or r-opsin related to insect opsins (based on organelles called rhabdomeres), which depolarize rather than hyperpolarize. It has also been discovered that both types of opsin work in opposition in the reptile parietal (pineal) eye.

At an even more basic level, excitable neurons have ion channels which undergo conformation changes associated with voltage, and orbital or ‘ligand’-binding, both of internal effectors such as G-proteins and externally via neurotransmitters, such as acetyl-choline. They also have osmotic and mechano-receptive activation, as in hearing and can be also activated by photoreception in certain species. At a ground level all conformation changes of ions channels are capable of exchanging photons, phonons and orbital perturbations representing a form of quantum synesthesia.

Attention has more recently been focused on biophotons as a possible basis of processing in the visual cortex based on quantum releases in mitochondrial redox reactions [lx, lxi, lxii]. Microtubules have also been implicated.

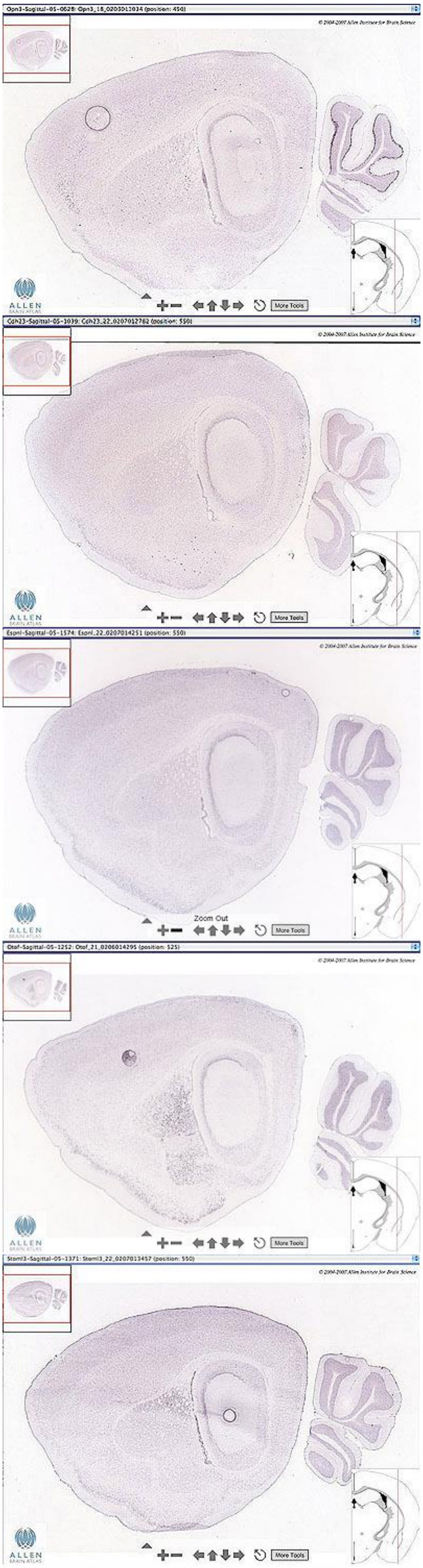

Fig 7b: Large scale mouse brain expression profiles of encephalopsin (Opn3), otocadherin (Cdh23), espin (Espnl), otoferlin (Otof) and Stom3 (Allen Brain Atlas [lxiii]) illustrate the wide and discretely specific expression of sensory transduction molecules for three senses, vision, hearing and touch in the central nervous system. Does this mean that the 'internal model of reality' evokes subjective experience using similar molecules to the physical senses?

5. Computational Intractability, Classical Chaos and Quantum Uncertainty

The apparent contradiction between the idea of precise classical computation (which abhors disrupting noise) and the apparent unruliness of chaotic excitation, (which, although being in principle deterministic, becomes unpredictable, through amplification of small discrepancies due to sensitive dependence, resulting in an 'ergodic' trajectory, filling phase space in a similar to a random walk) can be resolved immediately we look more closely at the sort of computational problems a living nervous system actually needs to solve in minimal time to survive.

The traveling salesman problem – how to find the shortest path around n cities – is classed as *np*-complete [lxiv]. Characteristically to classically compute a given solution requires checking each of the $\frac{(n-1)!}{2}$ possible cyclic paths and finding the smallest. However because this is super-exponential, even for a small number of cities like say 25, the computation time required stretches out to the age of the universe. The same consideration applies to virtually every environmental decision-making process a living organism faces, such as which path to take to the water hole, since these all involve an exponentially increasing number of combinations of contingent factors in the open environment. An animal cannot afford to wait more than a split second making a real survival decision, or it may be leapt upon by a tiger and consumed, so nervous systems have to find an immediate real-time way of solving any such potentially intractable decision-making problem.

The solution used by artificial neural nets, which model a problem like the traveling salesman problem as an energy minimization on a landscape representing the distances between the cities, is to apply thermodynamic annealing, starting with a high temperature which prevents the dynamic becoming stuck in a high local minimum, gradually reducing the temperature of random fluctuations, arriving at a reasonable sub-optimal local minimum. Statistical computational methods of solution work similarly.

The Freeman model of perception fig 2(d) uses a transition from high-energy chaos to a lower energy strange-attractor in much the same way, using the high-energy chaos to avoid the system becoming trapped in a far-from-optimality attractor until the 'phase' space of the system has been fully explored.

Such a system provides for a smooth transition between a situation in which the boundary conditions lead to a clear computational outcome and hence a decision based on one choice having a manifestly higher probability of survival, and other situations, in which, like the problem of Archimedes' possibly crown, there is no predisposing resolution of the system because the problem has not yet been solved and the contextual factors remain ambiguous, or inconsistent.

Unlike the discrete Von Neumann or Turing machine, biological nervous systems appear to work on dynamical principles which provide the capacity to induce a transition from chaos to order, where the classical computer would run into the Turing halting problem – unable to determine whether, or when, the computational process will end.

Clearly such a transition will involve sensitive dependence on initial and other boundary conditions and will be in a classical sense unpredictable (just as the butterfly effect is) and since it involves molecular processes at the quantum level, may invoke quantum uncertainty as well. We thus need to investigate how these two effects might come together, and explore whether and how they might play upon the processes of perceptual recognition and conceptual insight.

The first point of reference is a brief review of the wave-particle relationship and how the uncertainty relationship comes about. By Einstein's law $E = h\nu$, the energy of a particle is equivalent to the frequency of the wave as the momentum is likewise to the wavelength. If we then want to measure the energy, this will be equivalent to measuring the frequency, but as we can't sample parts of a quantum wave, the only way we can know the frequency is effectively to count the beats against a reference frequency. The time delay $\Delta t = \frac{1}{\Delta \nu}$ between successive fronts where the two waves are in phase, giving constructive interference, then gives us the uncertainty relation $\Delta E \cdot \Delta t \; ; \; \frac{h}{2\pi}$.
Constructive interference from corresponding phase fronts passing through two slits also gives us the basis in wave-particle complementarity of the two-slit interference experiment fig 8. Complementarity is demonstrated in the release of a photon from an excited atom in the bulb, as a discrete localized 'particle', corresponding to an orbital transition from an excited atomic orbit. The photon then travels through both slits as a wave, which overlaps itself to form bright bands of constructive interference and is again absorbed as a particle by a silver atom on the photographic film. Although these discrete particles arrive one at a time and could appear anywhere the wave function is not precisely zero, as numbers of particles arrive, their statistical probability of occurrence is distributed according to the complex square of the amplitude of the wave $P = \varphi^* \varphi$.

The particle incidence gives rise to one of the fundamental unresolved questions of quantum theory. As the wave function doesn't determine where the particle should end up, it is deemed that the wave function has 'collapsed' at the point the particle is detected and unlike the linear evolution of the wave function, this collapse process is stochastically unpredictable, leading to the idea that there may be a deeper 'hidden variable' theory explaining how each photon actually 'decides' where it ends up.

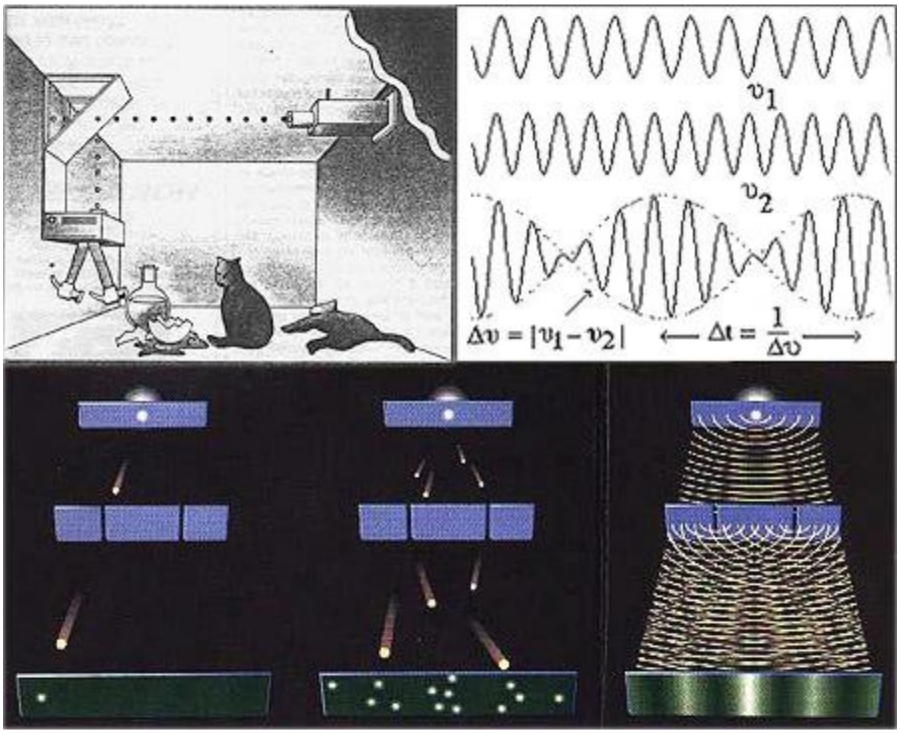

Fig 8: Top right: Beats of constructive wave interference determine the uncertainty principle. Bottom: Two-slit interference experiment illustrates wave-particle complementarity. Top left: Cat Paradox experiment.

The contrast between quantum theory, which leads only to parallel probabilities that the photon could be anywhere in its wave function, and the real world in which unique histories always occur, led to Schrödinger coining the 'cat paradox', in which a cat is predicted to be both alive and dead by quantum theory with differing probabilities, if a Geiger counter is set to break a vial of cyanide, but when we open the box the cat is either alive, or dead but not both. Various approaches, including hidden variable theories and quantum decoherence [lxv] caused by interaction with 'third-party' quanta have been invoked to explain this process but none eliminate the essential complementarity.

When we come to consider how systems, which would classically display features of chaos behave in the quantum world, we find a series of apparent contradictions, in the so-called quantum suppression of chaos. In fig 9 the quantum stadium is used to illustrate several features of this phenomenon. The classical stadium billiard is chaotic because the periodic orbits, some of which are shown in (d), are unstable, so that a ball with a trajectory differing by an arbitrarily small amount is deflected by increasing amounts by the curved boundary of the region, so that the periodic orbits are all repelling and almost every orbit is a chaotic trajectory which eventually fills the region 'ergodically' in an unpredictable, pseudo-random manner, as in (a), due to sensitive dependence on initial conditions.

The quantum wave function solutions (b) work differently, displaying peaks of the probability function around the periodic orbits, defying their repelling nature. The reasons can be easily understood of we use a semi-classical approximation, by releasing a small wave packet and watching the way it bounces back and forth as in (c). Whenever the wavelength of the packet forms a rational relationship with the length around a transit any of the reflecting periodic orbits, we get an eigenfunction of the quantum wave function, which constructively interferes with itself, as a standing wave, just as do the orbitals of an atom, to form a probability peak around the periodic orbit. Even when a trajectory is a little off the periodic orbit, the spreading wave packet still overlaps itself contributing to the probability peak.

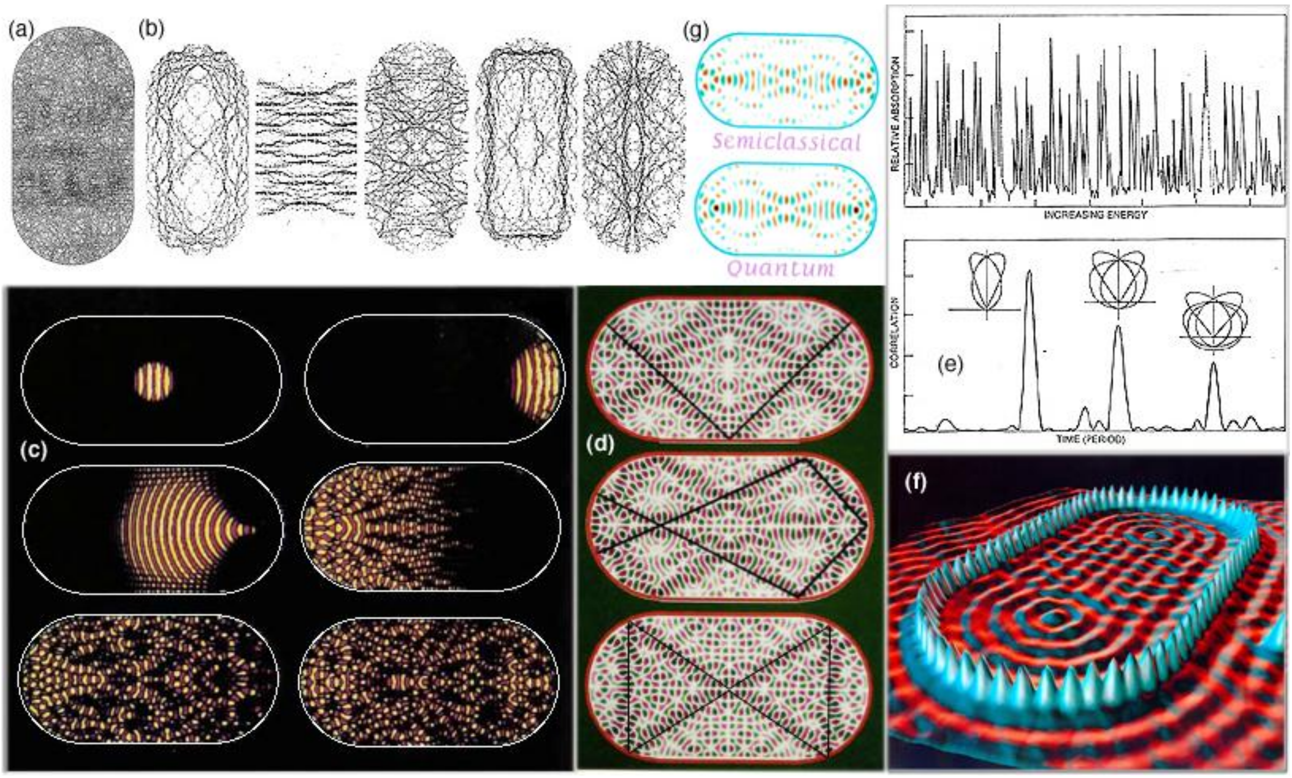

Fig 9: Quantum chaos: The classical stadium billiards is chaotic. A given trajectory has sensitive dependence on initial conditions. As well as space-filling chaotic orbits (a) [lxvi], the stadium is densely filled with repelling periodic orbits, three of which are shown in black in (d). Because they are repelling, neighbouring orbits are thrown further away, rather than being attracted into a stable periodic orbit, so arbitrary small deviations lead to a chaotic orbit, causing almost all orbits to be chaotic. The quantum solution of the stadium potential well (b) [lxvii] and (d) [lxviii] shows 'scarring' of the wave function along these repelling orbits, thus repressing the classical chaos, through probabilities clumping on the repelling orbits. A semi-classical simulation (c) shows why this is so. A small wavelet bounces back and forth, forming a periodic wave pattern, because even when slightly off the repelling orbit the wave still overlaps itself and can form standing wave constructive interference when its energy and frequency corresponds to one of the eigenvalues of a periodic orbit, even though the orbit is classically repelling. The quantum solution is scarred on precisely these orbits (d). This causes resonances such as absorption peaks of a highly magnetically excited atom (e) to coincide with the eigenfunctions of the repelling periodic orbits, just as the orbital waves of an atom constructively interfere with themselves, in completing an orbit to form a standing wave, like that of a plucked string. The result is that, over time, in the quantum system, although the behaviour may be transiently chaotic, it eventually settles into a periodic solution. Experimental realizations such as the scanning tunneling view of an electron on a copper sheet bounded by a stadium of carefully-placed iron atoms (f) [lxix], confirm the general picture, although, in this experiment, tunneling leaked the wave function outside too much to demonstrate proper scarring. The semi-classical approach matches closely to the full quantum calculation (g).

The end result is that for a variety of closed quantum systems, wave spreading eventually represses classical chaos by scarring, causing the periodic eigenfunctions to become eventual solutions of any time-dependent problem, although the initial trajectory behaves erratically, just as does an orbit in the classical situation. For example, a periodically kicked quantum rotator [lxx, lxxi] will stochastically gain energy, just as in the classical situation, until a quantum break time [lxxii], after which it will become trapped in one of the quantum solutions. A highly excited atom in a magnetic field will have its absorbance peaks at the periodic solutions, and quantum tunneling will likewise use scarred eigenvalues as its principle modes of tunneling [lxxiii, lxxiv].

These constraints do not apply to open systems, such as molecular kinetics where diffusion can carry molecules relatively vast distances. As a rough example, a glycine molecule at biological temperatures has a self-diffraction angle of wave-spreading of about 6.5°, showing this effect is significant [lxxv]. Moreover, the larger the system, the longer the delay until quantum break time sets in.

The implication is that sensitive dependence on initial conditions eventually gives way, at the quantum level, to quantum uncertainty of the scarred orbit, globally traversing the space concerned, and it does so by performing a transition from chaos to order dependent on the initial conditions initially following a chaotic trajectory and eventually entering into a periodic orbit. Since a chaotic system, whether quantum or classical has a dense set of periodic orbits there, is potentially an infinite number of these, although quantum separation of chaotic eigenfunctions [lxxvi], another feature of quantum repression of chaos, will lead to only a finite number being available at the energies concerned.

The implications are threefold:

1. Quantum suppression of chaos leads to a situation where:
   (a) quantum chaotic systems model a transition from chaos to order, just as insight processes involve a transition from chaos to order, and
   (b) quantum suppression of chaos by phase coherence parallels the way brain processes may use coherence to distinguish critical processes in conscious attention from the background.
2. The eigenfunctions of chaotic quantum processes are globally distributed over the phase space and thus, in so far as the outcomes depend on stochastic properties of wave-particle reduction, enable uncertainty to affect outcomes on the scale of the phase space orbit.
3. In processes that involve open systems, or large phase spaces whose quantum break time is much longer than the real time window, chaos and quantum uncertainty may combine to amplify uncertainty, so that it can affect global outcomes.

An indication of how the transition from classical to quantum chaos might lead to complex forms of quantum entanglement can be gleaned from an ingenious experiment forming a quantum analogue of the kicked top using an ultra-cold cesium atom kicked by both a laser pulse and a magnetic field. In figure 9b is shown the classical dynamical phase space of the kicked top showing domains of order where there is periodic motion and complementary regions of chaos where there is sensitive dependence on initial conditions as a result of horseshoe stretching and folding. In the quantum system (second row) in the ordered region (left), the linear entropy of the system is reduced and there is no quantum entanglement between the orbital and nuclear spin of the atom. However in the chaotic region (right) there is no such dip, as the orbital and nuclear spins have become entangled as a result of the chaotic perturbations of the quantum top's motion [lxxvii, lxxviii].

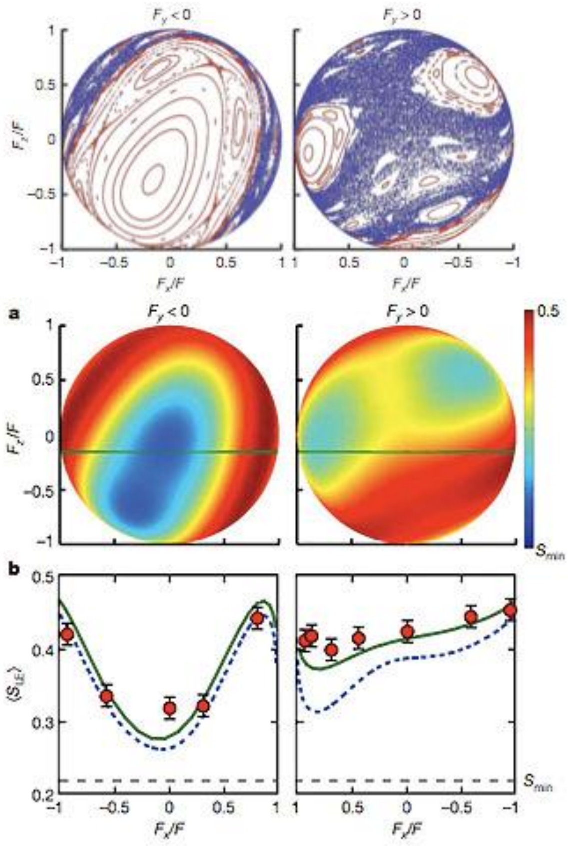

Fig 9b Classical and quantum kicked top and entropies.

6. The Evolution of Chaotic Sensitivity and the Emergence of Consciousness

We now return to the biological arena, to consider how nervous systems might have evolved the dynamics we associate with consciousness. Is the sort of dynamics we associate with the conscious brain a product of the complex interconnectivity of circuitry of relatively trivial neurons, as work with artificial neural nets and computational approaches, such as artificial intelligence might suggest? Or is it a fundamental aspect of living cells, which evolved with the earliest eukaryotes? Is it in the senses of a single celled-organism that we will naturally find the origin of chaotic excitability as a source for the quantum sensitivity that ultimately shaped the evolution of the conscious brain in higher organisms?

A realistic assessment of pyramidal neurons confirms that they are very complex dynamical systems in their own right, far from the trivial additive units which McCulloch-Pitts ‘neurons’ present in theoretical artificial networks, containing up to 10^4 synaptic junctions, having a variety of excitatory and inhibitory synaptic inputs involving up to four or five different types of neurotransmitter, with differing effects depending on their location on dendrites, the cell body, or axon-axonal connections.

Furthermore many of the critical features we associate with neurons, and their associated neuroglia, in the conscious brain, including excitability and the use of neurotransmitter molecules, are not only shared by other cells in the human body, but extend down to the earliest single-celled eukaryotes [lxxix].

The connection between bursting and beating in excitable cells was established by the Chay-Rinzel model and ensuing experiments [lxxx], which established chaotic dynamics in neurons, pancreatic b-cell exocytosis, and inter-nodal cells in the alga *Nitella* [lxxxi]. The association between excitability and exocytosis spanning the eukaryotes [lxxxii] is doubly significant in that, in addition to graded electrochemical and action potentials in the neuron, synaptic vesicles are also produced by exocytosis.

Earlier work had already demonstrated membrane potentials in *Amoeba proteus* [lxxxiii] associated with pseudopod formation, and action potentials in the amoeba *Chaos chaos* [lxxxiv, lxxxv], aptly so-named by Linnaeus [lxxxvi]. In ciliated protozoa, such as *Paramecium*,[lxxxvii, lxxxviii] and *Tetrahymena* [lxxxix] action potentials are associated with the motile actions of cilia in cellular locomotion.

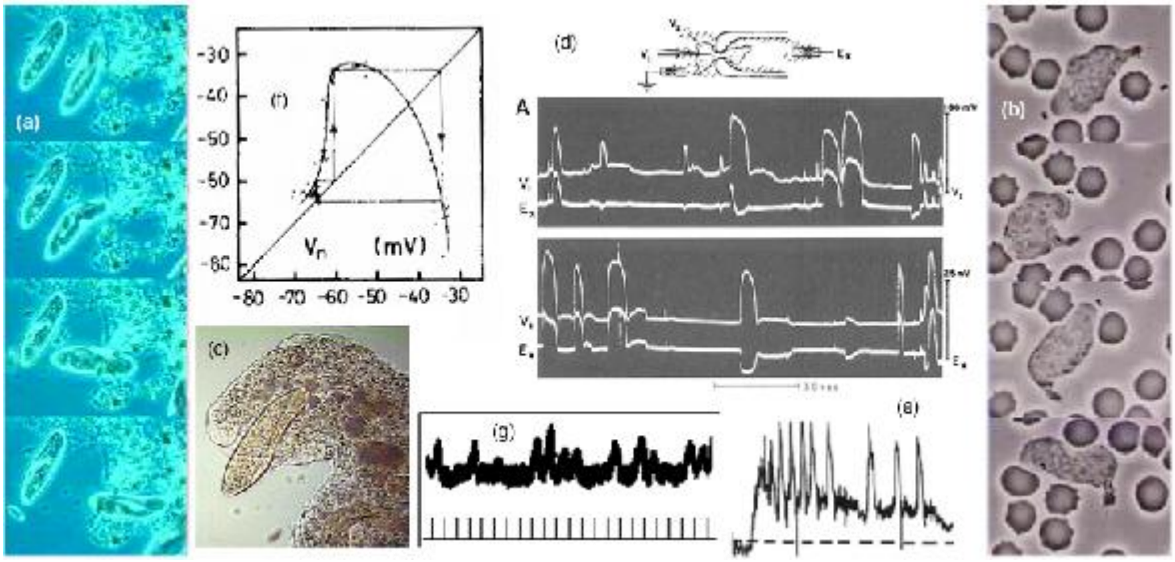

Fig 10: Real-time purposive behavior in single cells (a) *Paramecium* reverses, turns right and explores a cul-de-sac. (b) Human neutrophil chases an escaping bacterium (black), before engulfing it. (c) *Chaos chaos* engulfs a *paramecium*. Action potentials in *Chaos chaos* (d) and *paramecium* (e). Period 3 perturbed excitations in *Nitella* confirm chaos. (g) Frog retinal rod cells are sensitive to single quanta in an ultra-low intensity beam, with an average rate of one photon per click, but sometimes zero, or two, due to uncertainty in the beam.

The aggregation of slime moulds such as *Dictyostellium* is mediated by cyclic-AMP [xc, xci]. The ciliated protozoan *Tetrahymena pyriformis* [xcii, xciii] and flagellated *Crithidia jasciculata* [xciv] utilize serotonin, and the former also metabolizes dopamine and epinephrine [xcv, xcvi]. *Tetrahymena pyriformis* also has circadian light-related melatonin expression [xcvii].

Both amoebae and ciliates show purposive coordinated behaviour over real time, as do individual human cells such as macrophages. The multi-nucleate slime mould *Physarum polycephalum* can solve shortest path mazes and demonstrate a memory of a rhythmic series of stimuli, apparently using a biological clock to predict the next pulse [xcviii, xcix]. Chaotic excitation provides an excitable single cell with a generalized quantum sense organ. Sensitive dependence would enable such a cell to gain feedback about its external environment, perturbed by a variety of quantum modes - chemically through molecular orbital interaction, electromagnetically through photon absorption, electrochemically through the perturbations of the fluctuating fields generated by the excitations themselves, and through acoustic and mechanical interaction. Amoebae for example, although they lack specific sense organelles, are highly sensitive to chemical and electrical signals, as well as to bright light.

Such excitability in the single cell would predate the computational function of neural nets, making dynamical chaos fundamental to the evolution of neuronal computing rather than vice versa. A single cell has no capacity to solve decision-making problems through a neural net consisting of many cells, so has to rely on membrane excitation and internal regulatory systems, such as biological clocks and genetic switches to provide memory and a strategy for survival.

Fig 11: Hydra has only an undifferentiated nerve net (a), yet catches prey by coordinated action of its tentacles (b) and has no less than 12 different forms of motion, from stages of somersaulting to snail-like gliding.

When we move to the earlier metazoa such as *Hydra*, we already have many of the neurotransmitters, G-linked protein receptors, ion channels and essentially all the neuronal machinery we associate with vertebrate nervous systems, causing the basis of central nervous system function and dynamics to be common to the entire animal kingdom. *Hydra*, which supports only a primitive diffuse neural net and whose tissues can dynamically reorganize themselves, for example if it is turned inside out, we find the organism has a rich repertoire of up to 12 forms of 'intuitive' locomotion, and is able to coordinate tentacle movements and tumbling, and other forms of movement using similar global dynamics to those in amoebae and *Paramecium*, or a more advanced organism, such as a snail. We can thus see that nervous systems have arisen from the adaptive dynamics of individual eucaryote cells, rather than being composed of a logical network made out of essentially trivial formal neurons.

As we move up the evolutionary tree to complex nervous systems, such as in vertebrates, we still see the same dynamical features, now expressed in whole system excitations such as the eeg, in which excitatory and inhibitory neurons still provide a basis for broad-spectrum oscillation, phase coherence and chaos in the global dynamics, with the synaptic organization enabling the dynamics to resolve complex context-sensitive decision-making problems, involving memories of past situations and specific adaptations to current ones. However the immediate decision-making situations around which life or death results, in the theatre of conscious attention in real time, are qualitatively similar in nature to those made by single celled organisms, such as *Paramecium*, based strongly on immediate sensory input, combined with a short term anticipation of immediate threats, in a context of remembered situations from the past that bear upon the current existential strategy.

Looking back more deeply in time, chaotic excitability and electrochemistry generally may be one of the founding features of eucaryote cells, dating from the RNA era, before coded protein translation [c, ci, cii]. Nucleotide coenzymes, believed to be molecular fossils from the RNA era, pervade electron transport pathways. Key chemical modifiers may have been precursors of the amine-based neurotransmitters, spanning acetyl-choline, serotonin, catecholamines and amino acids such as glutamate and GABA, several of which have potential pre-biotic or trans-biotic status. Positive amines for example may have chemically complemented negatively charged phosphate-based lipids in modulating membrane excitability in primitive cells without requiring complex coded proteins.

The sense modes we experience are not simply biological as such, but more fundamentally are the qualitative modes of quantum interaction between molecular matter and the physical universe. They thus have potential cosmological status. Vision deals with interaction between photons and orbitals, hearing with the harmonic excitations of molecules and membrane solitons, as evidenced in the action potentials arising from cochlear cells. Smell is the consequence of orbital-orbital interaction, as is taste. Touch is a hybrid sense involving a mixture of these.

The limits to the sensitivity of nervous systems are likewise constrained by the physics of quanta, rather than biological limits. This is exemplified by the capacity of retinal rod cells to record single quanta fig 10(g), and by the fact that membranes of cochlear cells oscillate by only about one H atom radius at the threshold of hearing, well below the scale of individual thermodynamic fluctuations and vastly below the bilayer membrane thickness. Moth pheromones are similarly effective at concentrations consistent with one molecule being active, as are the sensitivities of some olfactory mammals.

The very distinct qualitative differences between vision, hearing, touch and smell do not appear to have a physiological support in the very similar patterns of electrical excitation evoked in their cortical areas. However, if all these excitations can occur simultaneously in the single cell, chaotic excitation could effectively become a form of cellular multi-sensory synaesthesia [ciii], which is later specialized in the brain in representing each individual sense mode. Thus in the evolution of the cortical senses from the most diffuse, olfaction, the mammalian brain may be using an ultimate universality, returning to the original quantum modes of physics in a way which can readily be expressed in differential organization of the visual, auditory, and somato-sensory cortices according to a single common theme of quantum excitability. This is consistent with cortical plasticity, which for example, enables a blind person to use their visual areas for other sensory modes.

It is thus natural to postulate that cellular ‘consciousness’, as a focused global dynamical electrochemical response to a cell’s environment, is a pivotal feature which as been elaborated and conserved by nervous systems because it has had unique survival value for the organism. It is a logical conclusion that the conscious brain has been selected by evolution because its biophysical properties provide access to an additional principle of predictivity not possessed by formal computational systems. One of the key strategies of survival implicated in brain dynamics is anticipation and prediction of events [civ, cv, cvi, cvii]. Computational systems achieve this by a combination of deductive logic and heuristic calculation of contingent probabilities. However quantum non-locality may also provide another avenue for anticipation, which might be effective even across the membrane of a single cell, if wave reductions are correlated in a non-local manner in space-time. We shall examine this possibility next.

7. Quantum Entanglement and the Transactional Interpretation

All forms of quantum field theory stem from the special relativistic form of the energy $E = \pm\sqrt{\mathbf{p}^2 + m^2}$. This gives two solutions, one a positive energy solution traveling in the usual (retarded) direction in time and the other a negative energy (advanced) solution, traveling backwards in time.

All quantum mechanical calculations are based on these dual solutions of special relativity, including those of quantum electrodynamics, the most accurate physical theory ever devised [cviii]. Wheeler and Feynman noted that 'absorber' theory [cix], in which the advanced solutions were included, gave the same predictions as descriptions in which the advanced solutions were omitted as unphysical. Indeed all Feynman space-time diagrams implicitly contain both the advanced and retarded solutions.

For a photon, which is its own anti-particle, the advanced and retarded solutions of electron-electron repulsion by exchanging virtual particles fig 12(3a-c) are identical, as a negative energy advanced photon IS a positive energy retarded photon. Likewise electron scattering becomes positron creation-annihilation when time reversed (d). The delayed choice experiment and quantum erasure, fig 12 (1,2) confirm that changes after emission, or even at absorption, can influence the path taken by a photon or other exchanged particle [cx].

In John Cramer's transactional interpretation [cxi], such an advanced 'backward traveling' wave in time gives a neat explanation, not only for the above effect, but also for the probability aspect of the quantum in every quantum experiment. Instead of one photon traveling between the emitter and absorber, there are two shadow waves, which superimposed make up the complete photon. The emitter transmits an offer wave both forwards and backwards in time, declaring its capacity to emit a photon. The potential absorbers of this photon transmit a corresponding confirmation wave. These, traveling backwards in time, send a hand-shaking signal back to the emitter, fig 12(4a). The offer and confirmation waves superimpose constructively to form a real photon only on the space-time path connecting the emitter to the absorber.

The transactional interpretation offers the only viable explanation for the apparently instantaneous connections between detectors in pair-splitting EPR experiments in which a pair of correlated photons are emitted by a single atom [cxii, cxiii, cxiv], in which neither of the photons has a defined polarization until one of them is measured, upon which the other immediately has complementary polarization. In fig 12(4b), rather than a super-luminal connection between detectors A1 and A2, the two photons' advanced waves meet at the source emission point in a way which enables the retarded waves to be instantaneously correlated at the detectors. One can also explain the arrow of time, if the cosmic origin is a reflecting boundary that causes all the positive energy real particles in our universe to move in the retarded direction we all experience in the arrow of time and increasing entropy [cxv].

The hand-shaking space-time relation implied by the transactional interpretation makes it possible that the apparent randomness of quantum events masks a vast interconnectivity at the sub-quantum level, reflecting Bohm's implicate order [cxvi], although in a different manner from Bohm's pilot wave theory [cxvii]. Because transactions connect past and future in a time-symmetric way, they cannot be reduced to predictive determinism, because the initial conditions are insufficient to describe the transaction, which also includes quantum boundary conditions coming from the future absorbers. However this future is also unformed in real terms at the early point in time emission takes place. My eye didn't even exist, when the quasar I look out at emitted its photon, except as a profoundly unlikely branch of the combined probability 'waves' of all the events generating parallel 'probability universes' throughout the history of the universe between the time, long ago, that the quasar released its photon, and me being in the right place, at the right time to see it distant epochs later.

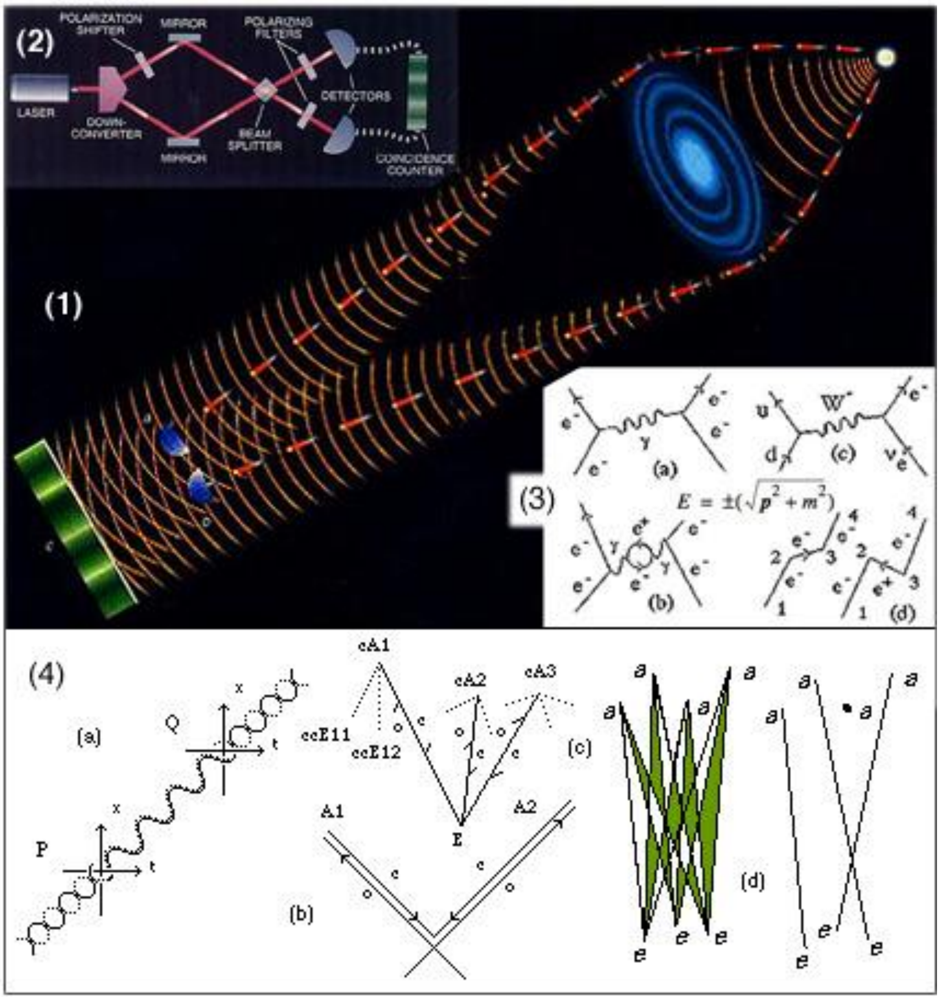

Fig 12: Wheeler delayed choice experiment (1) shows that a decision can be made after a photon from a distant quasar has traversed a gravitationally lensing galaxy by deciding whether to detect which way the photon traveled or to demonstrate it went both ways by sampling interference. The final state at the absorber thus appears to be able to determine past history of the photon. Quantum erasure (2) likewise enables a distinction already made, which would prevent interference, to be undone after the photon is released. Feynman diagrams (3) show similar time-reversible behavior. In particular time reversed electron scattering (d) is identical to positron creation-annihilation. (4a) In the transactional interpretation, a single photon exchanged between emitter and absorber is formed by constructive interference between a retarded offer wave (solid) and an advanced confirmation wave (dotted). (b) EPR experiments of quantum entanglement involving pair-splitting are resolved by combined offer and confirmation waves, because confirmation waves intersect at the emission point. Contingent absorbers of an emitter in a single passage of a photon (c). Collapse of contingent emitters and absorbers in a transactional match-making (d).

In the extension of the transactional approach to supercausality [cxviii, cxix], a non-linearity collapses the set of contingent possibilities to one offer and confirmation wave, fig 12 (4c,d). Thus at the beginning, we have two sets of contingent emitters and absorbers and at the end each emitter is now exchanging with a specific absorber. Before collapse of the wave function, we have many potential emitters interacting with many potential absorbers. After all the collapses have taken place, each emitter is paired with an absorber. One emitter cannot connect with two absorbers without violating the quantum rules, so there is a frustration between the possibilities, which can only be fully resolved if emitters and absorbers are linked in pairs. The number of contingent emitters and absorbers are not necessarily equal, but the number of matched pairs is equal to the number of real particles exchanged.

This transactional time symmetry is paralleled in the implicit time reversibility of quantum computation, which also depends on a superposition of states. Recent experiments with photosynthesis [cxx] have shown how quantum computation could play an integral role in biological and hence brain processes. When a photosynthetic active centre absorbs a photon, the wave function of the excitation is able to peform a quantum computation which enables the excitation to travel down the most efficient route to reach the chemical reaction site. The transactional interpretation may thus combine with effective forms of biological quantum computation to produce a space-time anticipating quantum entangled system, which may be pivotal in how the conscious brain does its processing.

8. Consciousness Revealed

It is at this point that the influence of the conscious observer and the hard problem become an intriguing challenge to the scientific description. The brain is not a marvelous computer in any classical sense - we can barely manage a seven-digit span, but it is a phenomenally sensitive anticipator of environmental and behavioral change. Subjective consciousness has its survival value in enabling us to jump out of the way when a tiger is about to strike, not so much in computing which path the tiger might be on, (because this is an intractable problem, and the tiger can also take it into account in avoiding the places we would expect it to most likely be), but by intuitive conscious anticipation.

Fig 13: Evidence of immediate anticipatory subjective consciousness. A seagull just manages to escape a shark strike, before flying off.

The brain, using phase correlation in its own wave dynamics, as a basis for decision-making, parallels the way in which the wave function and its constructive interference determines the probabilities in the reduction of the wave packet. We thus may need to consider the possibility that global brain excitations form an ‘inflated’ quantum system and that the brain uses a form of quantum anticipation involving emission and absorption of its own excitations in a way which enables it to have an 'intuitive' non-computable representation of future states which complement computational processing and which would be unavailable to a classical computer. Quantum coherence is already a technique in imaging, demonstrating an example of quantum coherence in biological tissues at the molecular level [cxxi, cxxii].

In this sense, the enigma of subjective consciousness may exist partly because such excitations cannot be reduced to classical prediction, or quantum transactions would introduce a causal 'back-to-the-future' feedback loop. Thus the brain, in developing the internal model of reality represented by the 'Cartesian theatre', may have opted for a complementarity between subjective consciousness and objective brain function, to maintain 'entangled' anticipation, which is an evolutionary adaptation to the transactional relationship underlying wave-particle complementarity, bringing the two complementarities into conjunction.

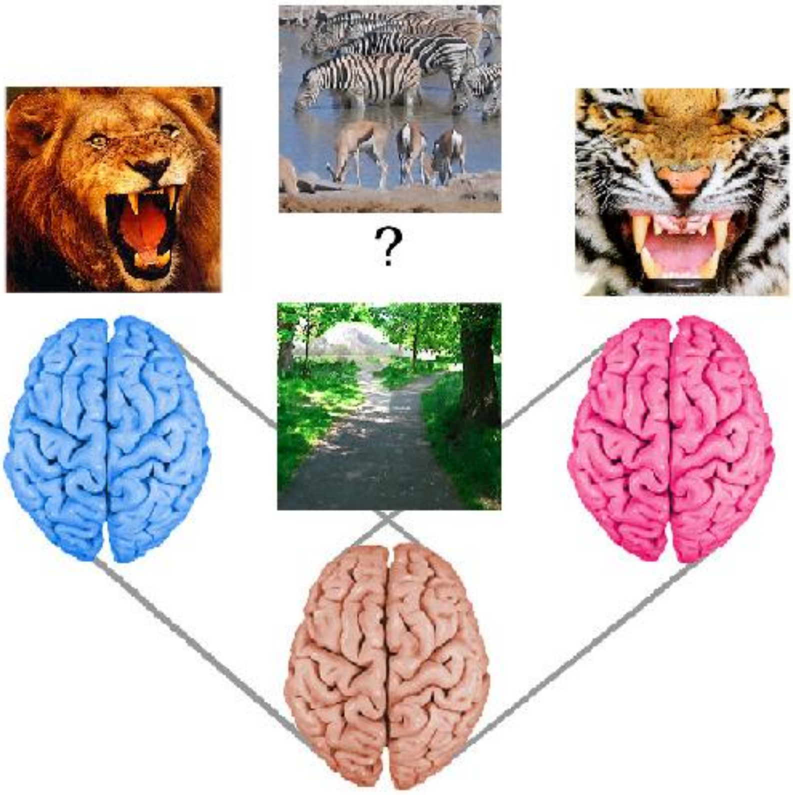

Fig 14: Transactional view of a hunter trying to find a safe path to the waterhole. Both the open hilly path and the jungle path (right) have lions or tigers, which might attack the hunter. Paranoia suggests the hunter takes the hilly path as his quantum anticipation makes him feel uneasy about the forested path, since in the probability universe where he take this path he gets a severe fright. Usually these anticipations will be almost immediate, as in fig 13.

In this respect, subjective consciousness may present an existential cosmological situation, as noted in Indian philosophy, in which consciousness is described as 'finer' than matter, thus gaining a complementary existential status to the physical universe, in the manner of the Tantric dance of Shiva as the undivided field of subjective consciousness and Shakti as *maya* – the multiplicity of material manifestations, again reflecting the continuous-discrete wave-particle relationship, and do this by manifesting in subjective consciousness aspects of the space-time traversing sub-quantum dynamics that underlies the wave-particle complementarity at the foundation of the quantum description of the cosmological universe.

To make this point in a closing tale we narrate the following descriptive evolutionary account.
A hunter is at a fork in the path to the water hole, seeking to get an antelope for meat, but wary of himself getting taken by a big cat in the process. As the man stands pondering and studying the tracks on the path and the sounds and smells blowing across the savannah and through the jungle, his brain develops a resonant coherent excitation – the hunter's 'stealth' – a state of awareness empty of structured thought, anticipating the slightest movement around him.

There are two histories of varying duration, from immediate awareness, to the imminent future, that the vagaries of fate on the day could bring about. The man could walk down the shady path or the one over the rocks.

As things transpire, there is a hungry tiger on the shady path, which is poised to leap on anything coming its way. However the man's brain wave is resonating in an entanglement with his future brain states and there are two parallel universes of future states, one down the shady path and the other down the rocky one.

Now the brain state going down the shady path has a catastrophe - one hell of a scare, or outright death, painfully mauled by the big cat. The hunter's stalking brain state gets absorbed down there and the absorber's advanced wave runs back through space-time in his brain state along the path he just traversed, to the point where the man is still standing at the fork trying to decide what to do.

On the other path he simply walks to the water hole, because the lions are elsewhere today, and shoots a small antelope with his poisoned arrow and takes it back to a woman in the village, so she might consent to have sex with him. This outcome also absorbs the resonating brain wave and sends its advanced wave back to the hunter at the crossroads, but it doesn't excite his paranoia.

At the crossroads the man is feeling disquiet. His amygdala is giving him conniptions of foreboding. He feels bad about the shade under the trees. He doesn't like the rocky path either, because lions spend a lot of time slouching in the little gullies in the rocky hills, but having already pondered for long enough to contemplate, and being desirous of having sex before the moon sets, he decides, on a sheer hunch, which he can't fully describe, to go ahead on the hunt, by walking carefully along the stony path.

He ends up having children and his children have too and each have often since felt pretty paranoid about a lot of things, but sometimes they just feel its a sunny day, and the shade under the trees looks cool, and although a few have been picked off by big cats, most of them have taken some good hunks of meat back to the village and had some sex for themselves too. And so the story carries on long enough for the hunter's great-grandson to sit down and get ready to share a good roast leg of antelope, while the women throw some sweet potatoes into the fire, to pick up his flute and cock his bowstring against a cooking pot to pluck for a tune, and tell a few jokes, and scary stories too, to get the woman he admires to draw in close and put her arms around him, and do that funny thing of wiggling her middle finger in the palm of his hand that means she wants to take him off for the night for a 'walking marriage', once the fire has died down low [cxxiii].

So it is that the anticipatory quantum chaos of the living cell has become the contemplative mind of the lonely hunter, in the generations of conscious beings traversing the sentient wave-particle universe.

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