Generation of the Stream of Consciousness by Neuronal Synaptic Interaction

Andrew Duggins [1,2] *

[1] Western Clinical School, Faculty of Medicine and Health, University of Sydney; andrew.duggins@sydney.edu.au
[2] Department of Neurology, Westmead Hospital; andrew.duggins@health.nsw.gov.au
* Correspondence: andrew.duggins@sydney.edu.au; Tel.: +61-413-475-681

Abstract: In previous work, a quantum mathematical formalism associated an element of experience with a single sensory neuron, as a local reduction of a global mental state. In contrast to the binary objective states of neuronal polarisation/depolarisation, neuronal experience was modeled as a continuous variable, the instantaneous value of which could only be estimated statistically from an ensemble of evoked responses to stereotyped stimulus presentation. In the present work, the quantum operations formalism of energy dissipation through amplitude damping is adopted to explain how smooth evolution of conscious experience might arise from discrete spikes and discontinuous synaptic transmission between neurons.

Keywords: stream of consciousness; quantum mechanics; decoherence theory; synaptic transmission; spike; action potential; neural code; neural correlate of consciousness

1. Introduction

1.1. Conceptual Background

At the click of a Geiger counter, an observer infers that a nearby Americium-74 nucleus has decayed to Neptunium-72, emitting an alpha particle. Yet before and after this nuclear transmutation, the universe is in a coherent superposition of states of parent and of daughter radionuclide. Moreover, the state vector of the universe moves smoothly and continuously through Hilbert space over the lifetime of the radionuclide from the parent to daughter eigenspace, a decay that had appeared spontaneous and random generated by the time-independent interaction between nucleus and its immediate environment. Even considering only the reduced state of this one nucleus, the probability weighting of the parent in an incoherent mixture with daughter radionuclide must smoothly decay over time. These dynamics only appear as an abrupt transition because out of the mixture of parent and daughter radionuclides only one or other can be manifest in the world of the observer at a point in time.

This account raises the question whether other apparently discrete spontaneous events arising in the natural world might be generated similarly. This would be particularly plausible where transition events in subsystems were known to correlate with the state and smooth trajectory of a spatially distributed system of which subsystems were all part. The brain is such a multipartite and anatomically distributed system, in which the stream of unified consciousness is driven by

transition events in neuronal components. Specifically, we consider whether a single spike, and the chemical synaptic transmission that results, might be modelled as a continuous interaction between an efferent and afferent neuron.

1.2. Existing Model: axioms and quantum foundations

In the author's previous work, two 'bridging principles' for the mind-brain relation were presented as axiomatic foundations of a neuronal model of sensory perception. The first postulate was that the "contribution of a single sensory neuron to the neural code for the sensory environment parallels the relationship between a neuronal element of experience and the overall sensory percept" [1]. As an example, if as suggested by the experiment of Britten [2] the organism's behavioural response to direction of visual motion, within a limited region of the visual field, can be predicted almost entirely by the response of a single, carefully selected neuron in the motion-sensitive cortex V5, then the neuron singlehandedly *encodes* this aspect of the sensory environment. The first bridging principle goes further to say that such a V5 neuron also affords, within a limited region, this same limited aspect of motion experience. The second postulate extended the mind-brain parallel to neuronal relations: "however the similarity between environmental features specified by a pair of neurons is encoded in their joint activity, this objective association parallels the qualitative proximity of respective neuronal elements of experience" [3]. Previous work emphasised perceptual rather than conceptual experience, but in what follows it will be assumed that these bridging principles can be extended to a more general correspondence between objective and subjective representation of information. A third and final bridging principle was suggested in section 1.1 of the current paper, but is here stated again formally: neuronal synaptic transmission generates not only the evolution of an objective neural representation of information but also the dynamics of conscious experience (those elements of experience and their relations corresponding to that objective representation by the first and second bridging principles).

Notwithstanding the close association, implied by these bridging principles, between elements of experience and their neural correlates, a purely physicalist approach, it was argued, would fail to capture two essential features of consciousness, subjectivity and unity. A starting point to the development of a model to describe these features was the principle of evoked responses in neurophysiology. Neural responses are quantised as spikes. Over an ensemble of stereotyped stimulus presentations, the best description of a sensory neuron's response to the stimulus at a point in time is its instantaneous firing rate, averaged across trials, not the number of spikes that have already occurred on an individual trial, or the objective state of the neuron that pertains at that moment. The quantum mathematical formalism is consistent with an interpretation that the state of a system really exists and has statistical effects over an ensemble of trials with identical starting conditions, even though the state itself is not directly measurable. In the quantum mechanical mathematical formalism of neural signaling that was developed, this feature of the quantum state was identified with the subjectivity of a neural element of experience. Spikes were considered to be objective transition events between definite levels of neuronal potential, even as an element of experience, inaccessible to direct measurement, smoothly decayed (like the quantum conception of alpha decay mentioned above). When the model was applied to the neurophysiologic scenario of repeated stereotyped stimulus presentations, the expectation value of spike potential across trials

was not only proportional to the instantaneous firing rate, but also to a scalar quantity of experience inherent in the inaccessible neural state (a 'perception value', see below).

If only this part of the quantum formalism had been appropriated, consciousness would have been neuro-anatomically locally explicable, consistent with the 'microconsciousness' theory of Zeki: "Activity in each separate processing node generates a microconsciousness for the attribute for which that node is specialised. Consequently, there are several microconsciousnesses, corresponding to the activity of cells at different nodes within different processing systems" [4]. It seemed to the author that such "summative atomism" was a poor description of the phenomenon: "a sub-mind is an atrocious monstrosity, just as is a plural-mind - neither having any counterpart in anybody's experience, neither being in any way imaginable" [5]. Indeed, the unity of consciousness seemed to be a fundamental feature. A unified consciousness was considered to be singular and not plural; complete in itself, not a fraction of a greater whole. In contrast, sensation, cognition, emotion and volition were considered not complete experiences but aspects of the subject's consciousness. Whatever level of perceptual or conceptual experience is introspected upon, it always seemed possible to consider a higher level at which the relation between simultaneous percepts or concepts is experienced. The unified mental state was thus proposed to exist at the apex of a hierarchy of bound percepts and concepts. The author shared with Nagel the view that "It seems inevitable that psychophysical explanation will apply first at the level of some kind of elements of experience; but if these elements come together in a single consciousness, they must also be components of a single point of view" [6]. This suggested that, just as the bound percept might be resolved along multiple perceptual dimensions, perhaps a unified consciousness might usefully be represented as a mental state vector in a subjective space spanned by all of the dimensions of perceptual experience.

With these ideas in mind, two other features of the quantum mathematical formalism, superposition of states and tensor product combination of state spaces, were applied to a neuronal model that had been extended to the whole brain. This facilitated description of the mental state as a pure, inseparable state (a vector or uni-dimensional projector) on this combined system of vast dimension. There was proposed a direct correspondence between the unity of experience, a property of the system as a whole, and such coherence of the state of that system. The reduced state of any subsystem of one or many neurons would be a mixed-state density operator. Were this not so, the completeness privilege of consciousness described above would be lost. Such a mental state would be not only unified but also emergent: it would reduce to, but be not entirely constituted in the semi-classical phenomenal correlates of firing rate at the single neuron level, mentioned above. The objective manifestation of an inseparable pure mental state would be firing correlations between neurons in anatomically remote regions that have no direct synaptic connection with each other, perhaps correlations that could not have been established classically by synaptic input from a common source.

In a decoherence theoretic interpretation of quantum mechanics, the emergence of a probability-weighted mixture of discrete objective states is the local manifestation of a smooth, unitary evolution generated by the interaction between a system and its environment [7]. In the further development of the neuronal model of consciousness to be presented below, it is proposed

that such a decoherence theoretic framework can reconcile discontinuous synaptic transmission with the stream of consciousness. Specifically, complex neuronal vector spaces, which might have seemed an unnecessary extravagance when modelling subjectivity and unity, will facilitate a description of unitary evolution of the mental state[1]. Of course, if this were merely the application of quantum physics to the brain, considered as an open quantum system, its quantum state would no longer remain pure after a vanishingly small decoherence time, although the state of a very large composite system including the brain and some part of its physical environment would remain pure. In order to maintain the picture of a pure mental state, the only interaction that will be considered in this neuronal model is that occurring at the synapse. Interactions that occur between sub-neural structures and their physical environment will be neglected.

Of course, classical neural dynamics, generated by synaptic transmission, are already well described. At a synapse on the dendrite of a recipient neuron, excitatory neuro-transmitters, released as a spike depolarises the pre-synaptic terminal, increase sodium permeability by opening chemically-gated channels and partially depolarise the post-synaptic membrane. Partial depolarisation at the trigger zone, by passive (or 'electrotonic') conduction of this excitatory post-synaptic potential, may reach a threshold at which voltage-gated sodium channels open, making the transmembrane potential abruptly positive. This opens similar channels in the adjacent neural membrane, so that complete depolarisation extends rapidly throughout the neuron as a spike. What is to be presented here will challenge none of this. Partly this is because the model is a coarse-grained description, neglecting all this subcellular activity to represent a spike as nothing more than a Dirac delta function. More importantly though, the contention is that the continuous evolution of the mental state reduces to the discrete synaptic transmission of information of the classical neuron doctrine at a local level of explanation, in the same way that the click of the Geiger counter is a local manifestation of the unitary evolution of the state vector of the universe.

1.3. Existing Model: mathematical formalism

In previous work, a unified consciousness, or mental state, was modelled as a vector on a composite tensor product of single neuronal complex vector spaces [3]. Each of these neuronal spaces was spanned by an orthonormal basis of integer 'action potential' states $|n\rangle$. These were eigenvectors of a hermitian number operator N: states of inevitability of corresponding integer spike counts n, but in contradistinction to conventional neuroscience not the depolarisation events themselves. A superposition principle was introduced in which pure states $|\psi\rangle$, sums of integer action potential states weighted by complex amplitudes $\langle n|\psi\rangle$, were all valid single neuronal states. If a state $|\psi\rangle$ were normalised, the squared modulus $|\langle n|\psi\rangle|^2$ would be the prior probability that a neuron in that state would ultimately spike n times, and the expectation value of N, $\langle N\rangle$, a sum of eigenvalues n weighted by these respective probabilities, would be the expected spike count. The proposed equivalence of using the uni-dimensional projector $|\psi\rangle\langle\psi|$ or the vector $|\psi\rangle$ for the description of a pure state of a neuron implied that a global phase $e^{i\theta}$ across amplitudes $\langle n|\psi\rangle$

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[1]Unitary evolution implies that the evolution operator when multiplied by its adjoint yields the identity (see section 3.1 Unitary dynamics of isolated neurons). It is a concept unrelated to the unity of consciousness, modelled in this formulation as an inseparable, pure mental state of the composite neuronal system.

would have no subjective or objective meaning. The significance of relative phase differences (which remain in either description) will be revealed below.

Application of the same superposition principle to the composite space yielded entangled mental states that were not tensor products of single neuronal states, putting the concept of emergence of consciousness in mathematical form [3].   Consciousness still had a neural correlate, however, in that local reduction of the pure mental state to the single neuron A was shown to be the density matrix ρ^A, a probability-weighted mixture of uni-dimensional projectors. A 'memoryless firing' assumption, in which the posterior probability of a future spike would be unaffected by a period of neuronal silence, implied that the instantaneous firing rate would be proportional to the expected spike count with proportionality constant w [1]. In the same way that the instantaneous firing rate might quantify a single sensory neuron's contribution to the objective neural code for an environmental stimulus, it was proposed that a scalar 'perception value', also proportional to $\langle N \rangle$ but with constant r, would quantify that same neuron's contribution to the subjective percept. Similarly, instantaneous firing rate dependence, a manifestation within a neuronal pair of an entangled mental state, might quantify both an objective inter-neuronal code and subjective phenomenal proximity between neural elements of experience [3].

2. Materials and Methods

Here we argue *reductio ad absurdum* that without synaptic transmission, action potentials would remain sequestered in neurons, perception values would be unchanging and consciousness static. We extend the quantum mechanical formalism summarised above to show that a single neuron isolated in this way could nevertheless undergo a unitary evolution generated by N in which integer action potential eigenstates remain unchanged but for acquisition of a relative phase $-n\omega t$. We extrapolate that in any neural system in which, by virtue of isolation, there is conservation of action potential, the subjective state of that system could nevertheless undergo a unitary evolution U. But synaptic interaction within that system would require that the eigenvectors of U were no longer single neuron integer action potential eigenstates. Applying this principle to a hypothetical isolated 2-neuron system, we model the oscillatory flow of a single action potential between component neurons A and B by synaptic transmission as a Jaynes-Cummings interaction [8]. We use an operator sum formalism to reduce this unitary evolution to a description of the continuous evolution of the single neuron state ρ^B. We qualify the perception value concept, replacing the general constant r with 'nervous energy': a neuron-specific experience-per-spike dependent on ω. We show how, in a realistic brain of polysynaptic neuronal interaction, this allows reconciliation of oscillatory flow of action potential between a neuronal pair with exponential decay in firing of the efferent neuron, of rate constant w, predicted by the memoryless firing assumption [1].

3. Results

3.1. Unitary dynamics of isolated neurons

If we were able to set $w = 0$, and in doing so abruptly impose upon the brain complete neuronal isolation, then a neuron's action potential could no longer be realised as spikes. If a single neuron were in a pure state $|\psi\rangle$ with probability $|\langle n|\psi\rangle|^2$ of n eventual spikes prior to this imposed isolation, it would still have the same probability of n spikes after such isolation were relieved. While synaptic transmission to or from the neuron remained impossible, $\langle N \rangle$ and perception value would remain constant. In the proposed mathematical formalism the evolution of single neuronal elements of experience is entirely attributable to spikes and synaptic transmission.

Neuronal isolation would nevertheless be compatible with an evolution in which, over time t, incremental integer action potential states acquire a relative phase ωt. This implies an association between relative phase and experience that will be justified below. An operator U on the single neuron space to effect such an evolution would be unitary, meaning that $U^\dagger U$ is the identity I for example the operator

$$U(t) = \sum_n e^{-in\omega t} |n\rangle\langle n|$$

$$U^\dagger(t)U(t) = \sum_n |n\rangle\langle n|$$

This particular U is generated by N, and leaves the phase of the ground state $|0\rangle$ unchanged. Of course any operator that imposed the same relative phase but a different global phase on the neural state would describe an identical evolution. The evolution of an isolated single neuron in a superposition of 0- and 1-action potentials is depicted in Figure 1. It will be mathematically convenient, when we consider the contribution of such single-neuron evolution to a multi-neuron system, to use an equivalent U, generated by an operator sharing with N eigenvectors belonging to eigenvalues of unit separation (so that they again acquire relative phase $-\omega t$), presented here in matrix form with respect to the basis $\{|n\rangle\}$:

$$-\frac{Z}{2} = \begin{bmatrix} -\frac{1}{2} & 0 \\ 0 & \frac{1}{2} \end{bmatrix}$$

In a 2-neuron system within which individual neurons were isolated, an evolution on the composite space could only impose a relative phase on tensor products of single neuron integer action potential states, and could neither introduce nor abolish entanglement in a pure state superposition thereof. The quality of a very limited consciousness would remain static. The tensor product of single neuron unitary operators to effect this evolution, $U^A \otimes U^B$ might be generated by an 'uncoupled' operator [4]

$$-\frac{Z_A}{2} \otimes I^B + I^A \otimes -\frac{Z_B}{2} = \begin{bmatrix} -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

where the choice of $-\frac{Z}{2}$ leaves the phase of the 1-action potential eigenspace unchanged.

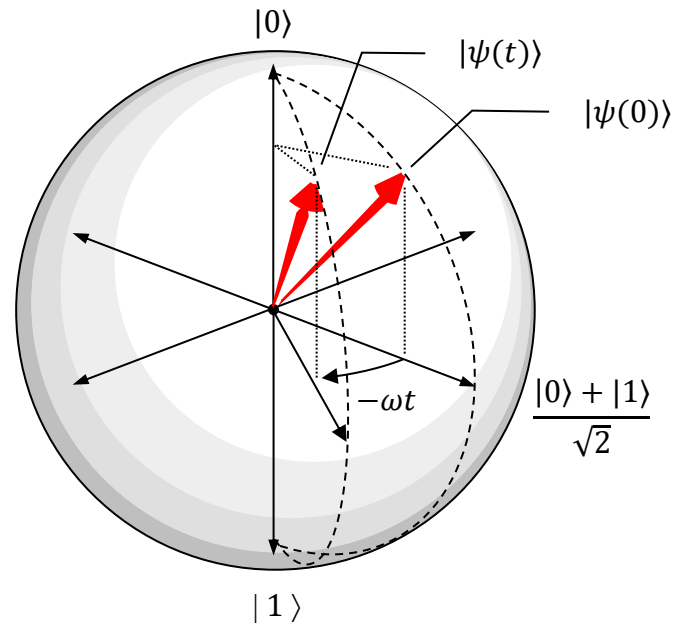



Figure 1. Evolution on the Bloch sphere of a superposition state of an isolated single neuron: $|\psi(0)\rangle = \langle 0|\psi(0)\rangle|0\rangle + \langle 1|\psi(0)\rangle|1\rangle$. $|\psi(0)\rangle$ is assumed to have a relative phase of 0. The one-action potential state acquires a phase of $-\omega t$ over time t (ω assumed positive, phase acquisition negative), relative to the zero-action potential state.

3.2. Unitary dynamics of synaptic interaction

More generally of course, a multi-neuron system might be isolated, in the sense that there could be no synaptic transmission to or from the wider neural environment, even as such interaction was ongoing between component neurons. Action potential would be conserved within the system, even as it flowed between components. Within a 2-neuron system (Figure 2), an interaction between neurons might generate a unitary evolution that would not preserve $|0^A\rangle|1^B\rangle$ or $|1^A\rangle|0^B\rangle$ eigenvectors, but would nevertheless conserve one action potential.

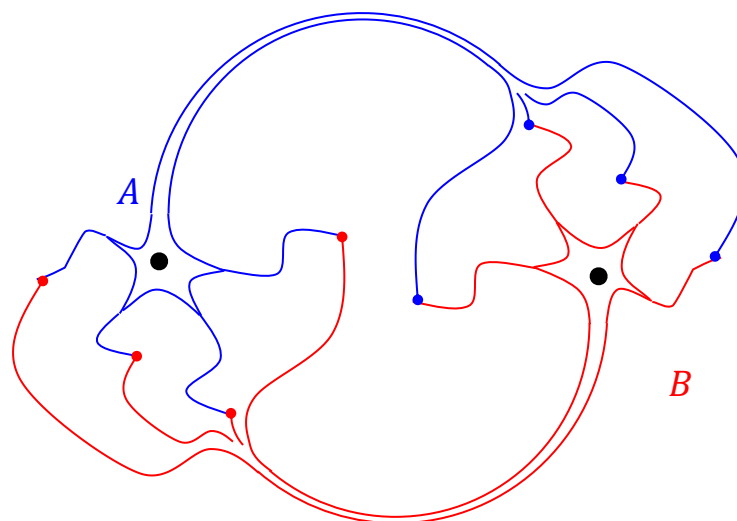



Figure 2. A fictitious isolated 2-neuron system. Like the isolated single neuron, the 2-neuron system should undergo unitary evolution, without gain or loss of action potential. Here though, potential should flow between neurons as spikes.

If neuron B is initially in the 1-action potential state, while A is initially in the ground state, then with prior probability $P(t)$, after some brief time t has elapsed, a single spike may have occurred in B. The reduced state of neuron B will then be in a mixture of the 0-action potential state weighted by probability $P(t)$ and the 1-action potential state weighted by the probability $1 - P(t)$:

$$\rho^B = P(t)|0^B\rangle\langle 0^B| + \big(1 - P(t)\big)|1^B\rangle\langle 1^B|$$

This is consistent with an evolution that takes the pure initial state $|0^A\rangle|1^B\rangle$ to a weighted superposition of $|0^A\rangle|1^B\rangle$ and $|1^A\rangle|0^B\rangle$, where the squared modulus of the amplitude of the second term is the firing probability:

$$|0^A\rangle|1^B\rangle \xrightarrow{t} \sqrt{1 - P(t)}|0^A\rangle|1^B\rangle - i\sqrt{P(t)}|1^A\rangle|0^B\rangle$$

$$\begin{bmatrix} 0 \\ 1 \\ 0 \\ 0 \end{bmatrix} \xrightarrow{t} \begin{bmatrix} 0 \\ \sqrt{1 - P(t)} \\ -i\sqrt{P(t)} \\ 0 \end{bmatrix}$$

As in the non-interacting neuron model above, we choose an evolution in which $|0^A\rangle|0^B\rangle$ and $|1^A\rangle|1^B\rangle$ acquire a positive and negative phase respectively, determined by single neuron evolution, but the phase of the $|0^A\rangle|1^B\rangle$ term in the superposition does not change. The phase of the $|1^A\rangle|0^B\rangle$ term is chosen to simplify the mathematical form of the operator that generates this evolution.

The columns of the operator that achieves these transformations, $U^{AB}(t)$, are orthonormal (since U^{AB} is unitary) and reflect the symmetry of the system:

$$U^{AB}(t) = \begin{bmatrix} e^{i\omega t} & 0 & 0 & 0 \\ 0 & \sqrt{1 - P(t)} & -i\sqrt{P(t)} & 0 \\ 0 & -i\sqrt{P(t)} & \sqrt{1 - P(t)} & 0 \\ 0 & 0 & 0 & e^{-i\omega t} \end{bmatrix}$$

3.3. Evolution of the reduced neural state: spike elements

More generally still, if neuron B is initially in a superposition of 0- and 1-action potential states weighted by c_0 and c_1 respectively (and neuron A is again assumed to start in the ground state) then a matrix equation for the unitary evolution of the initial product state is

$$\begin{bmatrix} e^{i\omega t} & 0 & 0 & 0 \\ 0 & \sqrt{1 - P(t)} & -i\sqrt{P(t)} & 0 \\ 0 & -i\sqrt{P(t)} & \sqrt{1 - P(t)} & 0 \\ 0 & 0 & 0 & e^{-i\omega t} \end{bmatrix} \times \begin{bmatrix} c_0 \\ c_1 \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} c_0 e^{i\omega t} \\ c_1\sqrt{1 - P(t)} \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ -c_1 i\sqrt{P(t)} \\ 0 \end{bmatrix}$$

$$U^{AB}(t)|0^A\rangle \otimes |\psi^B(0)\rangle = |0^A\rangle \otimes S_0(t)|\psi^B(0)\rangle + |1^A\rangle \otimes S_1(t)|\psi^B(0)\rangle$$

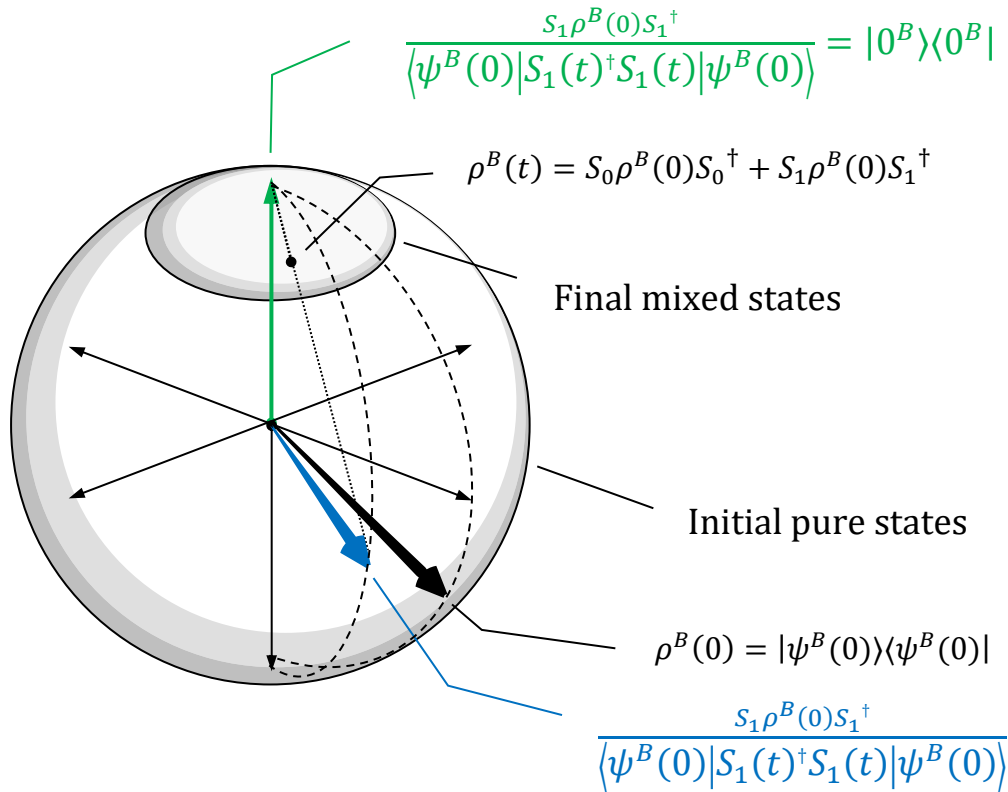
where 'spike elements' S_0 and S_1 are operators $\langle 0^A|U^{AB}|0^A\rangle$ and $\langle 1^A|U^{AB}|0^A\rangle$ on B, representations of which are the submatrices of U^{AB}, $\begin{bmatrix} e^{i\omega t} & 0 \\ 0 & \sqrt{1 - P(t)} \end{bmatrix}$ and $\begin{bmatrix} 0 & -i\sqrt{(P(t)} \\ 0 & 0 \end{bmatrix}$ respectively. The spike probability is the squared modulus of the second term

$$\langle\psi^B(0)|S_1(t)^\dagger S_1(t)|\psi^B(0)\rangle = P(t)|c_1|^2$$

Spike elements decompose the transformation of ρ^B through synaptic transmission:

$$|\psi^B(0)\rangle\langle\psi^B(0)| \rightarrow S_0|\psi^B(0)\rangle\langle\psi^B(0)|S_0{}^\dagger + S_1|\psi^B(0)\rangle\langle\psi^B(0)|S_1{}^\dagger$$

as illustrated in Figure 3, and in matrix form:

$$\begin{bmatrix} |c_0|^2 & c_0c_1{}^* \\ c_1c_0{}^* & |c_1|^2 \end{bmatrix} \xrightarrow{t} \begin{bmatrix} e^{2i\omega t}|c_0|^2 + P(t)|c_1|^2 & e^{i\omega t}\sqrt{1-P(t)}\,c_0c_1{}^* \\ e^{i\omega t}\sqrt{1-P(t)}\,c_1c_0{}^* & (1-P(t))|c_1|^2 \end{bmatrix}$$

4   **Figure 3.** Evolution of the reduced state of neuron B, part of an isolated 2-neuron system as

5   in Figure 2. Here the initial composite state $|0^A\rangle|\psi^B(0)\rangle$ is separable, so the initial reduced

6   state $\rho^B(0)$ is pure, depicted as a black arrow on the surface of the Bloch sphere. Unitary

7   evolution of the combined system is equivalent to the operation of spike elements S_0 and S_1

8   on the neural space of B. After a brief period of time, in which the probability of a spike in

9   neuron B is approximately $\langle\psi^B(0)|S_1(t)^\dagger S_1(t)|\psi^B(0)\rangle$, the reduced state evolves smoothly to a

10 weighted mixture $\rho^B(t)$ of the zero-action potential state (green arrow) and the no-spike

11 pure state (blue arrow), that mixture depicted as a point in the interior of the sphere.

14   *3.4. Synaptic Interaction on the 1-action potential manifold: Part I*

15   Entangled states of 1-action potential $\frac{1}{\sqrt{2}}(|0^A\rangle|1^B\rangle \pm |1^A\rangle|0^B\rangle)$ are unchanged by the operation

16   of U^{AB}, but for the acquisition of relative phase. On the 1-action potential manifold of states, these

17   states are also eigenvectors of an interaction operator X. We might insist, as previously, that relative

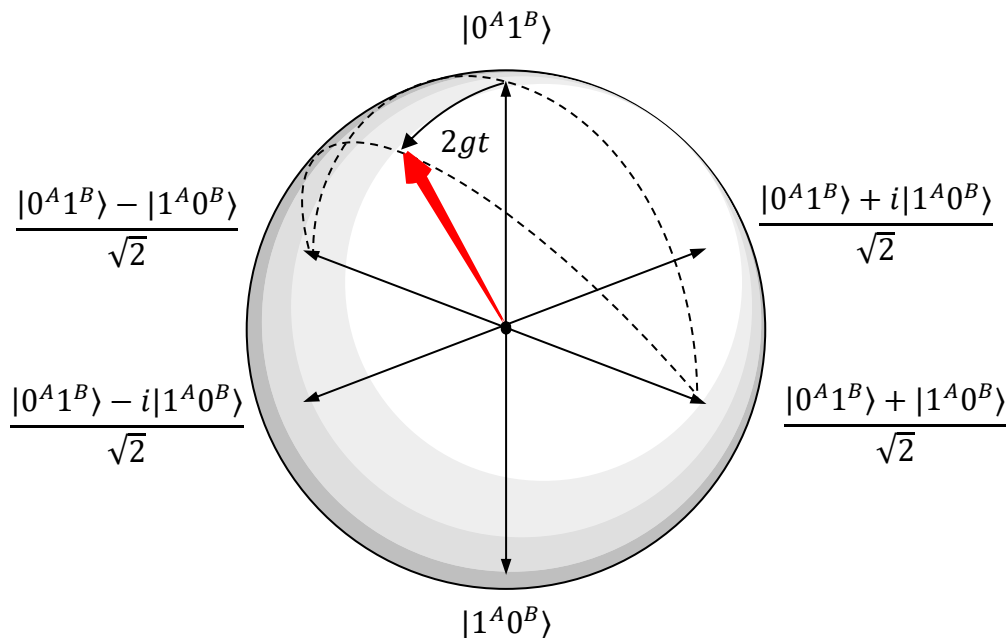
18   phase must accumulate linearly over time, in which case X generates an evolution on this manifold

19   e^{-iXgt}

20   where g parameterises the strength of synaptic coupling (Figure 4). We can equate this with the

21   central submatrix of $U^{AB}(t)$, substituting $\sin^2 gt$ for the prior probability of a single spike $P(t)$:

22                    $\begin{bmatrix} \cos gt & -i\sin gt \\ -i\sin gt & \cos gt \end{bmatrix}$

23   The action potential then 'sloshes' back and forth between neurons at a frequency of $\frac{g}{\pi}$.

26   **Figure 4.** The $|0^A1^B\rangle$, $|1^A0^B\rangle$ manifold of states of the isolated 2-neuron system in Figure 2,

27   depicted as a Bloch sphere. After a brief period of time t, the initial separable state $|0^A1^B\rangle$

28   has evolved to the entangled state $\cos gt|0^A1^B\rangle - i\sin gt|1^A0^B\rangle$, reflecting a spike probability

29   in neuron B of approximately $\sin^2 gt$.

30

31

32   *3.5. A paradox: oscillation versus decay*

33   There is an inconsistency here with our earlier prediction that $\langle N \rangle$ and perception value should

34   be proportional to a neuron's instantaneous firing rate (Figure 5a). An instantaneous firing rate

35   must be the gradient with which spike probability increases over time. But in the unitary evolution

36   that we have described, over a brief time period t

37                                    $$P(t) = \sin^2 gt \cong g^2 t^2$$

38   so the instantaneous firing rate of neuron B increases in proportion to time:

39                                    $$f_B(t) \cong 2g^2 t$$

40   Initially, when $\langle N^B \rangle$ is maximal, the instantaneous firing rate is zero (Figure 5b)!

41

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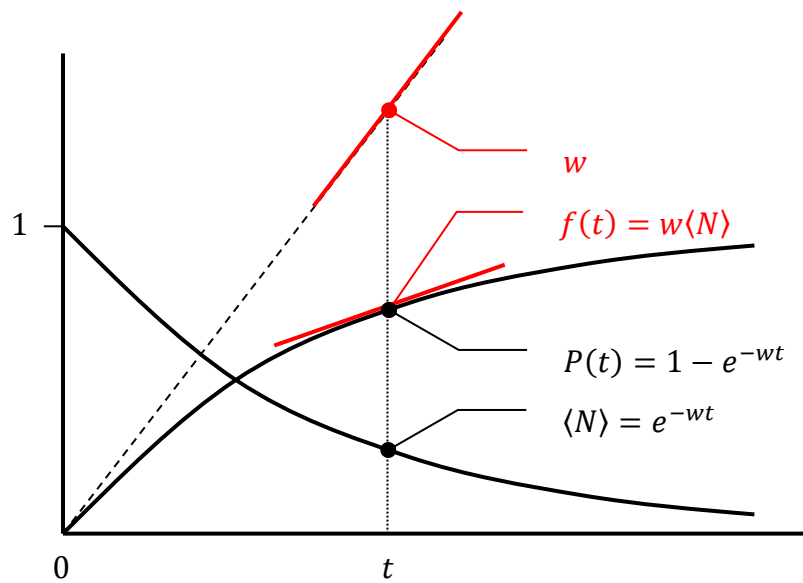
43   **Figure 5a.** Changes in $\langle N \rangle$; spike probability $P(t)$; and instantaneous firing rate $f(t)$ in an

44   interacting neuron initially in the one-action potential state, according to the 'memoryless

45   firing' assumption. Compared with Figure 5b, the instantaneous firing rate decays

46   exponentially over time from an initial rate constant of w, remaining proportional to $\langle N \rangle$.

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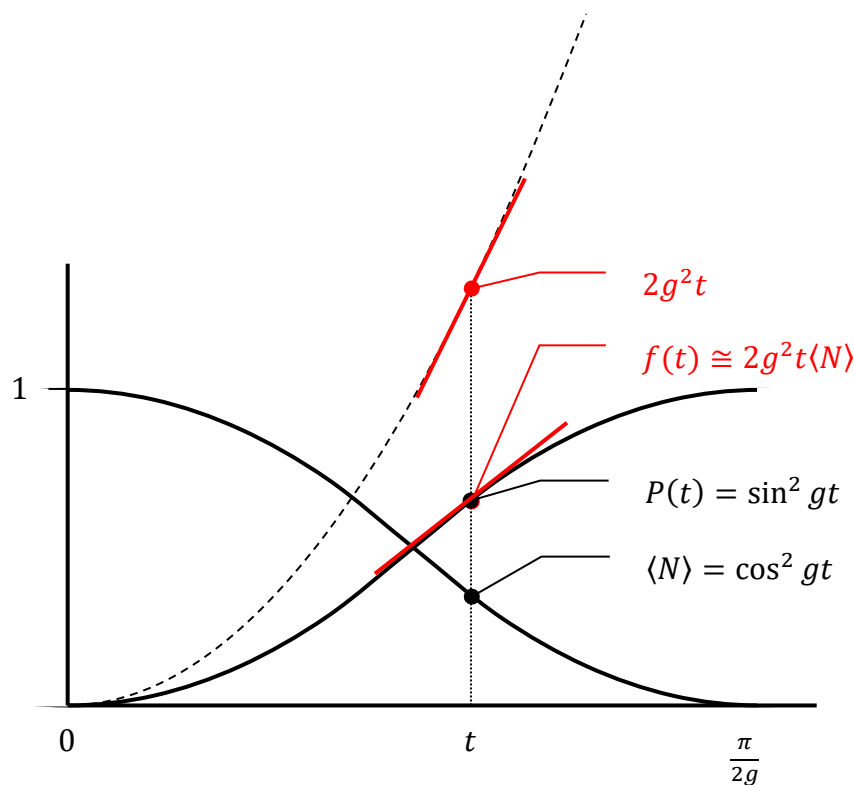

51   **Figure 5b.** Changes in $\langle N \rangle$; spike probability $P(t)$; and rate of accumulation of spike
52   probability, the instantaneous firing rate $f(t)$ in neuron B, part of the isolated 2-neuron
53   system in Figure 2 that is initially in the state $|0^A 1^B\rangle$. Initially, instantaneous firing rate
54   increases with time. These changes correspond to the evolution of the composite state
55   depicted in Figure 4, but they do not accord with the prediction that instantaneous firing
56   rate should vary with $\langle N \rangle$.

57

58   The perception value was supposed to be a general description of the subjective
59 correlate of the neural response on a single trial, compatible with the instantaneous firing
60 rate as a description of the objective neural response over an infinite ensemble of
61 stimulus repetitions. We would be loath to abandon the simple linear relationship
62 between perception value and firing rate that follows from the memoryless firing
63 assumption [1]. Yet the current model is particularly attractive in that it links the
64 dynamics of experience to synaptic interaction, as most neuroscientists would require. In
65 fact, reconciliation between these positions is possible, if we recognise and overcome a
66 limitation of the current model.

67 *3.6. Variable nervous energy of the action potential*

68   We must reject the implicit assumption that different neurons with the same spike
69 potential (the same expected spike count $\langle N \rangle$) should afford the same perception value (we
70 cannot assume that the proportionality constant r, between $\langle N \rangle$ and the perception value,
71 is the same for different neurons). While it would seem essential, if a quantum formalism
72 is to have any validity in modeling brain activity, for all action potentials in a particular
73 neuron to be identical, action potentials of a pre-synaptic efferent and post-synaptic

74   afferent neuron could differ. We have not uncovered any objective manifestation of the

75   value of ω, so it would seem reasonable to allow the level of perceptual experience that

76   could be attributed to a neuron at a given instantaneous firing rate to be determined by a

77   neuron-specific ω, if that would lead to a resolution of the paradox.

78

79   To achieve this, we will need a 'nervous energy' operator on the neuronal space

80
$$H = \hbar\omega N$$

81   where $\hbar$ is a fundamental constant across all neurons, and $\hbar\omega$ replaces r. The nervous

82   energy of 1 action potential

83
$$\langle 1|H|1\rangle = \hbar\omega$$

84   is the 'experience-per-spike' of that neuron. Perception is an immeasurable quantity, and

85   a neuron's contribution to consciousness can only be defined relative to other neurons, so

86   we might reasonably allocate $\hbar$ a value of 1.

87   *3.7. Synaptic Interaction on the 1-action potential manifold: Part II*

88   The isolated single neuron will now evolve as

89
$$U(t) = e^{-iHt}$$

90   The uncoupled operator that generates the evolution of the 2-neuron system of isolated individual

91   neurons becomes:

92
$$-\omega^A \frac{Z^A}{2} \otimes I^B - I^A \otimes \omega^B \frac{Z^B}{2}$$

93   This adds a contribution δ to the nervous energy of synaptic interaction on the one action

94   potential manifold

95
$$\begin{bmatrix} \delta & g \\ g & -\delta \end{bmatrix}$$

96   where δ is the deviation of each ω from the average

97
$$\delta = \frac{(\omega^B - \omega^A)}{2}$$

98   If we define a Rabi frequency

99
$$\Omega = \sqrt{g^2 - \delta^2}$$

100   then the evolution generated on this manifold, illustrated in Figure 6, becomes

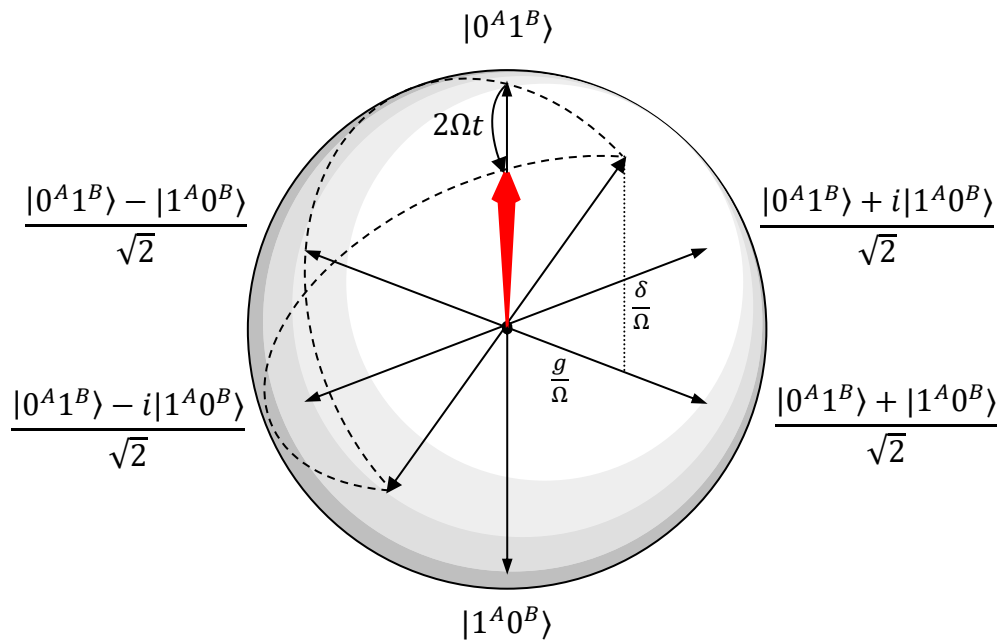
101
$$\begin{bmatrix} \cos\Omega t - i\left(\frac{\delta}{\Omega}\right)\sin\Omega t & -i\left(\frac{g}{\Omega}\right)\sin\Omega t \\ -i\left(\frac{g}{\Omega}\right)\sin\Omega t & \cos\Omega t + i\left(\frac{\delta}{\Omega}\right)\sin\Omega t \end{bmatrix}$$

102   There is still an oscillatory flow of action potential, but as the discrepancy in ω between

103   efferent and afferent neuron increases, the weighting of the 1-action potential state in $\rho^B(t)$

104   dips to a lesser extent ($\frac{g^2}{g^2+\delta^2}$) and is more promptly restored (period $\frac{\pi}{\Omega}$).

105

106

107 **Figure 6.** Evolution of the $|0^A 1^B\rangle$, $|1^A 0^B\rangle$ manifold of states of an isolated 2-neuron system on
108 the Bloch sphere. Compared with Figure 4, where the nervous energy of the one-action

109 potential state is the same in neurons A and B, here $\delta = \frac{\omega^B - \omega^A}{2}$ may be non-zero. As before g

110 parameterises the strength of synaptic coupling. The angular frequency of oscillatory flow
111 of action potential between neurons $\Omega = \sqrt{g^2 + \delta^2}$. Compared with the evolution of an initial
112 1-action potential state of B plotted in Figure 5b, here the nadir of spike potential occurs
113 earlier and is less profound.

114

115   These dynamics describe the interaction between a single source and target neuron.
116 Only when we discard the fanciful model of two isolated but interacting neurons, and
117 impose instead the constraints of realistic neuronal connectivity, do these dynamics yield
118 the constant initial firing rate of the source that we require. The argument for a linear
119 accumulation of spike probability in this latter case is based on a standard derivation [10]
120 of 'Fermi's Golden Rule' [11] in the parallel quantum mechanical formalism, and will be
121 presented here only in outline. In fact a single neuron is likely to provide synaptic input
122 to a large number of target neurons. The prior probability that a single spike in the source
123 will ultimately lead to a spike in any of one of these targets will be extremely small. We
124 will assume a constant weak coupling g between a single source neuron B and any one of
125 a large number of targets A.

126

127   If each target neuron were initially in the ground state then collectively they would
128 act as a reservoir: if t remains small, the probability of spike occurrence in B could be
129 approximated as the sum of weights for the $|1^A\rangle\langle 1^A|$ state in each $\rho^A(t)$. In a target neuron
130 with similar angular velocity to the source, the weight of this state initially increases as

131
$$\frac{g^2}{g^2+\delta^2}\sin^2\Omega t \cong g^2 t^2 \qquad (\delta^2 \cong 0,\, t \text{ small})$$

132   as in Figure 5b. Meanwhile, in a target neuron with angular velocity ω^A very different

133   to ω^B, the weight of the $|1^A\rangle\langle1^A|$ state becomes a 'sinc-squared' function of δ:

134
$$\frac{g^2}{g^2+\delta^2}\sin^2\Omega t \cong g^2 \frac{\sin^2\delta t}{\delta^2} \qquad (g^2 \ll \delta^2)$$

135   The width of this function narrows as $\frac{1}{t}$ even as its peak increases with t^2. Assuming

136   that there are so many target neurons that the distribution of target angular velocities ω^A

137   around ω^B can be considered continuous, and moreover that the number of target

138   neurons within a narrow range $\Delta\omega^A$ is relatively constant at q, the combination of these

139   effects that leads to a linear accumulation of spike probability:

140
$$P(t) = \pi q g^2 t$$

141   The initial firing rate of the 1-action potential state in B is constant, as we require (Figure

142   5a):

143
$$w = \pi q g^2$$

3.8. Temporal frequency of the stream of consciousness

145   w is the rate constant of an exponential decay in the spike potential of the source,

146   expressed in terms of the strength and density of synapses on target neurons. Experience

147   will also have 'relaxation' dynamics, in which a proportion $\frac{1}{e}$ of the initial perception

148   value decays within an average spike time of $\frac{1}{w}$. In effect, w is the maximal temporal

149   frequency of the stream of consciousness. $\frac{1}{w}$ is also the minimal temporal resolution of

150   spike trace recording that is sufficient to make reliable inferences about consciousness.

151   For example, an estimate of spike frequency (across a finite number of trials) in bins of

152   width less than $\frac{1}{w}$ is sufficient to predict the continuously evolving perception value with

153   reasonable confidence. If the instantaneous firing rates of two neurons A and B are

154   dependent, so that

155
$$\frac{f_{AB}(t)}{f_A(t)f_B(t)} \neq 1$$

156   then some dependence in firing is likely to persist for at least a period $\frac{1}{w}$. This can be

157   thought of as the fundamental temporal (im)precision of firing correlation. A metric of

158   paired association between spike counts in coincident bins of width $\frac{1}{w}$ will capture the

159   qualitative proximity between neural elements of experience [3]

160

161   Although there is a spread of perception values among target neurons that is greater

162   with an increasing firing rate of the source (reminiscent of the energy-time uncertainty

163 relation of quantum mechanics) the perception value of the source neuron is single-
164 valued at an instant in time. Moreover, provided that we consider a closed neural system
165 that includes the source and all target neurons, the evolution of the mental state will still
166 be unitary and completely deterministic.

167 **4. Discussion**

168   While this paper has focused narrowly on neural state evolution, it is the third of a
169 triptych of papers outlining the author's new model of consciousness (see references [1]
170 and [3]). At this point it is worth taking stock of what that model has achieved, and
171 defending some of the decisions that have been made in its development. After a brief
172 summary of the model, the first part of this Discussion will reflect again upon how the
173 model characterises the subjective representation of information, and its relationship to
174 the neural code. The second part reconsiders the quantum aspects of the model, and
175 implications for the function of consciousness; the final part the primitive evolution of
176 the isolated neuron characterised by ω , and neural system evolution generated by
177 synaptic interaction. The Conclusions anticipate future directions of model development.

178 *4.1. Model summary*

179   Three features of consciousness are considered to be fundamental: subjectivity, unity
180 and smooth evolution. A model of a consciousness with these features is constrained by
181 three bridging principles, this term and the modelling approach originally suggested by
182 Chalmers [12]. All three principles posit the subjective mirroring of objective neural
183 information processing: the first relates single neuronal activity to a neural element of
184 experience, the second relates paired association in neural activity to the qualitative
185 relationship between such neural elements, the third relates the dynamics of both
186 consciousness and objective neural representation to synaptic transmission. The
187 instantaneous firing rate and firing rate dependence are taken to be the relevant measures
188 of single neuronal activity and paired association between neurons respectively. The
189 model uses a quantum mechanical mathematical formalism, adapted to the inter-neuronal
190 synaptic level of interaction, to reconcile the existence of a mental state, having the three
191 fundamental features, with these relevant objective measures of neural activity.

192 *4.2. Subjective representation and the neural code*

193   The definition of consciousness adopted in this paper is a general one provided by
194 Searle [13]: "Consciousness consists of inner, qualitative, subjective states and processes
195 of sentience or awareness." It is worth noting that this descriptive domain, the scope of
196 the current model, is much broader than that considered by previous pioneers of
197 quantum consciousness, whose ideas on conscious evolution will be discussed below.
198 Penrose [14] concentrates more narrowly on conceptual rather than perceptual
199 experience, particularly the dawning of awareness of a solution to a difficult problem,
200 which seems to arise abruptly from unconscious processing. Stapp, on the other hand,
201 refers to both a stable volitional state of consciousness, and reflections upon primitive

202 experiences [15]. It is the author's expectation that Searle's broader consciousness, when
203 analysed through introspection by other human subjects, will be found to have the same
204 three features that the author considers fundamental: it seems likely, given the common
205 neuro-anatomy and physiology between humans, that the essential qualities of experience
206 are shared. On the other hand, it is possible that the three fundamentals reflect the
207 author's particular cultural influences. Nevertheless, their statement seems important, to
208 establish terms of reference for the scheme.
209
210   Even if it were common to most subjects, one of these features of consciousness
211 might be claimed to be illusory, and the foundations of the model claimed unsound as a
212 result. For example a critic might assert that "The continuous evolution of my experience
213 is an illusion". Such criticism is easier to defend. If we define an illusion to be a
214 subjective experience that deviates from reality, then the statement is as internally
215 inconsistent as the assertion "This statement is false". If the reality is that my experience
216 is discontinuous, then there is no such thing as "the continuous evolution of my
217 experience". Conversely, if I do indeed experience continuous evolution, then this is a
218 subjective reality, and there is no illusion.
219
220   One might also question the validity of one or all of the three bridging principles. In
221 his original exposition, Chalmers considered "bridging principles . . . basic elements to
222 our theory, not to be further explained" that "add the minimal component" to objective
223 neuroscience to "bring subjective experience in" [12]. In the case of the three bridging
224 principles above, contemplation of a model of consciousness not bound by neural
225 constraints will be the only 'further explanation', offered not so much as proof by
226 contradiction, but as a parsimony defence. That chemical synaptic transmission is a
227 cardinal form of communication between neurons is beyond serious neuroscientific
228 dispute.   There is also a weight of neuroscientific evidence that neurons represent
229 information in their firing rates and firing dependencies. Within this body of evidence,
230 there is an extensive literature that supports these representations being neural correlates
231 of consciousness in a range of experimental paradigms. So if consciousness is not neural,
232 then there must be two parallel pathways, one objective and one subjective, both
233 representing and transmitting the same information, separate but correlated. If this does
234 not already seem extravagant, consider that the information processing in the subjective
235 pathway would still need to influence behavioural outputs expressed as spike patterns in
236 motor cortex, lest consciousness were to be relegated to the status of epiphenomenon.

237 *4.3. Quantum aspects and implications*

238   The major achievement of the current model is the reconciliation of a mathematical
239 formalism, suited to the description of consciousness, with the classical neuron doctrine
240 of spikes and synaptic transmission. The model's most serious potential pitfall is that
241 quantum mechanics, from which the formalism is borrowed, usually applies at a vastly
242 smaller physical scale. This is the level of certain biologic particles, fields and their

243 interactions, in the quantum physical description of which, others have attempted to
244 include consciousness. Here the fundamental units are not spikes but the atomic-level
245 particles of a quantum many-particle system, for example the unbound electrons
246 (fermions) of Valentine [16] or the Nambu-Goldstone boson modes of Vitiello [17].
247 Although the mathematical formalism of quantum field theory underlying such models is
248 well developed, the connection between the condensation of quantum fields and neuronal
249 membrane depolarisation often remains obscure, or at least nebulous: "a wave packet …
250 acting as a bridge from quantum dynamics at the atomic level through the microscopic
251 pulse trains of neurons to the macroscopic properties of large populations of neurons"
252 [18].
253
254   There is one other reason why quantum mechanics has been attractive for theorists of
255 consciousness: it has the potential to exploit a loophole in the causal closure contract of
256 classical neuroscience, thereby allowing consciousness a functional role. Chalmers argues
257 that to make the assumption that there are functional properties that distinguish a brain
258 endowed with conscious experience is to ignore, or at least trivialise the 'hard problem'
259 [19]. According to this view, it would be impossible both to describe consciousness
260 adequately and to ascribe some function to it. It is true that if a model were to capture the
261 private and subjective quality of the conscious state, then the representation of that state
262 could not also be a directly observable neural property. However, it is not generally the
263 case that states or realities that are not directly observable have no statistically
264 measurable objective effects. The quantum mathematical formalism of the current model
265 expresses this duality even at a single neuron level. The perception value is a subjective
266 reality that exists when a sensory neuron responds to a stimulus, but is inaccessible
267 directly to neurophysiologic observation (see section 1.2). The instantaneous firing rate,
268 over an ensemble of stereotyped stimulus presentations, is the statistical objective effect.
269
270   So what then is this function of consciousness? We will consider this first from a
271 systems-neuroscience and second from a single cell perspective. It is common in
272 neuroscientific theorising to hear perceptual experience described as distillation of order
273 from the chaos of sensory input. Koch speculates that "Natural selection pursued a
274 strategy that amounts to summarizing most of the pertinent facts about the outside world
275 compactly and sending this description to the planning stages to consider the organism's
276 optimal course of action" ([20], 14.1). In the current model, this summary of pertinent
277 facts could be exponentially more compact than a purely classical neuronal register. A
278 linear increase in the number of neurons would be associated with an exponential
279 increase in the dimension of the tensor product of neural spaces. Just as a single neuron
280 could be in a superposition of 0- and 1-action potential states, a pure state of m neurons
281 could be in a superposition of at least 2^m states of definite spike potential. Perhaps then,
282 consideration of 'optimal course of action' is quantum computation on all this data.
283 Conceivably, myriad synaptic interactions that evolve a pure mental state may drive an
284 exponential number of parallel computations upon the sensory input, which might
285 ultimately interfere as some desirable behavioural result.

286

287   The model should also allow correlations between neurons in anatomically remote
288 higher-order sensory cortices that have no direct synaptic connection with each other,
289 correlations beyond what could have been established classically by common synaptic
290 input from some lower level of the sensory hierarchy. One would anticipate an increased
291 efficiency of spike generation afforded by synchronous inputs to a common target neuron
292 in motor cortex: "100 fast excitatory inputs, distributed over the dendritic tree of a large
293 pyramidal neuron, are sufficient to generate …(a spike)…if they are activated within a
294 millisecond of each other. If the presynaptic spikes arrive smeared out over a 25 msec
295 window, however, twice as many synapses are needed to fire the cell" ([20], 2.3).

296

297   A caveat to this discussion is that these putative benefits to brain function are non-
298 local effects of a pure mental state. They depend on the quantum mathematical formalism
299 applying simultaneously to interactions ongoing at two entirely different physical scales,
300 the atomic scale of quantum physics and the microscopic scale of synaptic transmission
301 (see Conclusions). Popescu's application of a quantum model to statistical mechanics sets
302 a precedent for this kind of approach, offering an ontic rather than epistemic
303 interpretation of the probabilities that define entropy [21]. Applied to the context of
304 neuroscience, these results lend credence to the idea that we might just as well derive
305 firing probabilities from a density operator that is the reduction of a definite pure mental
306 state as regard these probabilities as a manifestation of our lack of knowledge about of
307 the actual state of the brain.

308 *4.4. Evolution of a closed neural system*

309   If a model is to allow the state of a 'closed' multi-neuron system, lacking synaptic
310 interaction with external neurons, continuously to evolve (see Conclusions), then it must
311 also allow the individual neuronal constituents of that system, when isolated, to evolve
312 continuously in a more limited way. This was the origin of the idea of an immutable but
313 neuron-specific ω, a rate of acquisition of relative phase of a 1-action potential state of
314 the neuron. A critical step in the model's further development was the introduction of
315 nervous energy, bringing together seemingly disparate concepts of a neuron's
316 contribution to consciousness and its dynamics: the operator, the expectation value of
317 which describes the magnitude of a neural element of experience, is the very same one
318 that generates isolated neuronal evolution.   In order for the perception value and
319 instantaneous firing rate of a source neuron to remain proportional, in the process of
320 synaptic transmission modelled as action potential flow, a reservoir of target neurons of
321 differing ω was found to be necessary. These target neurons then must also differ
322 according to ω in their contribution to consciousness, heuristically in magnitude of
323 experience-per-spike.

324

325   For the current computational model of brain to be implemented in the future, a
326 potential objective neural property constraining ω will need to be explored. The
327 conjecture of the author is that this may be related in some way to a neuron's objective

328   size. When the vibrating length of an open violin A-string is shortened or 'stopped' by a

329   finger, its fundamental frequency or pitch rises, perhaps to B. Considering the A and B

330   fundamentals to be analogous to the 1-action potential ω of a larger or smaller neuron

331   respectively, natural/artificial harmonics created by lesser finger pressure at $\frac{1}{2}$, $\frac{1}{3}$, $\frac{1}{4}$ of

332   the length of the string could be considered analogues of 2-, 3-, 4-action potential states.

333   *4.5. Evolution by synaptic interaction: measurement and decoherence*

334   Nervous energy transfer in chemical synaptic transmission, as proposed, is analogous

335   to radiative energy dissipation by photon emission. Indeed, the model of synaptic

336   interaction between one source and many target neurons is formally identical to the

337   interaction of an atom in its first exited state with an environment, consisting of a

338   reservoir of simple harmonic oscillators prepared in the ground state.   Experimental

339   interrogation of the environment for the occurrence of photon emission could be viewed

340   as causing a collapse of the atom to one or other definite energy state, which would not

341   have occurred without the experimenter's intervention.   However, if the interaction

342   between atom and environment admits an interpretation as a unitary evolution on the

343   combined system, there must simultaneously be photon emissions as discrete events,

344   even as the energy of the atom decays continuously.   Analogously, in the current model

345   of neural dynamics, we allow spikes as discrete events, even as the nervous energy

346   decays continuously. We have adopted here not only a quantum mathematical formalism,

347   but a decoherence theoretic interpretation of quantum mechanics that sees measurement

348   as a local manifestation of unitary interaction between system and environment [7].

349   Although a quantum system undergoes an abrupt objective transition (with a probability

350   that is usually regarded as irreducible), the evolution of a pure state of system and

351   environment remains strictly deterministic.

352

353   When this model is extended to the level of the complex neural system that is the

354   whole brain, a multitude of synaptic interactions between component neurons generates a

355   continuous unitary evolution of a coherent mental state in a tensor product neural space,

356   which is associated with the 'stream of consciousness'.   This clearly conflicts with other

357   quantum theories [14, 15], which attribute 'moments' of consciousness to collapse of the

358   state vector. This difference reflects both divergent concepts of consciousness and

359   interpretations of quantum mechanics.

360

361   Stapp stays true to von Neumann's original division of quantum evolution into three

362   processes [22]. Applied to brain dynamics, Process 2 allows a superposition of physical

363   brain states to undergo unitary evolution until Process 3 intervenes such that the

364   superposition collapses to one specific physical state. In sensory perception, Stapp

365   imagines that a simple task of a sensory system may be to answer the question "is a

366   particular stimulus present?" If the system collapses to a neural representation of that

367   stimulus, the organism experiences "the conscious acquisition of the knowledge

368   associated with that answer 'Yes.'"[23]. Process 1 is, according to von Neumann [22], the

369 determination of which question to ask, presumably in the case of brain dynamics a direct
370 consequence of the definite physical state of the brain that was realised by the last
371 Process 3 event.
372
373   Penrose [14] characterises von Neumann's Process 3 as reduction **R** of a
374 superposition state that has previously evolved deterministically according to unitary
375 evolution **U** (Process 2). The issue of when **R** supervenes upon **U** is highlighted as the
376 measurement problem. Penrose speculates that **R** occurs whenever the states in
377 superposition diverge sufficiently in space-time to meet an objective threshold, hence
378 objective reduction **OR**. In the brain, Hameroff and Penrose [24] suggest that, via **U**
379 interactions between adjacent subunits, microtubule superpositions extend across
380 significant regions of the brain, before **OR** occurs as a moment of consciousness. Stapp
381 [23], eschewing an objective criterion, allows 'conscious effort' an influence in limiting
382 the duration of unitary evolution (Process 2) , thereby holding the focus of attention
383 before collapse occurs (Process 3). The experience of effort is, according to this
384 suggestion, something different from the experience of everything else (Process 3).
385
386   For other theorists, it is the experience of freely willed action that seems abrupt and
387 random, and that is modelled as a non-deterministic measurement process. Like Stapp,
388 Beck and Eccles [25] would like to give consciousness agency in influencing neural
389 events. To do so they propose a "mechanism (that) clearly lies beyond ordinary quantum
390 mechanics" [25]. For these authors, quantum measurement takes place at the synapse,
391 particularly in the supplementary motor cortex involved in planning movement.   In
392 contrast to Stapp, their metaphysical force influences the probability of synaptic vesicle
393 release, a probability that would be irreducible in the standard quantum mechanical
394 sense: "the mental intention (the volition) becomes neurally effective by momentarily
395 increasing the probability of exocytosis in selected cortical areas" [25].
396
397   There has been telling criticism of previous quantum models of neural signalling.
398 Tegmark [26] equates objective states of neuronal polarisation or depolarisation to the
399 decoherence of about 10^6 sodium ions into a definite position outside or inside the
400 membrane respectively. He calculates that decoherence occurs within a time ($T2$) of order
401 10^{-19} seconds, much less than the "characteristic dynamical time scale of cognitive
402 processes", which he estimates to be somewhere between 10^{-2} and 10^0 seconds. The
403 implications are that pure superposition states do not survive long enough even in a
404 single neuron to allow quantum computation, and certainly not across the "complex
405 network of ~ 10^{11} neurons …linked to our subjective perceptions" that we would need to
406 invoke some unity of consciousness.
407
408   Even so, Tegmark argues that if one adopts, as we have done, the reasonable
409 assumption that "different neuron firing patterns correspond in some way to different
410 conscious perceptions, then consciousness itself cannot be of a quantum nature even if

411   there is a yet undiscovered physical process in the brain with a very long decoherence
412   time…The reason is that as soon as such a quantum subsystem communicates with the
413   constantly decohering neurons to create conscious experience, everything decoheres"
414   [26]. This seems a powerful argument against any of the pre-existing quantum theories of
415   consciousness mentioned above.

5. Conclusions

417   The formalism of consciousness developed in this paper preserves a pure mental
418   state because it is limited to a description of interactions between neurons. We have
419   chosen to treat the brain as an isolated system precisely so that we can maintain the
420   picture of the unity of consciousness. The flow of action potential in synaptic
421   transmission is equivalent to nervous energy dissipation, rendering reduced states of
422   single neurons mixed [3], and quantum effects negligible at the single cell level.
423   Superpositions of 0- and 1-action potential states, of neural histories in which a spike has
424   and has not occurred, are not evident to the neuroscientist. The lack of any local neuronal
425   footprint of consciousness is also entirely consistent with the theory. However, prediction
426   of quantum effects at a neural system or whole brain level will depend on how the
427   formalism can be reconciled with quantum physics: specifically, how quantum coherence
428   might be preserved within a neural system, in the face of continuous interaction between
429   neurons and their extracellular environment. Perhaps it is evolution that has resolved this
430   paradox, through natural selection of a concatenated neural architecture to refocus the
431   mental state on a conscious neuronal subspace, thereby achieving a superlative feat of
432   quantum error correction. Only if this turns out to be possible could one start to consider
433   attributing experience to a non-biologic quantum computer. However, even if such
434   attempts at reconciliation ultimately prove futile, it is hoped that they will illuminate the
435   way in which standard quantum mechanics may require modification to become a
436   satisfactory description of consciousness.

437

438   Quite apart from these big questions of context of the current theory in contemporary
439   science, there remains, of course, much to be done to extend the model to ever more
440   realistic neural systems. Firstly we need to acknowledge that spikes rarely occur as
441   isolated events. Future work will need to relate the decay of superposition states of
442   multiple action potentials to the probability distribution of multiple-spike trains.

443

444   Secondly, there is a need to explore how a directional flow of action potential through
445   a neuron can be modelled. All that has been described in the current paper is the continuous
446   evolution of a neural element of experience that parallels objective discontinuous spike
447   formation and synaptic transmission. Considering the subjective aspect, the specific
448   starting condition considered in the paper, one action potential in the source neuron and
449   no action potentials in a reservoir of target neurons, is a highly structured state. In an
450   information theoretic sense, the entropy of the combined subjective state increases through
451   synaptic transmission. The dynamics that ensue from this specific starting condition are

452   indeed irreversible in time. It is acknowledged, however, that there is more to the story
453   that will need to be told in future work. The limitation of the current model that it seemed
454   to allow bidirectional or reversible flow of action potential through the neural circuit: not
455   only synaptic transmission forward from axon to dendrite, but backward from dendrite to
456   axon. Moreover, in what has been presented, there is a lack of sustainability of evolution
457   in time. In time, all neurons connected by synapses would relax to about the same spike
458   potential: a maximum entropy state of brain.
459

460   Examining the sub-cellular objective dynamics that correlate with the evolution of
461   experience that has been modelled (see section 1.2), they are found to be largely passive
462   (not energy-requiring), involving the discharge of transmembrane potential. In contrast,
463   the other component of objective dynamics that is yet to be modelled, membrane
464   repolarisation (also neurotransmitter synthesis or reuptake) is ATP-dependent. The energy
465   debt incurred is ultimately repaid through cellular metabolism. The processes of glycolysis
466   and oxidative phosphorylation that transform ADP back to ATP also generate heat. In a
467   thermodynamic sense, it is these other aspects of subcellular evolution that are irreversible.
468

469   These considerations motivate the following sketch of a future extended model of
470   neural states and their evolution. I suspect that to describe unidirectional action potential
471   flow and a sustained stream of consciousness, a model with at minimum two neural
472   compartments would be required. We could label these compartments 'dendritic' and
473   'axonal' in order to indicate that synaptic transmission is to be represented by action
474   potential flow from the axonal compartment of the source to the dendritic compartment of
475   the target neuron, but these compartments should not be associated too literally with
476   objective functionally specialised parts of the neuron. The extended 2-compartment model
477   would also include a new continuous process that would pump or shunt action potential
478   unidirectionally from dendritic to axonal compartments. One would hypothesise that
479   without the effect of this pump, action potential flowing into the dendritic compartment
480   by synaptic transmission from some other source would quickly become distributed
481   between compartments. The operation of the pump would ensure that virtually none
482   remained in the dendritic compartment, and would erase a bit of information about action
483   potential location. By Landauer's Principle, such information erasure would be dissipative
484   [27]. The objective neural correlate would be the energy expenditure per spike of membrane
485   repolarisation, mentioned above. Note that the model of consciousness as described above
486   would otherwise remain unaltered: the perception value of the neuron would still be the
487   expectation value of the number of action potentials; the stream of consciousness would
488   still be generated by synaptic interaction.
489

490   Finally, we will consider here, at least in broad conceptual terms, the evolution of a
491   complex neural system such as the brain, which is not closed even in the limited sense of
492   synaptic interaction, but which communicates with the outside world via a peripheral
493   nervous system. Even if we assume that physical interactions within the central nervous

494 system are unchanging, the nervous energy that generates the evolution of the mental
495 state still cannot be time-independent. As we extend our definition of brain to include
496 structures that seem ever less likely to support consciousness, such as thalamic relay
497 nuclei, spinal cord and dorsal root ganglia, external influences will still modulate the
498 potential of component neurons to fire. According to the model we have developed, there
499 is still a flow of action potential to and from the composite neural system.
500
501   In our description of source and target neurons detailed above, we could have
502 predicted the same evolution of spike potential if we had modelled synaptic interaction
503 as a small oscillatory perturbation of the nervous energy of the source at angular
504 frequency Ω [28]. In this approximation, the state of the source neuron would then remain
505 pure, undergoing unitary evolution, but with a time-dependent nervous energy. By
506 analogy, we propose that taking any reasonable definition of brain, the neural interaction
507 with the periphery, modelled as a perturbation of the composite nervous energy, is
508 sufficiently small and slowly changing that unitary evolution of a mental state vector
509 remains a reasonable approximation of the conscious state of the brain. If the
510 perturbation of the nervous energy represents the interaction of brain with the sensory
511 environment, generating 'perceptual' experience, then perhaps the unitary evolution
512 generated by time-independent interactions within brain is the 'conceptual' component of
513 the stream of consciousness.

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