

# The Quantum-Classical and Mind-Brain Linkages: The Quantum Zeno Effect in Binocular Rivalry

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## Abstract

A quantum mechanical theory of the relationship between perceptions and brain dynamics based on von Neumann's theory of measurements is applied to a recent quantum theoretical treatment of binocular rivalry that makes essential use of the quantum Zeno effect to give good fits to the complex available empirical data. The often-made claim that decoherence effects in the warm, wet, noisy brain must eliminate quantum effects at the macroscopic scale pertaining to perceptions is examined, and it is argued, on the basis of fundamental principles, that the usual decoherence effects will not upset the quantum Zeno effect that is being exploited in the cited work.

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## I. INTRODUCTION

Efstathios Manousakis[1] has recently given a quantum mechanical description of the phenomena of binocular rivalry that fits the complex empirical data very well. It rests heavily upon the quantum Zeno effect, which is a strictly quantum mechanical effect that has elsewhere been proposed as the key feature that permits the free choices on the part of an observer to influence his or her bodily behavior. The intervention by the observer into the physical dynamics is an essential feature of orthodox (Copenhagen and von Neumann) quantum mechanics. Within the von Neumann dynamical framework this intervention can, with the aid of quantum Zeno effect, cause a person's brain to behave in a way that causes the body to act in accord with the person's conscious intent. Atmanspacher, Bach, Filk, Kornmeier and Roemer[2] have proposed for the phenomena of bistable (Necker cube) perception a theory that rests on an effect that resembles the quantum Zeno effect. However, their treatment is based not on quantum theory itself, but on what they call weak quantum theory. This is a theory that exhibits a quantum-Zeno-like effect but does not involve Planck's quantum of action, which is the quantity that characterizes true quantum effects. The approach of Manousakis would therefore seem superior, because it uses the known actual quantum Zeno effect that arises from orthodox quantum theory itself, rather than upon a new conjectural unorthodox foundation. On the other hand, using the orthodox physics-based approach might seem problematic, because it depends on the existence of a true macroscopic quantum effect in a warm, wet, noisy, brain, and it has been argued that such effects will be destroyed by environmental decoherence[3]. That often cited argument covers many quantum effects, but fails for fundamental reasons described in the following sections to upset the quantum Zeno effect at work here.

## II. COUPLED OSCILLATORS IN CLASSICAL PHYSICS

It is becoming increasingly clear that our normal conscious experiences are associated with local  $\sim 40Hz$  oscillations of the electromagnetic fields at selected correlated sites on the cerebral cortex. These sites are evidently dynamically coupled, and the brain appears to be approximately described by classical physics. So I begin by recalling some elementary facts about coupled classical simple harmonic oscillators (SHOs).

In suitable units the Hamiltonian for two SHOs of the same frequency is

$$H_0 = \frac{1}{2}(p_1^2 + q_1^2 + p_2^2 + q_2^2). \quad (1)$$

If we introduce new variables via the canonical transformation

$$P_1 = \frac{1}{\sqrt{2}}(p_1 + q_2) \quad (2)$$

$$Q_1 = \frac{1}{\sqrt{2}}(q_1 - p_2) \quad (3)$$

$$P_2 = \frac{1}{\sqrt{2}}(p_2 + q_1) \quad (4)$$

$$Q_2 = \frac{1}{\sqrt{2}}(q_2 - p_1), \quad (5)$$

and replace the above  $H_0$  by

$$H = (1 + e)(P_1^2 + Q_1^2)/2 + (1 - e)(P_2^2 + Q_2^2)/2, \quad (6)$$

then this  $H$  expressed in the original variables is

$$H = H_0 + e(p_1q_2 - q_1p_2). \quad (7)$$

If  $e \ll 1$  then the term proportional to  $e$  acts as a weak coupling between the two SHOs whose motions for  $e = 0$  would be specified by  $H_0$ .

The Poisson bracket (classical) equations of motion for the coupled system are, for any  $x$ ,

$$dx/dt = \{x, H\} = \sum_j \left( \frac{\partial x}{\partial q_j} \frac{\partial H}{\partial p_j} - \frac{\partial x}{\partial p_j} \frac{\partial H}{\partial q_j} \right). \quad (8)$$

They give

$$dp_1/dt = -q_1 + p_2e, \quad (9)$$

$$dp_2/dt = -q_2 - p_1e, \quad (10)$$

$$dq_1/dt = p_1 + q_2e, \quad (11)$$

$$dq_2/dt = p_2 - q_1e. \quad (12)$$

For  $e = 0$  we have two uncoupled SHOs, and if they happen to be in phase then we have, for any positive constant  $C$ , a solution

$$p_1 = C \cos(t), \quad (13)$$

$$q_1 = C \sin(t), \quad (14)$$

$$p_2 = C \cos(t), \quad (15)$$

$$q_1 = C \sin(t). \quad (16)$$

These equations specify the evolving state of the full system by a trajectory in  $(p_1, q_1, p_2, q_2)$  space that, for each of the two individual systems, is just a circular orbit in which the energy of that system flows periodically back and forth between the  $q_i^2$  coordinate space (potential energy) and  $p_i^2$  momentum space (kinetic energy) aspects of the system.

For the coupled system, the integration of the time derivatives gives, up to first order in  $e$  and second order in  $t$ ,

$$p_1 = C(1 - t^2/2 + et), \quad (17)$$

$$p_2 = C(1 - t^2/2 - et), \quad (18)$$

$$q_1 = C(t + et^2/2), \quad (19)$$

$$q_2 = C(t - et^2/2). \quad (20)$$

This shows that if the small coupling  $e$  is suddenly turned on at  $t = 0$ , then the first-order deviation of the classical trajectory from its  $e = 0$  form will be linear in  $Cet$ . This result holds independently of the relative phase or amplitudes  $C > 1$  of the two SHOs.

When we introduce the quantum corrections by quantizing this classical model we obtain an almost identical quantum mechanical description of the dynamics. In the very well known way the Hamiltonian  $H_0$  goes over to (I use units where Planck's constant is  $2\pi$ .)

$$H_0 = \frac{1}{2}(p_1^2 + q_1^2 + p_2^2 + q_2^2) = (a_1^\dagger a_1 + 1/2) + (a_2^\dagger a_2 + 1/2). \quad (21)$$

The connection between the classical and quantum descriptions of the state of the system is very simple: the point in  $(p_1, q_1, p_2, q_2)$  space that represents the classical state of the whole system is replaced by a “wave packet” that, insofar as the interventions associated with observations can be neglected, is a smeared out (Gaussian) structure centered for all times exactly on the point that specifies the classical state of the system. That is, the quantum mechanical representation of the state specifies a probability distribution of the form  $(\exp(-d^2))$  where  $d$  is the distance from a center (of-the-wave-packet) point  $(p_1, q_1, p_2, q_2)$ , which is, at all times, exactly the point  $(p_1, q_1, p_2, q_2)$  that is the classical representation of the state.

According to quantum theory, the operator  $a_i^\dagger a_i = N_i$  is the number operator that gives the number of quanta of type  $i$  in the state. The classical constant  $C$  appearing in the classical treatment is the classical counterpart of  $\sqrt{N}$ , in the following sense: if the center of the wave packet lies at distance  $C$  from the origin  $(p_1, q_1, p_2, q_2) = (0, 0, 0, 0)$ , then the “expectation value” of  $N$  in this state is  $C^2$ . So the classical and quantum descriptions are almost identical: there is, in the quantum treatment, merely a small smearing-out in  $(p, q)$ -space, which is needed to satisfy the uncertainty principle.

This correspondence persists when the coupling is included. The coupling term in the Hamiltonian is

$$\begin{aligned} H_1 &= e(p_1 q_2 - q_1 p_2 - p_2 q_1 + q_2 p_1)/2 \\ &= ie/2(a_1^\dagger a_2 - a_1 a_2^\dagger - a_2^\dagger a_1 + a_2 a_1^\dagger). \end{aligned} \tag{22}$$

The Heisenberg (commutator) equations of motion generated by the quadratic Hamiltonian  $H = H_0 + H_1$  gives the same equations as before, but now with operators in place of numbers. Consequently, the centers of the wave packets will follow the classical trajectories also in the  $e > 0$  case.

### III. APPLICATION

With these essentially trivial calculations out of the way, we can turn to the implied physics. The above mathematical deductions show a near identity between the classical and quantum treatments. If at  $t = 0$  we suddenly turn on the coupling we see that the classical trajectory suddenly departs from the unperturbed path in a linear (in time  $t$ ) fashion. In the classical case that is the full small- $t$  story. But in orthodox quantum theory there is, in principle, an added observer-dependent effect. The observer, in order to get information about what is going on about him into his stream of consciousness, must initiate probing actions. According to the elaboration of the theory of von Neumann[4] described in Refs[5–8], the brain does most of the work. It creates, in an essentially mechanical way, generated by the quantum equations of motion, a proposed query. Each possible query is associated with a projection into the future that specifies the brain’s computed “expectation” about what its state will be after getting the feedback from the query (i.e., a feedback from the associated act of observation.) The physical manifestation of this act is called “process 1”

by von Neumann. It is a key element of the mathematics associated with the process of observation: i.e., with the entry into the observer's stream of consciousness of information about the state of the physical world.

In order to focus on the key point, and also to tie the discussion comfortably into the understanding of neuroscientists who are accustomed to thinking that the brain is well described in terms of the concepts of classical physics, I shall consider first an approximation in which the brain is well described by classical ideas. Thus the two SHO states that we are focusing on are considered to be imbedded in a classically described brain that is providing the potential wells in which these two SHOs move. It is the degrees of freedom of the brain associated with these two SHOs that are, according to theory being discussed here, the neural correlates of the consciousness of the observer during the period of the experiment. Hence it is they that are affected by von Neumann's process 1. The remaining degrees of freedom are treated in this approximation as providing the background classically described potential wells in which these consciousness-related SHOs move. One of these SHOs corresponds to the neural correlate of the percept associated with one eye, the other SHO is the neural correlate of the percept associated with the other eye. This approach reduces the situation to an exactly solvable problem not clouded by the infinity of effects whose consideration usually places any rational understanding of the connection between mind and brain beyond our conceptual reach.

In the binocular rivalry context, let the unperturbed ( $e = 0$ ) motions represent the computed (expected-by-the-brain) evolution of these two SHO states when both eyes are seeing essentially the same scene, and are exciting highly similar responses, and let the  $e > 0$  case represent the dynamics of the combined system in the binocular rivalry case, where the neural correlates of the two possible percepts are dissimilar. The "expectation" naturally follows the unperturbed orbit, which corresponds to normal experience, in which both eyes view essentially the same scene. But if  $t = 0$  represents the time of the last observation, then for small  $t > 0$  the actual brain state in the rivalry case will diverge from the computed-on-the-basis-of-past-experience state, due to the difference of the actual state from the normal state. In the binocular rivalry case, according to the equations derived above, the path of the (center of, and hence the entire) actual Gaussian wave packet will, like its point classical counterpart, diverge linearly in  $t$  from the path expected by the brain on the basis of past experience. The divergence of the Gaussian wave packet in the rivalry

case from its “expected” circular orbit is readily visualizable in a two dimensional  $(p, q)$  space.

According to the basic statistical law of quantum theory, the probability that the actual state of the brain, immediately after the feedback has occurred, will be in the “expected” state is equal to the square of the absolute value of the overlap (integral) of the actual and “expected” wave functions. The collapse action occurs in the subspace that is associated with the occurring experience. The overlap of these two Gaussians is  $(\exp(-d^2/2))$ , where  $d$  is the distance between their centers. Because this distance  $d$  increases like  $Cet$ , the probability that the actual state will be found at time  $t$  to be in the “expected” state goes to lowest order in  $t$  like  $(1 - (Cet)^2/2)$ . And this result is independent of the relative phases of the two oscillators. The fact that this probability is unity minus a correction of order  $(Cet)$  squared, means that if the probing actions come repetitiously at time intervals  $\delta t \ll 1$  such that also  $Ce\delta t \ll 1$ , then the probability that the state will remain on the unperturbed orbit for, say, a second will remain high even though the classical trajectory moves linearly away from the unperturbed orbit by an amount of order  $Ce$ . If  $\delta t$  is of the order of a few milliseconds, then the factor  $Ce$  must be less than about unity. Because the number of quanta  $N$  in the “classical” state is presumably very large, and  $C = \sqrt{N}$ , the coupling  $e$  needs to be less than about  $1/\sqrt{N}$ .

The slowing of the divergence of the actual orbit from the computed (circular-in-this-case) orbit is a manifestation of the quantum Zeno effect. The representation in the brain of the posing of the question of whether the state of the neural correlate of the occurring percept is the computed/expected state is von Neumann’s famous process 1, which lies at mathematical core of von Neumann’s quantum theory of the relationship between perception and brain dynamics.

Because this argument is about possibilities that nature could exploit, I shall consider the cases where  $e < 1/\sqrt{N}$ . In these cases there will be, in this quasi-classical model, by virtue of the quantum Zeno effect, a large difference between the observed path predicted by quantum theory and the path specified by the deterministic equations of classical physics.

I have focused here on the leading powers in  $t$ , in order to emphasize, and exhibit in a very simple and visualizable way, the origin of the key result that for small  $t$  on the scale, not of the exceedingly short period of the quantum mechanical oscillations, nor even on  $\sim 25ms$  period of the  $\sim 40Hz$  scale of the classical oscillations, but on the scale of the

difference of the periods of the two coupled modes, there will be, by virtue of the quantum mechanical effects associated with the process of rapid repeated observations, a shift from a linear to a quadratic-in-time departure of the state of the system from the state specified by von Neumann's process 1. This deviation from unity corresponds to the factor  $(\cos(et))^2$  in the more complete probability expression. Manousakis's work is based on these factors  $(\cos(et))^2$  with times  $t$  corresponding to intervals between conscious perceptions of the same scene, and the complementary factor  $(\sin(et))^2$  at the termination of repetitions of the same percept. The success of Manousakis's work is the first quantitative indication that von Neumann's quantum theory of observation works well in actual practice at this level of brain dynamics. There is, of course, the powerful indirect evidence stemming, firstly, from the massive empirical successes of orthodox quantum theory, which uses this collapse theory of observation to overcome the huge logical difficulties stemming from the uncertainty principle, and secondly, from fact that it allows us to understand within the framework of orthodox basic physics the evident capacity of our conscious thoughts to influence our physical actions, and thereby to enter into the process of natural selection.

In the broader quantum mechanical context, the deterministic quantum mechanical generalization of the deterministic classical law of motion generates merely the set of possible process 1 actions: it neither chooses between the generated possible process 1 actions, nor selects the times  $t$  at which the chosen process 1 actions will actually occur. Within the pragmatic orthodox quantum theory these choices are therefore treated as, and are called, "free choices on the part of the experimenter". The computations given above show, in particular, that the choices of the rapidity of the acts of observation can, under appropriate physical circumstances, and by virtue of the quantum Zeno effect, be causally efficacious in the physically described world.

The discussion has focused so far on one very small region of the cortex, or rather on one pair of causally linked regions, with one member of the pair associated with one possible experience, and the other member of the pair associated with the rival possible experience. But each possible experience is presumably associated with the excitation of a large collection of such localized regions. Following the principles of quantum *field* theory the quantum state is represented by a tensor product of states associated with the individual tiny regions. Each such region interacts with its own immediate environment. The mechanism under consideration here does not involve bringing the "amplitudes" located in different tiny regions of the



cortex together, and observing interference effects. Consequently, the usual argument[3] to the effect that “decoherence” effects will destroy quantum effects has no immediate bearing on the *basically field theoretic* (as contrasted to ordinary first quantized quantum theoretic) situation being discussed here. The quantum Zeno effect being examined here arises from the product—not the sum—of the effects associated with different local regions. Hence random phase factors attached—by virtue of weak interactions with differing individual local environments—to the above described wave packets associated with different regions do not affect the quantum Zeno effect described here, which are controlled by the essentially classical trajectories and the absolute values squared of the overlap integrals.

In the language of the description used above, the relevant classical trajectories will be in a space of a large number of doublets of variables  $(p_j, q_j)$  with many doublets corresponding to cortical sites associated with the image from one eye, and many other doublets corresponding to cortical sites associated with an image from the other eye. There will be essentially classical couplings between the trajectories associated with one image and the trajectories associated with the other image. But the probability considerations pertaining to the powers of  $t$  that arise from the absolute values of the overlap integrals of the Gaussian wave packets carry over directly to the higher-dimensional case, due essentially to the multi-dimensional generalization of the theorem of Pythagoras. Adding extra environmentally induced phase factors to the wave packets in the  $(p_j, q_j)$  spaces associated with the different sites has no effect on the occurring product of probability factors.

In the approximation considered above we have taken into account: (1), the effective potential wells in which the presumed-to-be-important correlated SHO motions can be considered to move; (2), the interactions with the environments that introduce the uncontrolled phase shifts that produce the usual environmental decoherence effects; and (3), the coupling between the two extended collective modes that are being excited by the strong optical stimuli from the two eyes. Within this approximation we have obtained a very simple understanding of the origin and relevance of the quantum Zeno effect in the phenomenon of binocular rivalry. Of course, the brain is a complex system, and this simple approximation cannot be the whole story. But the suggestion here is that this relatively simple quasi-classical model displays the essence of the quantum mechanical understanding of the dynamical connection between (conscious) percepts and their neural correlates. According to this approach, the classical structure of our experience arises primarily not from envi-

ronmental decoherence effects, as is often assumed, but rather from the close dynamical connection described above between the quantum and classical dynamics of the SHO states that enter into the collapse events that according to von Neumann's quantum theory of perception tie our experiences to their neural correlates.

This model assumes that the process 1 actions associated with our experiences single out these pure quantum states. I have often suggested[8–10] that the best candidates for the states corresponding to the process 1 actions associated with our experiences are the so-called coherent states of the electromagnetic (Coulomb) field[12]. These states, localized in the array of excited cortical or other sites corresponding to the neural correlates of the occurring thought/percept, are exactly what have been used here. They are dynamically robust[9], and as emphasized above, are closely connected to classically described aspects of the brain, and thereby to the observer's classical description of her or his perceptions. The quantum-classical linkage that is crucial to the pragmatic success of quantum theory arises naturally by connecting brain states to streams of consciousness in the way described here.

The question naturally arises how particular conscious thoughts come to be associated with particular patterns of cortical excitations. Is some miracle required to fix these connections? No! The process is completely natural and rationally understandable. As extensively discussed in Ref. [5], and re-emphasized in Ref. [6], trial and error learning beginning before birth and involving feedback loops pertaining to physically effective process 1 actions that link effortful feelings to subsequent experiences eventually produce conscious awareness of, and then application of, correlations between controllable efforts and their feedbacks, and these applications automatically strengthen the correlations between intentional and perceptual thoughts and the patterns of brain activity that are their causal counterparts in the brain. This theory of perception is naturalistic and assigns to our conscious thoughts, as components of the natural order, a causal role that is closely aligned to the role of our thoughts in empirical scientific practice.

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