Can all neurobiological processes be described by classical physics?

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We discuss results recently given in an article by M. Tegmark (MT99) where he argues that neurons can be described appropriately by pure classical physics. This letter is dedicated to the question if this is really the case when the role of dissipation and noise – the two concurrent phenomena present in these biological structures – is taken into account. We argue that dissipation and noise might well be of quantum origin and give also a possible reason why neural dynamics is not classical.

In his recent work M. Tegmark (MT99) states that certain processes in biological neural networks, such as the firing of neurons, occur independently of coherent quantum effects. As a result these processes evolve according to classical physics and are in addition subject to dissipation and noise, which account for the interaction with some environment. The latter involves ”[...] all degrees of freedom that the observer is not paying attention to.” [4]. The author further concludes that dissipation and noise should be added as extra classical entities. In particular, dissipation turns out to be important, because its characteristic timescale becomes comparable to the typical dynamical timescale of the system.

In this letter we discuss the role of dissipation and noise, arising from the interactions between the system (here, biological neurons) and the environment in some more detail. We focus on the question when dissipation and noise can considered to be classical and when this is not the case at all. We think that a satisfactory answer has not been given in MT99. Thus it remains an open question whether neurobiological structures evolve independently of quantum effects or not.

Dissipation

The interaction between system and environment produces dissipation. This phenomenon reflects the possibility that during time evolution accessible modes change into inaccessible modes belonging to the environment. Our question here is what origin the dissipative processes described in MT99 really have. To discuss this problem we utilize the coarse-graining paradigm to distinguish between system and environment. This means that an original (classical or quantum mechanical) physical structure is subdivided into two parts which eventually become the system and the environment [4]. Usually this division is realized by introducing a coarse graining procedure, i.e. small spatial lengthscales are filtered out appropriately (for details, see [5]). Then there are two basic possibilities:

a. Dissipation is essentially a classical phenomenon. Then dissipation emerges after coarse graining a subsystem that is completely representable by classical physics. This kind of dissipation we call classical dissipation.

b. Dissipation is a quantum phenomenon. Then it is a by-product of coarse graining a subsystem that cannot be described by classical physics appropriately and the resulting dissipation cannot be obtained via coarse graining a classical subsystem. This kind of dissipation we call quantum dissipation.

Examples for both kinds are known. For instance, consider a subsystem that is represented by the Euler equation. Then the resulting (coarse grained) system exhibits dissipation arising from unresolved scales [2]. On the other hand in [3] we showed that already non-interacting quantum field theories reveal dissipative behavior after being averaged over small spatial volumes. However, it turns out that quantum dissipation is inherently different from its classical counterpart. This is because the former acts non-locally in time, i.e. the state at an arbitrary time $t$ depends on the system’s history between $t - \tau_m$ and $t$, where $\tau_m$ denotes a non-vanishing memory time. Contrary to that a classical subsystem that is completely determined by local (in space and time) equations of motion would – after spatial coarse graining – lead to a local evolution in time. Thus the resulting equations would not involve a memory term and in this situation $\tau_m$ would become infinitesimal small.

1 The original physical structure is actually a system which does not have an environment. This means that its temporal evolution does not depend on inaccessible modes. In what follows, we call this particular structure subsystem.
As a next point we briefly discuss the nature of the noise term itself. Noise is generated by (hidden) modes of the environment which – during their temporal evolution – occasionally become part of the system. A detailed description of the noise arising from the coarse graining procedure for quantum systems is given in [5] as well as in [3]. Again it is obvious to introduce classical and quantum noise using the same kind of classification as in the previous section. But then it is not immediately clear whether there is a substantial difference between the latter and the former. However, since noise always appears together with dissipation it is natural to consider both – noise and dissipation – at the same time and therefore to investigate their cumulative effects. For instance, noise in a system with quantum dissipation would be represented by a non-Markovian random process (because of the dependence on the system’s history) while on the other hand classical dissipation would not change a given Markovian character of noise.

Possible origins of dissipation and noise in neurons

Now we ask if quantum noise and dissipation are relevant for the processes taking place in neurons despite the fact that (according to the results in MT99) coherent quantum effects over spatial distances become negligible. The decoherence analysis in MT99 can be discussed in the context of arguments given in [3]. There we used the coarse graining paradigm to show that near the classical limit additional terms appear within the classical equations of motion. These terms account for quantum dissipation, quantum noise and for the quantum potential (or Bohm-potential). In fact, the latter term is responsible for non-local quantum effects in space. Thus the results in MT99 and in particular the expression given for the off-diagonal elements of the system’s density matrix suggest that coherent quantum effects coming from the quantum potential are unimportant. At the same time however, quantum dissipation and quantum noise need not to be negligible. To proof that they actually are, one would additionally have to show that on timescales relevant for the macroscopic system these terms provide a very small contribution. For example, one necessary condition would be the fact that the memory time, $\tau_m$, is much smaller than the dynamical time of the system. At this point it is worthwhile to note that the dynamics of biological neurons involves some non-local temporal behavior. The so-called 'neuron firing', which is the initial emission and following propagation of an action potential (spike) along the axon, prerequisites that incoming electric signals reach some certain threshold. More specifically, excitatory postsynaptic signals propagate towards the axon-hillock where they lead to a large probability for the emission of a spike when the sum of these incoming signals within a short period of time exceeds a threshold $[\text{1}]$. This process is called temporal summation and the aforementioned 'short period of time' is known to be of the order of tens of milliseconds $[\text{2}]$. Thus signal processing in a neuron involves a memory effect. Facing this fact we ask the obvious question if the memory time present in neural signal processing has something to do with the memory time $\tau_m$ that results from a quantum mechanical description of the system. If $\tau_m$ turns out to be much smaller than memory timescales observed in neurons then we would have to look for a classical theory that explains the considered non-local effect. So far, it is not clear how such a theory might look like and what the physical assumptions are that form its basis. But since coarse grained quantum mechanics provides very naturally a non-local temporal behavior it seems – at least at the present stage – reasonable not to preclude quantum physics from neurobiological processes.

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3. A.M. Lisewski, preprint quant-ph/9905014
4. M. Tegmark, preprint quant-ph/9907009
5. J. Rau and B. Müller, Phys. Rep. 272, 1 (1996)

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This number is close to the dynamic timescale of a neuron being around $10^{-3} \rightarrow 10^{-1}$ s.