QUANTUM MECHANICS & THE BRAIN, AND SOME OF ITS CONSEQUENCES

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ABSTRACT: In this paper we examine the consequences of von Neumann's interpretation of quantum mechanics in the context of an insect conditioning experiment. We argue that either the insect has a mind (consciousness?), therefore collapsing the wave function, or it does not, therefore reacting to superpositions in a different way. Thus, a device to condition insects could be used to test von Neumann's interpretation, if insects are not conscious. If, on the other hand, insects possess a mind, such experiment would open up the possibility of using insect experiments to test Stapp's theory of mind-matter interaction.

KEYWORDS: Foundations of quantum mechanics; Measurement problem; von Neumann interpretation

INTRODUCTION

In 2007, Pat Suppes (1922-2014) and the first author (JAB) were asked to write a paper to a special session on *Quantum Interactions* at the Association for the Advancement of Artificial Intelligence (AAAI) Spring Symposia at Stanford University. The proposal of this session was to bring together researchers from different areas, such as language, psychology, economy, etc., who were interested in the possibility of using quantum mechanics (including its contextual probabilistic calculus) as a tool in their disciplines. For this conference, they both wrote an article on the possibility of conditioning cockroaches or other insects to a single photon, and discussed the possible implications of this to our understanding of the quantum (Suppes and de Barros, 2007). Though their conclusions were not groundbreaking, and the proposed experiment was technically very difficult to be performed, it seemed at the time like an interesting possibility.

Now, more than seven years past the initial insect-conditioning paper, Sean O'Nuallain organized, during the Foundations of the Mind II conference at University of California, Berkeley, a special session in honor of Pat Suppes, who passed away in 2014. It is heartening for us to be able to talk about the cockroach conditioning work again, and to find connections between it and the many different topics discussed in this conference. In particular, contrary to what Pat and JAB thought initially, onecan get very interesting conclusions from a possible insect-conditioning experiment. It is the goal of this paper to sketch such conclusions, in particular with respect to von Neumann as well as Henry Stapp's work (who also gave a talk at this conference).

Let us start with a quick review of the motivation for this paper. The proposed connection between the mind and the quantum mechanical collapse of the wave function, known as the von Neumann interpretation of quantum mechanics (vN), is well known, and dates back to the early 20th Century. Its motivation lies in the famous measurement problem, which in a simplified way is a puzzle over two apparently contradictory dynamics that quantum systems undergo through their evolution. Though vN offers a complete solution to the measurement problem, perhaps its dual character, where mind and matter seem to be in different realms and follow different physical laws, is considered unsatisfactory to the majority of physicists working on the foundations of quantum mechanics, who prefer themselves other interpretations, such as Bohm or many-worlds (see Tegmark (1998) andSchlosshauer et al. (2013) for surveys of Physicists views about different interpretations of quantum mechanics). However, up to this day, which interpretation of quantum mechanics one favors is merely an esthetic or personal choice, since no experiment can yet rule out some of the most popular interpretations[1].

This paper is organized as follows. First, we present the measurement problem, and show how von Neumann's interpretation solves it. Then, we briefly discuss the single-photon insect-conditioning experiment introduced in Suppes and de Barros (2007), and present the main argument of the paper. We end with some discussions and possible consequences of plausible experimental outcomes.

[1] Even the local hidden-variable ensemble interpretations, favored by Einstein, are still not ruled out, despite an overspread belief on the contrary. This is mainly because of the existence of loopholes in experimental procedures that cannot exclude certain models Fine (2009). However, as this paper was being written, a new experiment claims to have finally closed the detection loophole (see http://arxiv.org/abs/1508.05949).

THE MEASUREMENT PROBLEM

To better understand the measurement problem, we point out that quantum systems are represented by vectors |y⟩ in a Hilbert space *H*, and we have a one-to-one correspondence: for every state of a system we have a vector, and for every vector we have a realizable state. The physical evolution of such a system is given by Schrödinger's equation, which in the mathematical formalism is represented by a unitary evolution operator $\hat{U}\left(t,t_0\right)$ that, if applied at the state of a system at time t_0, gives the state at time *t*:

$$|\psi(t)\rangle = \hat{U}\left(t,t_0\right)|\psi\left(t_0\right)\rangle.$$

Notice that the above equation is deterministic, as the state at time *t* is completely given by the initial state at time t_0. However, Û is not the only type of evolution a quantum system undergoes. If a measurement is made, then the system undergoes a probabilistic evolution given by Born's rule. For example, if the measurement made is of the observable Ô, which can be written in terms of its projector basis $\hat{P}_i = \delta_{ij}\hat{P}_i\hat{P}_j$ as

$$\hat{O} = \sum_i o_i \hat{P}_i,$$

then each measurement outcome o_i occurs with probability $P\left(o_i\right) = \left|\hat{P}_i|\psi\rangle\right|^2$, and if the actual observed value is o_j, then the state collapses to a new state

$$|\psi\rangle \rightarrow \frac{\hat{P}_j|\psi\rangle}{\langle\psi|\hat{P}_j|\psi\rangle}.$$

That the evolution under a measurement cannot be obtained from the Schroedinger's equation should be obvious, as the unitary evolution operator Û is linear, whereas the projection during a measurement cannot be obtained by a linear operation. However, to make this explicit, von Neumann asked the following question: what happens if we treat the measuring apparatus as a quantum system? Following von Neumann, let $\mathcal{H}$ and $\mathcal{H}_1$ be the Hilbert spaces of the system and measurement apparatus, respectively. In fact, we don't need to treat the measurement apparatus in all its complexity: we can consider an $\mathcal{H}_1$ that represents only the degrees of freedom of the apparatus pointer. With this in mind, the state of the system plus apparatus could be represented by a vector belonging to the product space $\mathcal{H}\otimes\mathcal{H}_1$.

Since measurements take eigenstates of the measurement into themselves, but with changes to the pointer of the measurement apparatus, we can now start building the evolution operator for the measurement process. Let us start with the simplest case of measuring, where the observable is simply a projection operator, $\hat{P}$. This operator has two eigenvalues, 0 or 1, and two eigenvectors, $|0\rangle$ and $|1\rangle$, corresponding to the two eigenvalues. Imagine that the system is, before a measurement, in the state $|0\rangle$. Then, the initial state of the system immediately before the measurement is $|0\rangle\otimes|\text{ready}\rangle$, where $|\text{ ready}\rangle$ is simply the state of the measuring apparatus when it is ready to accept a system to be measured. After their interaction, if a successful measurement happened, the final state should be $|0\rangle\otimes|\text{points to "0"}$, signifying that the state of the system was unchanged (it is an eigenstate of the measurement apparatus) and that the measurement device now points to the property "0" for the system. If we think of the measurement as dictated by Schroedinger's equation, then we should have a unitary operator $\hat{U}_M\in\mathcal{H}\otimes\mathcal{H}_1$ with the following property:

$$\hat{U}_M\in\mathcal{H}\otimes\mathcal{H}_1$$

Similarly, for eigenstates $|1\rangle$, we have

$$\hat{U}_M|1\rangle\otimes|\text{ready}\rangle=|1\rangle\otimes|\text{points to "1"}\rangle.$$

However, as we know from the one-to-one relationship between system and Hilbert space, it is always possible to construct the system in a superposition of the state $|0\rangle$ and $|1\rangle$. If this is the case, then we have that a measurement would be the operator $\hat{U}_M$ applied to the superposition, and we would have

$$\hat{U}_M\left(c_0|0\rangle+c_1|1\rangle\right)\otimes|\text{ready}\rangle=c_0|0\rangle\otimes|\text{points to "0"}\rangle$$
$$+c_1|1\rangle\otimes|\text{points to "1"}\rangle.$$

Notice that the right hand side of the equation is also a superposition, and, more importantly, is not an eigenvector of the measurement operator $\hat{P}\otimes\hat{1}$, meaning that a measurement was actually not performed. This is the core of the measurement problem: we cannot represent the probabilistic collapse of the wave function with a unitary operator (i.e., with Schroedinger's evolution).

In his argument, von Neumann points out that what constitutes a measurement device is arbitrary. Say we start with a state where we have a superposition of a single photon and the vacuum state. We can think of a photo-detector as a single atom, who can absorb the photon and then generate a (microscopic) current due to the photoelectric effect. But this “measurement device,” when interacting with the photon, will then be in a superposition of either absorbing the photon or not. We can then use another measuring device to observe the atom, and see if it absorbed the photon. This additional measurement device can then be observed by yet another one, and so on, until we reach the eye of the experimenter, which is itself a detector. From the eye, we can think of the optic nerve, the brain itself, and finally the mind. von Neumann argues that wherever you see this chain of apparatuses, there is never a clear point where we should not see a superposition, except that we in fact never see a superposition. So, he argues that the only place in the chain of measurement apparatuses that we know for sure the wave function collapses (i.e., no superposition) is when there a conscious experience by the observer that determines, “oh, yes, I see a pointer in a determinate position.” In other words, the interaction of the mind with a physical system changes the laws of evolution of the system itself. If the system is not interacting with a mind, then it evolves in a deterministic way, according to Schroedinger’s equation, and if the system interacts with a mind, the wave function collapses to one of the eigenstates of the measurement apparatus.

Von Neumann’s solution is, clearly, dualist. It posits the existence of a matter that satisfies a different set of physical laws than a mind, which causes matter to evolve in a different way that it would without its presence. For that reason, von Neumann’s interpretation found strong resistance from the physics community, who by and large think of it more as a curiosity, but does not take it seriously as a candidate for the solution to the measurement problem. However, we should point out that it is, from a conceptual point of view, if not unpalatable, at least a perfectly logical and reasonable solution to it.

TESTING VON NEUMANN

We now turn to the main idea of this paper. We start with an insect conditioning experiment. As proposed by Suppes and de Barros (2007), some insects can detect single photons. Since insects can also be conditioned, it follows that it should be possible to use the classical conditioning paradigm to train an insect to respond to single photons. Of course, such experiments are technically very difficult and delicate, first because generating single photons on demand is a tall order, and second because insect conditioning is not as easy a straightforward as, say, dog conditioning (and anyone who tried to train a dog also knows it requires lots of patience and persistence).

Let us imagine that single-photon insect conditioning is possible[2] , and that it can performed successfully in a controlled lab environment. Imagine now the following photon states

$$|R\rangle = |0\rangle_L \otimes |1\rangle_R$$

and

$$|L\rangle = |1\rangle_L \otimes |0\rangle_R,$$

where the subscript L refers to the left eye and R to the right. States $|R\rangle$ ($|L\rangle$) are simply those where a single photon is sent to the right (left) eye and a vacuum states is sent to the left (right) eye. We can imagine a successful conditioning where the cockroach moves its antenna to the left if state $|L\rangle$ is sent and to the right if $|R\rangle$ is sent. An interesting question is what happens if the superposition

$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(|R\rangle + |L\rangle\right)$$

is sent to the cockroach. The answer, according to von Neumann, depends on whether the cockroach is conscious (or has a mind) or not. Let us examine each case separately.

If the cockroach is conscious, then the superposition state $|y\rangle$ will collapse into either $|R\rangle$ or $|L\rangle$.. Given the superposition chosen, the cockroach will move its antennae either to the right of to the left with probability 1/2. This is pretty much the same prediction that most other interpretations of QM would give, but for von Neumann, it would have to imply the cockroach is conscious.

If the cockroach is not conscious, then the superposition state $|y\rangle$ will not collapse, and the cockroach's antennae will go into a superposition of right/left. This superposition could in principle be used to generate another superposed state, which could be tested experimentally. This would be a surprising result, as the cockroach is a macroscopic object, but it would be implied by von Neumann's interpretation.

FINAL COMMENTS

In this paper, we sketch an thought experiment, based on another experiment proposed by Suppes and de Barros Suppes and de Barros (2007), where we do not falsify von Neumann's, but either show it correct (perhaps falsifying other theories) or that it may lead to panprotopsychism. Panprotosychism comes from it in the following way: if cockroaches cause the collapse, what if we just now remove its neural system from the body, and have it connected to wires that correspond to the outputs? What if

[2] Recent experiments suggest it may be very difficult do to so. See, e.g. Honkanen et al. (2014).

we replace the neural circuitry with silicon based systems that can "learn" and be conditioned like the cockroach (or even simply respond to inputs from left or right differently)? This would suggest even those systems, if not keeping the superposition, would be conscious, according to von Neumann. We could even imagine the tiniest system that leads to collapse, and such system would also be conscious.

On the other hand, the collapse of the wave function for such systems would open up the possibility of studying Stapp's model of the inverse quantum Zeno effect (QZE) (Stapp, 2009; , 2014), proposed to study the possibility that the mind can affect matter (thus solving the old problem of the mind-body causal interaction). Since cockroaches' neuronal pathways can be easily mapped (as opposed to humans or more complex animals), the sources of neural oscillators that can be candidates for Stapp's inverse QZE can be detected and studied.

We point out that the proposed experiment has some serious challenges that need to be addressed before it can be considered successful. The most relevant difficulty is the probable effects of decoherence in such systems. This issue will be discussed more carefully in a future paper.

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