Can we Falsify the Consciousness-Causes-Collapse Hypothesis in Quantum Mechanics?

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Abstract In this paper we examine some proposals to disprove the hypothesis that the interaction between mind and matter causes the collapse of the wave function, showing that such proposals are fundamentally flawed. We then describe a general experimental setup retaining the key features of the ones examined, and show that even a more general case is inadequate to disprove the mind-matter collapse hypothesis. Finally, we use our setup provided to argue that, under some reasonable assumptions about consciousness, such hypothesis is unfalsifiable.

Keywords Measurement problem · von Neumann-Wigner interpretation · collapse of the wave function · fourth-order interference

1 Introduction

One of the central issues within Quantum Mechanics (QM) is the measurement problem. Though many different solutions to it have been offered (e.g. [1,2,3,4,5,6]), there is no consensus among physicists that a satisfactory resolution has been achieved. Perhaps the main reason for this disagreement is the lack of clear experimental procedures that could distinguish an interpretation from another. For example, Bohm’s theory yields exactly the same predictions as the standard Copenhagen interpretation for quantum systems [7], at least for most measurable quantum systems[1].

Among the proposed solutions, perhaps one of the most controversial is von Neumann’s idea that a measurement is the result of the interaction of a (conscious) mind
This idea posits two distinct types of dynamics for quantum systems: one linear, to which all matter is subject under its standard evolution, and another non-linear and probabilistic, to which matter is subject when it interacts with an observer's mind. This is a substance-dualist view, where matter and mind exist in different realms and satisfy different laws of nature. This interpretation has Henry Stapp as its currently best-known supporter. We shall label the hypothesis that the interaction with a mind causes the collapse of the wave function the \textit{Consciousness Causes Collapse Hypothesis} (CCCH).

Recently, some authors claimed that CCCH was inconsistent with already available empirical evidence (see, e.g. [13,14]). In this paper, we examine CCCH with respect to such claims, in particular those of [13], and show that their proposal does not provide a way to falsify CCCH. We then modify their proposal to a stripped-down version that retains the main features of an experiment needed to falsify CCCH. This exposes a fundamental problem: to test CCCH one would need to make a conscious being part of the experimental setup. Unless we subscribe to a panpsychist view of consciousness (which CCCH proponents usually do not), such types of experiment pose a fundamental problem: to have a conscious being, one needs reasonably high temperatures (compared to absolute zero). Thus, any experiment that distinguishes two orthogonal states of a measurement, as we shall see is necessary, cannot be brought to its original quantum state, as this would imply controlling all the quantum states in a thermal bath. Therefore, For All Practical Purposes (FAPP), the outcomes of such experiments would be inconclusive, and they would not test CCCH. In fact, this suggests that, due to environmental decoherence, CCCH is unfalsifiable FAPP.

We organize this paper in the following way. In Section 2 we briefly discuss the von Neumann interpretation of quantum mechanics. In Section 3 we present Yu and Nikolic’s experiment, and describe why it does not work as proposed. Then, in Section 4 we modify their experimental setup, and analyze under which conditions the modified experiment needs to be performed to test CCCH. We end the paper with some conclusions.

2 The Consciousness-Causes-Collapse interpretation of QM

In this section, we present the idea of the consciousness-causes-collapse interpretation, which originated from von Neuman’s work on the measurement problem in quantum mechanics. In his seminal book [15], von Neumann starts with the assumption that every physical system can be represented as a vector $|\psi\rangle$ in a Hilbert space $\mathcal{H}$. This representation is one-to-one, in the sense that not only every system has a corresponding vector, but that to every vector there is, in principle, a corresponding system. Observable quantities are represented in this Hilbert space as linear Hermitian operators. The spectral decomposition theorem tells us that a Hermitian operator $\hat{A}$ can be written as

$$\hat{A} = \sum_i a_i \hat{P}_i,$$

where $a_i \in \mathbb{R}$ and $\hat{P}_i$ are projection operators such that $\hat{P}_i \hat{P}_j = \delta_{ij} \hat{P}_j$. In von Neumann’s view, the dynamics of a system is more complicated, and we should distinguish two types. One type is given when the system does not interact with a measurement device. When this is the case, the evolution of the state $|\psi\rangle$ follows a deterministic and
linear evolution given by Schrödinger’s equation. Namely, the state of the system at time $t_1 \geq t_0$ is given by
\[ |\psi(t_1)\rangle = \hat{U}(t_1;t_0) |\psi(t_0)\rangle, \]
where $\hat{U}(t_1;t_0)$ is a unitary evolution operator between $t_0$ and $t_1$ given by
\[ \hat{U}(t_1;t_0) = \exp \left[ -i \frac{\hbar}{\hbar} \hat{H}(t_1 - t_0) \right], \]
and $\hat{H}$ is the Hamiltonian operator. If, on the other hand, the system interacts with a measurement device, the evolution is not linear nor deterministic. During a measurement, each observable value $a_i$ has a probability $p(a_i) = |\langle \psi | \hat{P}_i | \psi \rangle|^2$ of being observed, and if the result of a measurement (with probability $p(a_i)$) is $a_i$, then the wave-function collapses into a new state
\[ |\psi\rangle \xrightarrow{a_i} \frac{\hat{P}_i |\psi\rangle}{\langle \psi | \hat{P}_i |\psi\rangle}. \]
So, according to this formulation, QM has two different types of evolution, one deterministic and one probabilistic; the former happens when there is no interaction with a measurement device, and the latter when such interaction occurs.

A natural question to ask within this theory is “what is a measurement device?” In principle, such a device, made out of “conventional” matter itself, should be describable by QM. Following von Neumann, let us assume this is the case, and let us have a Hilbert space $\mathcal{H} = \mathcal{H}_M \otimes \mathcal{H}_S$, where $\mathcal{H}_M$ is the space of the measurement device and $\mathcal{H}_S$ the space of the system being measured. Since we are considering this an isolated system, there is no interaction with an external measuring device (the device is part of the system itself). For simplicity, let us limit our measuring device to the observable
\[ \hat{O} = \hat{P} - \left( \hat{1} - \hat{P} \right) = 2\hat{P} - \hat{1}, \]
where $\hat{P}^2 = \hat{P} \neq \hat{1}$ is a projector, and $\hat{1}$ the identity operator. Clearly, $\hat{O}$ can have only two possible outcomes, $+1$ and $-1$. So, a measuring device for $\hat{O}$ needs to have the following properties. First, it should have a neutral state, its initial state, prepared to receive a system to be measured. We denote the neutral state of the measuring device by the vector $|\text{neutral}\rangle \in \mathcal{H}_M$. Second, the interaction of $M$ and $S$ should be such that the following evolution happens:
\[ |\text{neutral}\rangle \otimes |+\rangle \rightarrow \hat{U}_{\text{int}} |\text{neutral}\rangle \otimes |+\rangle = |\text{points to } +\rangle \otimes |+\rangle, \]
\[ |\text{neutral}\rangle \otimes |-\rangle \rightarrow \hat{U}_{\text{int}} |\text{neutral}\rangle \otimes |-\rangle = |\text{points to } -\rangle \otimes |-\rangle. \]
Here we represent the two possible final values of the measurement apparatus as either giving a measurement of “+” or “−,” depending on the initial state of the system.

Since, according to QM, any linear superposition of states $|\pm\rangle \in \mathcal{H}_S$ is possible, what happens when we use the above interaction to measure superpositions? If we have the superposition
\[ |\psi\rangle = c_+ |+\rangle + c_- |-\rangle, \]
because $\hat{U}_{\text{int}}$ is linear, it follows that
\[ |\text{neutral}\rangle \otimes |\psi\rangle \rightarrow c_+ |\text{points to } +\rangle \otimes |+\rangle + c_- |\text{points to } -\rangle \otimes |-\rangle. \]
This seems to be exactly what we wanted: we end up with a correlation between $|\pm\rangle$ and the pointer’s state $|\pm\rangle$ points to $|\pm\rangle$. However, it is straightforward to see that the final state is not an eigenstate of either projector $\hat{1} \otimes |+\rangle\langle+|$ or $\hat{1} \otimes |-\rangle\langle-|$, and therefore does not correspond to an actual measurement, where an actual collapse happens. This contains the essence of the measurement problem: a quantum system interacting with a measurement apparatus evolves according to a non-linear dynamics that is different from that given by the (linear) Schrödinger equation.

If the quantum system was in a superposition, von Neumann argued that the interaction of $S$ with a measurement apparatus $M$ would also result in a superposition. We could push this even further and think of another apparatus $M'$ that measures $M$ and $S$, and we would still have a superposition. In fact, we could keep doing this indefinitely, ever adding more measurement apparatuses that measure the previous measurement devices. We can even consider our eyes as a photodetector that measures this chain of apparatuses, and we have no reason to assume, according to Schrödinger’s equation, that we would not have a superposition. We can keep on going, including not only our eyes, but our optical nerves, up until we get to the brain, and we are left with a brain/measurement apparatus/system that is still in a superposition. In von Neumann’s own words:

“That this boundary [between observer and observed system] can be pushed arbitrarily deeply into the interior of the body of the actual observer is the content of the principle of the psycho-physical parallelism — but this does not change the fact that in each method of description the boundary must be put somewhere, if the method is not to proceed vacuously, i.e., if a comparison with experiment is to be possible. Indeed experience only makes statement of this type: an observer has made a certain (subjective) observation; and never any like this: a physical quantity has a certain value.”

That is intriguing, and since one never observes a superposition in a single measurement, this chain needs to stop somewhere.

Following the consequences of von Neumann’s ideas, London and Bauer pushed the boundary to the extreme (the reader is referred to the excellent historical survey provided in [16]). According to them, there is only one step when we know for sure that we do not have a superposition: when we gain conscious knowledge of the measurement apparatus, i.e. when matter interacts with the mind. That is because we are never aware of observing any quantum superposition. They then proposed that the interaction between mind and matter causes matter to evolve probabilistically, according to Born’s rule, and non-linearly. In other words, the mind causes the collapse of the wave function.

CCCH is substance dualist. As is well-known, dualist views of the mind suffer the problem of causal closure: how can the mind influence matter and vice versa? Though not directly addressing this issue, CCCH states that the mind causes matter to behave differently, following a dynamics that is not the same as when there is no interaction with a mind. So, in a certain sense, CCCH postulates their interaction, albeit in a very specific way. The question remains as to whether this interaction may be used to actually provide a way for the mind to affect matter in a (consciously) controlled way.

Henry Stapp proposed a clever solution to this problem by using the “inverse” Quantum Zeno Effect [17]. It would go beyond the scope of this paper to provide a detailed account of Stapp’s theory, but it is worth mentioning it to give an idea of what types of physics (or metaphysics) may unfold from the CCCH. In Ref. [18], it was shown that if we were to continuously observe an unstable particle, this particle would
not decay; this came to be known as the Quantum Zeno Effect (QZE). The QZE can be modified, and it can be shown that by continuous and variable observations it is possible to force a particle to change its quantum state. Following this idea, Stapp \[17\] used a harmonic oscillator in a coherent state\[2\] with amplitude \(\alpha\), given by the ket
\[
|\alpha\rangle = e^{-|\alpha|^2/2} \sum \frac{\alpha^n}{\sqrt{n!}} |n\rangle,
\]
where \(|n\rangle\) is an eigenvector of the number operator \(\hat{N} = a^\dagger a\) with eigenvalue \(n\), and showed that if we start in this state and our mind chooses to observe it, we end with a new amplitude \(\beta > \alpha\), whereas if it chooses not to observe, the state maintains amplitude \(\alpha\). In other words, the effect of the mind “observing” a system can make it change its state from \(|\alpha\rangle\) to \(|\beta\rangle, \beta > \alpha\). There might be some (surmountable) problems with this model, discussed in more detail in \[20,21\], but we emphasize that the CCCH, though not popular among physicists and presenting some difficult philosophical challenges, not only solves the measurement problem, but also provides a possible mechanism for the mind to affect matter, a major problem for substance dualists.

3 A proposed falsification of the CCCH

It is reasonable to ask whether CCCH is true or false. By true or false we of course mean whether there is supporting experimental evidence for it or if it can be or has been falsified, as we cannot, in a strict sense, prove a theory to be true. So, an natural question is how can we try to falsify CCCH.

In a recent paper \[13\], Yu and Nikolic argued that CCCH has already been falsified, and proposed further modifications of a given experimental setup to make such conclusions beyond any reasonable doubt. Their argument starts with the idea that
\[
\text{CCCH} \rightarrow (\text{CWF} \iff \text{PR}),
\]
where CWF is short for “collapse of the wave function” and PR for “phenomenal representation,” i.e. the presence of phenomenal consciousness. Therefore, they conclude, if it is possible to “observe” CWF without PR, then CCCH is falsified.

To understand Yu and Nikolic’s argument, and our criticism of it, we need to look into the details of how they account for the possibility of observing CWF without PR. They do so by using Kim et al.’s delayed choice experiment \[22\], which we now describe. In Kim et al. (see Figure 1), a laser beam impinges on a standard double slit, behind which a non-linear crystal is placed. Through parametric down conversion, a pair of photons, referred to as signal and idler, is generated in either region \(A\) or \(B\) of the crystal residing behind each slit. The signal photon is sent to a detector \(D_0\) that can be translated to reveal an interference pattern. The idler photon can be directed directly to either detector \(D_3\) or \(D_4\) (Figure 1(a)), thus allowing which-path information, or can be scrambled in a beam splitter \(BS\) (Figure 1(b)), erasing any which-path information.

\[2\] The coherent state \(|\alpha\rangle\) of a harmonic oscillator behaves, in some sense, in a similar way to its classical counterpart. For instance, its expected value also oscillates with the same frequency as a classical oscillator, and with amplitude of oscillation \(\alpha\). Coherent states are of great importance in quantum optics; see e.g. \[19\].
To understand Kim et al.’s experiment, it is important to notice first that it is a fourth-order interference experiment. Let us analyze what happens in each of the setups (for details relevant to the experiment discussed here, see, e.g., [25]). First, for the which-path information setup in Figure 1 (a), there is nothing unusual. The pair of photons is produced either in A or B, and if it is produced in A the idler photon is detected in D₃, and if in B it is detected in D₄. Since the signal photon is generated in either A or B, the final probability of observing it in the variable-position detector D₀ is the same as the sum of the two probabilities, and shows no interference effect, as expected. For the interference setup shown in Figure 1 (b), things are more subtle, and the experimental setup resembles, conceptually, what happens with ghost interference (another fourth-order interference experiment) [26]. When the idler photons from A or B are joined, we lose which path information, but, more importantly, the idler side of the apparatus becomes an interference device itself, sensitive to the momentum of the quantum state impinging on it. Different momenta, which are correlated with D₀,

\[\text{Fig. 1 Kim et al. experimental setup for the delayed choice quantum eraser [22].}\]
produce different interference patterns in $D_0$, and the overall probability distribution observed in $D_0$ is exactly the same as with setup (a). As a consequence, the conditional probability of detection on $D_0$ depends on a detection on $D_3$ or $D_4$ in the following way \cite{22}:

$$P(D_0, x|D_3) = N (\alpha x)^{-2} \sin^2 (\alpha x) \cos^2 (\beta x),$$  \hspace{1cm} (1)

$$P(D_0, x|D_4) = N (\alpha x)^{-2} \sin^2 (\alpha x) \sin^2 (\beta x),$$  \hspace{1cm} (2)

where $N$ is a normalization factor, and $\alpha$ and $\beta$ parameters that depend on the optical geometry of the experiment and the correlated photons wavelength. The two conditional probabilities in (1) and (2) are shown in Figure 2. As we can see, by conditioning the data on the detection of, say, $D_3$, we observe an interference pattern, and likewise for the conditioned data on $D_4$. However, as we can also see from Figure 2, the interference pattern obtained by conditioning on $D_3$ is shifted by $\pi/2$ with respect to the one from $D_4$ (this is also clear from (1) and (2)). This is a crucial point: the interference pattern does not appear on $D_0$ without correlating it with the detections on $D_3$ or $D_4$. In fact, if we look only at $D_0$, what we see is the unconditional $P(D_0, x)$, given by $P(D_0, x|D_3) P(D_3) + P(D_0, x|D_4) P(D_4)$, shown in Figure 3. If this were not the case, we would violate the no-signaling condition in quantum mechanics, as we could use a choice of detection apparatus in $D_i$ to communicate instantaneously (or to the past) between an experimenter controlling $D_i$ and another observing $D_0$. But since the observations are conditional, no violation of no-signaling occurs.

Returning to Yu and Nikolic’s idea, their proposal was to use the human eye as a photodetector instead of $D_i$. This would not be an impossible task, given that human eyes are sensitive to single photons. As such, they argue that, in the which-path setup where the idler photon goes to $D_3$ and $D_4$, we could replace detectors $D_3$ and $D_4$ with
a person observing the photons. If such observer were unconscious, then no collapse of
the wave function would happen, and we would have an interference pattern on \(D_0\).
Notice that Yu and Nikolic are referring to setup (a) in Figure 1 and they do not
consider setup (b), where interference patterns emerge in Kim et al.’s experiment. As
such, their proposal has a major flaw: one would not get an interference pattern on
\(D_0\) using setup (a) regardless of having a detector or an observer (conscious or not).
To obtain an interference pattern, any which-path information about the idler photon
needs not only to be erased by recombining the beams into an interferometer, but once
recombined one would need to detect such photon and use coincidence counts to obtain
the interference. If one used an actual person to observe \(D_3\) or \(D_4\), such coincidence
counts could only happen if such person was aware of the detection in their eye, as this
would be required for knowing which detections in \(D_0\) need to be counted. In other
words, a human (or any other animal) used in this experimental setup would have to
be aware of the detection of a photon within a certain window of time and be able
to behaviorally track (e.g. by recording on a piece of paper) such detection, such that
later on an interference pattern could be reconstructed by coincidence counts.

An interesting question is raised from Yu and Nikolic’s proposal: could we falsify
CCCH with some device of this type? As we saw, their claim that CCCH was (perhaps)
already falsified is not correct, as their reliance on the quantum eraser experiment did
not take into consideration the need for correlated counts. But perhaps some other
version of the experiment could to it. In the next section we will show a general type
of experiment to test CCCH, and use it to argue that it is impossible to falsify CCCH.

4 Is CCCH falsifiable?

In this section we describe a different proposed experiment to test CCCH. This experi-
ment is a natural extension of an earlier paper of Suppes & de Barros [27], and has
the main features necessary to test CCCH. Our goal here is not to propose a thought
experiment, but to examine the characteristics of a realizable experiment, and discuss
its conceptual and technical difficulties.

Since we want to test CCCH, like Yu and Nikolic, we start with the eyes as photo-
detectors. Nature provides us with exceptionally good photo-detectors in the kingdom
of Animalia (see references in [27]). Of particular interest, is the fact that some insects
have not only very efficient eyes (their efficiency is estimated to be between 40% and
78%), but very low dark-count rates (the locust \(\text{Schitocerca gregaria}\), for example, has
a dark-count rate of few photons per hour).

Perhaps one of the best candidates for such conditioning experiments is the cock-
roach (\(\text{Periplaneta americana}\)), for the following reasons [28]: it responds well to exter-
nal stimuli for conditioning, it is well adapted to respond to very low-light environments
(i.e. has good photo-detectors), and its neural circuitry is significantly easier to study
compared to other well-known insects (such as the ubiquitous fruit fly). So, for that
reason, in combination with the existence of successful conditioning experiments with

\footnote{In fact, the total number of photons reaching the participant (either human or not) is quite
large, and it is not until coincidence counts are performed that this number is reduced. So,
the task of reconstructing an interference pattern, even if the actual photon count per second
could be reduced to a reasonable number to be dealt with, would be very time consuming and
daunting.}
Fig. 4 Proposed experimental setup. A photon impinges on A or B, and an optical fiber, represented by the dotted line, takes it to either the left (L) or right (R) eye, respectively. If a photon reaches L, the cockroach is conditioned to push a button at the end of a circuit (dashed line), and if the L button is pushed, a single photon is emitted at a precise and very short window of time.

Insects, Suppes & de Barros [27] proposed that cockroaches could be classically conditioned to respond to single photons.

Here we assume that cockroach single-photon conditioning experiments could be successfully carried out, though probably there exists many technical difficulties (insect are not as easy to condition as some mammals). For our purpose, we will also assume that the cockroach is a conscious being. This is, of course, a controversial assumption, but the alternative would be to do our proposed experiment with more complex animals (say, humans). However, as it will become clear below, this assumption will not invalidate our conclusions, as they will apply to any animal.

The idealized experiment we propose is simple, and does not rely on entangled states (as does Kim et al.’s). Imagine we have a cockroach who has been conditioned to respond to single photons in the following way. If a photon impinges on the left eye of the cockroach, it moves its left antenna, whereas if a photon impinges on the right eye it moves its right antenna. The cockroach is then placed in a well isolated box where a photon can be sent to either the left or the right eye via optical fibers. If the cockroach’s left antenna moves, the cockroach sends a signal to a device T that will generate a single photon from A’; if the right antenna moves, a single photon is generated from B’.

Now, to understand the experimental conditions necessary for such experiment to work, let us examine it in detail. We start with the Hilbert space of this setup, given by $\mathcal{H} = \mathcal{H}_p \otimes \mathcal{H}_c \otimes \mathcal{H}_b \otimes \mathcal{H}_p'$, where $\mathcal{H}_p$ is the Hilbert space for the impinging photon, $\mathcal{H}_c$ the cockroach, $\mathcal{H}_b$ the box itself (with all necessary devices), and $\mathcal{H}_p'$ the outgoing photon. For example, when a single photon impinges on A, with

$$\rho_{1,0} = |1_A,0_B\rangle\langle 1_A,0_B|,$$

the initial state of the system is given by

$$\rho_{1,0} \otimes \rho_{\text{roach}} \otimes \rho_{\text{ready}} \otimes \rho_{\text{ready}} \otimes \rho_{0,0}.'$$
where
\[ \rho_{\text{roach ready}} = |\text{cockroach ready}\rangle \langle \text{cockroach ready}|, \]
\[ \rho_{\text{box ready}} = |\text{box ready}\rangle \langle \text{box ready}|, \]
and
\[ \rho_{0,0}^\prime = |0_A,0_B\rangle \langle 0_A,0_B|. \]
This system would evolve the following way:
\[
\rho_{0,0} \otimes \rho_{\text{roach ready}} \otimes \rho_{\text{box ready}} \otimes \rho_{0,0}^\prime \rightarrow \rho_{0,0} \otimes \rho_{\text{roach left antennae}} \otimes \rho_{\text{box ready}} \otimes \rho_{0,0}^\prime \rightarrow \rho_{0,0} \otimes \rho_{\text{roach ready}} \otimes \rho_{\text{box gen.photon A'}} \otimes \rho_{0,0}^\prime \rightarrow \rho_{0,0} \otimes \rho_{\text{roach ready}} \otimes \rho_{\text{box ready}} \otimes \rho_{0,0}^1, \]
where the label for the states should make them evident. A similar evolution would happen to \( \rho_{0,1} \), leading to
\[
\rho_{0,1} \otimes \rho_{\text{roach ready}} \otimes \rho_{\text{box ready}} \otimes \rho_{0,1}^\prime \rightarrow \rho_{0,1} \otimes \rho_{\text{roach}} \otimes \rho_{\text{box}} \otimes \rho_{0,1}^\prime.
\]
Finally, if we started with a superposition given by, say, the state
\[
\rho_{1,1} = \frac{1}{2} (|0_A,1_B\rangle \langle 0_A,1_B| + |1_A,0_B\rangle \langle 0_A,1_B| + |0_A,1_B\rangle \langle 1_A,0_B| + |1_A,0_B\rangle \langle 1_A,0_B|),
\]
we would end with the linear evolution
\[
\rho_{1,1} \otimes \rho_{\text{roach ready}} \otimes \rho_{\text{box ready}} \otimes \rho_{1,1}^\prime \rightarrow \rho_{0,0} \otimes \rho_{\text{roach ready}} \otimes \rho_{\text{box ready}} \otimes \rho_{1,1}^\prime.
\]
Clearly, if the experiment could be performed like above, if the input is a superposition, we can take the partial trace over all other variables, and the output will also be a superposition. In other words, because the evolution is linear, the partial trace over \( \mathcal{H}_p \otimes \mathcal{H}_c \otimes \mathcal{H}_b \) of \( \rho_{0,0} \otimes \rho_{\text{roach}} \otimes \rho_{\text{box}} \otimes \rho_{1,1}^\prime \) would result in \( \rho_{1,1}^\prime \in \mathcal{H}_p^\prime \). However, if the cockroach’s mind causes a collapse of the wave function inside the box, then the dynamics would not be linear, and the output would be the proper mixture
\[
\rho_{\text{mixture}}^\prime = \frac{1}{2} (|1_A,0_B\rangle \langle 1_A,0_B| + |0_A,1_B\rangle \langle 0_A,1_B|),
\]
and not the pure state \( \rho_{1,1}^\prime \).
However, from the system’s evolution above, we can see a major difficulty with such an experiment, which also will plague any other experiment attempting to falsify the CCCH. In order for a superposition to be detected at the output, the cockroach and box need to go back to its original quantum state. It is easy to see, for instance, that if the cockroach does not go back to its original state \( \rho_{\text{roach ready}} \), then the final state would be an entanglement between the different cockroach positions for inputs A or B. Then, if the outside experimenter observes this system (causing its collapse?), what they would see is a proper mixture, and not a superposition. Therefore, for such an experiment to work in testing CCCH, the whole cockroach+box needs to be brought back to its original state...
This means that every single atom that makes up the cockroach, for example, needs to be brought back to its original state. Of course, though a tremendously difficult task, it is not forbidden by quantum mechanics (though, not experimentally feasible, FAPP).

An attentive reader may counter-argue that a carefully designed experiment, where all degrees of freedom are followed, would allow for the differentiation between CCCH and its negation (if we accept the assumption that the cockroach is conscious). For example, one would not need to partial trace over the system to obtain the photon outcome in a superposition state: we could simply observe the whole system (cockroach + photon + box), and see that, if CCCH is false, it would be in a quantum superposition. For instance, this is similar to what is done in some recent Schrödinger "kitten" experiments, where mesoscopic systems are placed in a superposition state [2]. In fact, some researchers even proposed to create superposition states of bacteria [3] and even macroscopic living organisms, such as the tardigrade [31]. However, we must point out that all of those proposals have in common a very weak (and controlled) coupling with the environment, and usually at very low temperatures. For example, what makes the tardigrade interesting for this type of experiment is that it is able to survive in a vacuum for short periods of time as well as very low temperatures, close to absolute zero. Such low temperatures are necessary to decrease the coupling of the tardigrade with the thermal environment, and one may even argue that while in a superposition the tardigrade is not clearly "alive," less even "conscious," but certainly unable to provide a behavioral response, a requisite of any experimental setup similar to the one provided above. It is also important to note that for the experiments with Schrödinger kittens there is no measurement of the entire system, as the thermal environment is not measured.

We could try to circumvent the difficulty of thermal coupling of a large macroscopic system by focusing only on elements of the cockroach that are directly involved with the stimulus and response process. For instance, if we include only the perceptual and response systems of the cockroach, the number of particles that would need to be controlled and brought back to the original state is smaller than the totality of the cockroach. But if we do that, we should expect about $10^{20}$ atoms (not including the numerous photons) to be involved in such process, and the relevant subspace of the Hilbert space would still be extremely large. As mentioned in the previous paragraph, in order to perform such types of experiment with reasonable candidates for having phenomenal representation (a cockroach is already somewhat a questionable one), we need to decouple this system from the thermal bath. This is a necessary strategy to create quantum superpositions, as in this case, of living systems: their temperature needs to be lowered to a few kelvin.

It is questionable whether cockroaches or tardigrades are conscious, but any candidate for phenomenal consciousness is a living creature, and as such they cannot have consciousness, much less can move, at temperatures close to absolute zero, as required for quantum superposition experiments. Therefore, if we include the thermal bath on

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5 To be more precise, elements in the Hilbert space that are not entangled with the original photon state need not return to the original quantum state. Furthermore, for elements that are weakly entangled it may not be necessary to return them to the original state either, though not returning them would reduce the visibility of the quantum superposition. However, this is not essential for the arguments that follow, since the number of degrees of freedom that get entangled correspond to a macroscopic portion of the cockroach.

6 Unless we take a panpsychist view, which would, in the case of CCCH raise other problems.
the description of the system above, even if we could bring the cockroach+apparatus back to its original quantum state, the outcome of the experiment would be irreversibly entangled with the thermal bath, and we would always observe at the end a proper mixture, regardless of whether the cockroach caused a collapse or not. Since a thermal bath is a necessary condition for a living candidate to have phenomenal consciousness, CCCH is unfalsifiable.

5 Conclusions

CCCH is arguably one of the most controversial solutions for the measurement problem in quantum mechanics, and it certainly does not share wide support within the foundations of physics community. We understand here the measurement problem as the need to explain how the transition between the quantum description of a physical system and the classical description of the measuring apparatus comes to be, since such transition does not come from the dynamics of quantum theory (i.e., the unitary evolution given by Schrödinger’s equation). In such sense, CCCH achieves this goal, albeit in a way that is unappealing to most physicists, because of its substance-dualistic nature. This raises deep philosophical problems, as it brings extra metaphysical entities into play. However, this problem is not exclusive to CCCH. For example, the many-worlds interpretation of QM postulates the existence of an infinite number of parallel universes. Bohm’s theory, another popular interpretation, requires a physical reality that unfolds in an infinite-dimensional universe, and provides no clear explanation as to why we perceive a three-dimensional universe. In fact, all well-known interpretations bring extra metaphysical entities into play, with the exception perhaps of epistemic interpretations, who avoid such types of discussion.

Given its metaphysical implications, it is not surprising that CCCH is often criticized, but mostly on metaphysical grounds (as are many of the different interpretations of QM). However, if the mind plays a special role in the measurement process, perhaps we can use this to create experiments where one could try to falsify CCCH. In this paper we examined one experiment proposed by Yu and Nicolic. We saw that their proposal had a fatal flaw, as it did not consider the fact that to observe fourth-order interference requires coincidence counting. We then used this experiment as a springboard to a more general framework for how to attempt to falsify CCCH: produce an experimental setup where the non-linear nature of the quantum dynamics in the presence of consciousness can be distinguished from the linear dynamics in the absence of consciousness.

Another argument put forth against the CCCH was given by Thaheld, where the Stark-Einstein law was used to argue that classical information is passed to the eye-brain system via absorption of photons by the retinal molecules. We will not go into the details of Thaheld’s argument, since they are not required here, but we want to point out that the classical information is passed because of an entanglement between a photon and the “classical” environmental variables, and also that the Stark-Einstein law assumes, deep down, a collapse of the wave function (either photon is absorbed by the molecule or not). Thaheld’s argument against the CCCH also suffers from the same issues as the proposal put forth in Section 4.

Finally, we emphasize that any candidate for phenomenal consciousness, at least consensus candidates, would have to be kept at their habitat’s temperature. This implies that any such experiment would not be able to distinguish the linear from the
non-linear dynamics, as we would always have an irreversible entanglement with a thermal bath. Therefore, any experiment trying to falsify CCCH on the basis of its different dynamics is doomed.

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