OBSERVER-CENTERED DESCRIPTION OF MISINTERPRETED RESULTS IN BIOLOGY

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ABSTRACT
Benveniste's experiments have been the subject of an international scientific controversy (known as the case of the "memory of water"). We recently proposed to describe these results in a modeling in which the outcome of an experiment is considered personal property (named cognitive state) of the observer and not an objective property of the observed system. As a consequence, the correlations between "expected" results and observed results in Benveniste's experiments could be considered the consequence of quantum-like interferences of the possible cognitive states of the experimenters/observers.

In the present paper, we evidence that small random fluctuations from the environment together with intersubjective agreement force the "expected" results and the observed results experienced by the observers into a noncommuting relationship. The modeling also suggests that experimental systems with enough compliance (e.g., biological systems) are more suitable to evidence quantum-like correlations. No hypothesis related to "memory of water" or other elusive modifications of water structure is necessary.

In conclusion, a quantum-like interpretation of Benveniste's experiments offers a logical framework for these experiments that have remained paradoxical to now. This quantum-like modeling could be adapted to other areas of research for which there are issues of reproducibility of results by other research teams and/or suspicion of nontrivial experimenter effect.

Keywords: *Quantum-like probabilities; Quantum cognition; Experimenter effect; Memory of water; Scientific controversy.*

1. INTRODUCTION

In any scientific controversy, there are both sound and dubious arguments from each side. The "memory-of-water" controversy is no exception and we will show in this article that a third way is possible, one that dissolves the "paradoxical" results of these disputed experiments. The research of Benveniste's team on high dilutions (dubbed the "memory of water") became famous in June 1988 when *Nature* published an article suggesting that specific information on compounds of biological interest could be stored in water after serial high dilutions [1]. Although no molecule could be present in the samples containing the highest dilutions of the initial compound, changes of a parameter of a biological system were observed. After the investigation performed in Benveniste's laboratory and the resulting conflict, Benveniste's team explored new biological models and set up new devices [2].

In the years that followed, Benveniste claimed that electromagnetic waves emitted from a solution containing a molecular compound could be captured with an electromagnetic coil and then transmitted via an electronic device to a second coil containing a sample of water. He then reported that this "biological information" could be digitized and stored in a computer memory and then played to samples of water, which thus could induce specific biological effects. Other biological models were developed by Benveniste's team after the *Nature* article to evidence the reality of "high dilutions" and "digital biology". More particularly, two biological systems were developed with success. These were the isolated guinea pig heart, a classical model in physiology, and the *in vitro* plasma coagulation, which had the advantage to be possibly automated [3-12].

In the present article, we describe in detail neither the biological models nor the devices that were used to supposedly "imprint" molecular information in water. Details can be found elsewhere [2, 13]. Giving many technical descriptions in this article would miss the point. Indeed, the important issue is to decipher the logic of these experiments that tell us a coherent – but paradoxical – story. The thesis that we defend is that water does not play any role in these experiments [14]. First, there was a circular reasoning in the usual description of these experiments: 1) modifications of water induced changes of a biological model and 2) biological changes were the consequence of modifications in water structure. Second, no modification of water has ever been evidenced that could explain how the huge amount of information necessary to describe any biological macromolecule could be coded and stored in liquid structures. In the next section, we describe what is precisely paradoxal in these experiments.

2. WHAT ARE THE SCIENTIFIC FACTS IN BENVENISTE'S EXPERIMENTS?

First, we define a change of a biological parameter above background noise as "signal" and no change as "no signal" (i.e. change not different than background noise). In the experiments reported by Benveniste, the "expected" results (materialized by "inactive" or "active" samples) and the observed results ("no signal" or "signal") were correlated and, at first sight, this relationship was causal as any pharmacological effect. Samples supposed to be "inactive" were associated with "no signal"; samples supposed to be "active" were associated with "signal". Therefore, it was tempting and almost unavoidable that the "cause" of the biological change would be attributed to the procedure supposed to "imprint" information in water. Note that the change of a biological parameter was in itself an unexpected result according to mainstream science because no signal at all was supposed to be observed either with "inactive" or "active" samples.

Public demonstrations with the active participation of colleagues to the experiments were repeatedly organized by Benveniste [2]. These meetings were occasions for Benveniste to present his results and to involve other scientists in order to convince them of the validity of his theories; one of these demonstrations has been recently analyzed in depth [15]. These public experiments were designed as a proof-of-concept and were generally performed in two steps. In the first step, samples expected to be "inactive" or "active" on the biological system were prepared in another laboratory. These samples could be water samples or in last experiments were computer files. Blind samples received a code from a scientist not belonging to Benveniste's team. A series of "inactive" and "active" samples was nevertheless kept unblinded. In the second step, all samples were transported into Benveniste's laboratory, and the corresponding activity was tested on the biological model. When all measurements were done, the results were sent to the scientist that supervised and controlled the experiment, and that scientist could assess the rate of concordance (i.e., the rate of "success") between "expected" and observed results.

For these demonstrations, the results with the blind samples were not better than random: some samples supposed to be "active" were associated with no signal and conversely other samples supposed to be "inactive" were associated with signal. The most puzzling was that "success" was systematically obtained with samples prepared and assessed in parallel but kept open-label even though they were in-house blinded in Benveniste's laboratory.

These "failures" were interpreted by Benveniste as "jumps of activity" from one sample to another. These apparent "jumps" were not considered by Benveniste as a "falsification" (in the sense of Popper) of his hypotheses on "memory of water" and "digital biology". In consequence, these weird results induced only head-long technological rush of Benveniste's team to "improve reproducibility" and to protect the samples and/or the biological model from external disturbances such as electromagnetic waves, water contamination, etc. However, despite various improvements of the experimental conditions, the weirdness continued to be repeatedly observed and was the main stumbling block that prevented Benveniste's hypothesis to be convincing [2, 13, 16-18].

We defend the idea that the different outcomes according to the experimental conditions (inside vs. outside first assessment of "success" rate) is the only scientific fact, if any, that emerges from the story of "memory of water".

3. WHY AN OBSERVER-CENTERED QUANTUM-LIKE MODELING?

If there was really "something", physical or chemical, in water samples, as in classical pharmacology, modifications in blinding should not disturb the outcomes. Assessment of success firstly by outside observer or firstly by inside observer should not change the rate of samples with "success". Suppose now that there was no specific information in water samples and that these latter were all physically equivalent. In this case, we have no reason to expect differences in outcomes. How explain then that biological changes did occur? Tackling these outstanding results requires getting off the beaten track.

The formalism that we use is inspired by quantum cognition [19], relational quantum physics [20] and quantum Bayesianism [21, 22]. In these interpretations of quantum physics, what is described is not the physical world in itself but *what each observer experiences* (Figure 1). Therefore, the outcome considered in the present formalism to describe Benveniste's experiments is not the change of an experimental parameter in itself, but the experience elicited in the experimenter that records this change (or absence of change).

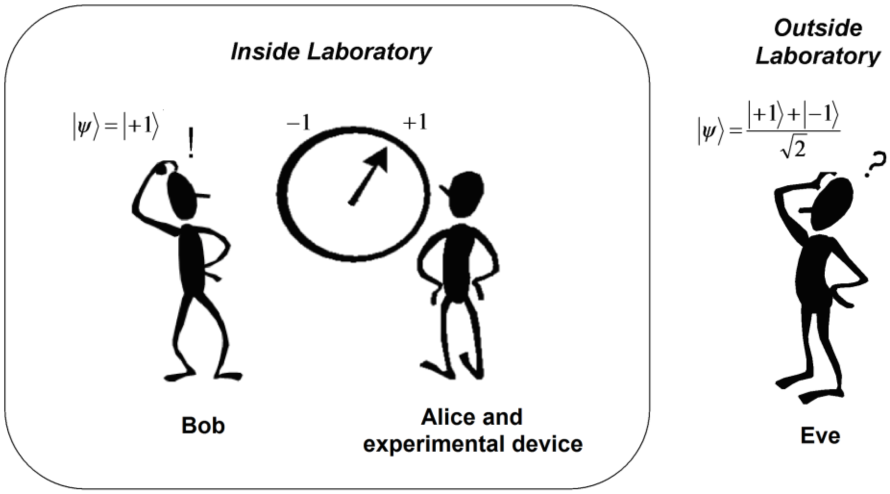

Figure 1. Different observers can have different reports of the same experimental situation.
Alice is the experimenter; she performs an experiment that has two possible outcomes: +1 or -1. For Eve, who is outside the laboratory without information on the outcome of the experiment, the cognitive state of each observer inside the laboratory is in a superposed state ("observer having experienced the outcome +1" and "observer having experienced the outcome -1"). However, when Alice performs an experiment, she experiences either +1 or -1 on her measurement device. In other words, her cognitive state is not in a superposed state, but in a "reduced" state. Bob is an observer inside the laboratory and he observes also that Alice is not in a superposed state. Moreover, Alice and Bob agree on their observations, either +1 or -1 (intersubjective agreement).

We define the cognitive state *A* as all possible experiences (with their respective probabilities) elicited in an observer who observes/measures an experimental device. Mathematically, *A* is represented by the vector of Ψ_A in a Hilbert vector space. Therefore, the cognitive state of one observer is depicted as the vector sum (i.e. the "superposition") of the possible experiences of the observer. This does not mean that the cognitive state of the observer is "really" in a superposed state. The wave function is simply a *predictive statistical tool.* Another important point is that the outcome does not preexist to the act of measurement for a given observer; the outcome is created by the measurement and an experiment has no outcome before being experienced [22].

Thus, the state vector of Ψ_A of the cognitive state *A* is the superposition of the two states A_{-1} and $A_{+1,}$ which are the two possible outcomes of a measurement:

$$|\Psi_A\rangle = a|A_{+1}\rangle + b|A_{-1}\rangle$$

The norm *a* of the vector, which is obtained after projection of Ψ_A on the axis of the state A_{+1}, is assimilated to a probability amplitude. Therefore, the probability of the cognitive state being associated with A_{+1} is a^2. Because the total of probabilities is equal to one, $a^2 + b^2 = 1$.

An observer has no access to the "internal state" of another observer, but these observers nevertheless construct a common reality by sharing their experiences; "reality" emerges as a consequence of intersubjective agreement.

4. OBSERVER-CENTERED DESCRIPTION OF BENVENISTE'S EXPERIMENTS

4.1 *First step*: Description of a relationship between "expected" and observed results

This first step has been previously described and will be briefly summarized [14]. Appendix 1 provides details of the calculations.

In this formalism, "expected" results and observed results are experienced by the experimenter, and we describe the relationship between these two sets of observables. We define the first set of observables ("expected" results) as A_{IN}/A_{AC}, which corresponds to the observation of "inactive"/"active" labels, and the second set of observables (observed results) as A_{CP}/A_{DP} , which corresponds to the observation of concordant/discordant pairs.

The observed biological system has two possible states: no signal or signal. "Success" is defined by the observation of a "concordant" pair (A_{CP}): A_{IN} associated with no signal or A_{AC} associated with signal. "Failure" is defined as the observation of a "discordant" pair (A_{DP}): A_{IN} associated with signal or A_{AC} associated with no signal. We define Prob_{quant} and Prob_{class} as quantum and classical probability, respectively.

The cognitive state A of the experimenter is described from an outside point of view (Figure 1). The aim of these experiments is to contrast the states A_{IN} and A_{AC} for the respective probabilities of "success". Therefore, the cognitive state A is described as a superposition of the eigenvectors of the first observable:

$$\left|\psi_A\right\rangle = \frac{\left|A_{IN}\right\rangle + \left|A_{AC}\right\rangle}{\sqrt{2}} \qquad \text{(Eq. 1)}$$

The eigenvectors of the first observable (A_{IN}/A_{AC}) are developed on the eigenvectors of the second observable (A_{CP}/A_{DP}):

$$\left|A_{IN}\right\rangle = \mu_{11}\left|A_{CP}\right\rangle + \mu_{12}\left|A_{DP}\right\rangle \qquad \text{(Eq. 2)}$$

$$\left|A_{AC}\right\rangle = \mu_{21}\left|A_{CP}\right\rangle + \mu_{22}\left|A_{DP}\right\rangle \qquad \text{(Eq. 3)}$$

There are some mathematical constraints ($\mu_{11}^2+\mu_{12}^2=1$, $\mu_{21}^2+\mu_{22}^2=1$ and $\text{Prob}_{quant}(A_{CP}) + \text{Prob}_{quant}(A_{DP}) = 1$). The calculations in Appendix 1 show that there are two solutions for the relationship between the two observables corresponding to two rotation matrices. Only for one solution, do observed results fit with "expected" results (Figure 2).

As calculated in Appendix 1, the corresponding solutions for probability of "success" or "failure" are:

$$\text{Prob}_{quant}(A_{CP}) = \frac{(\cos\theta+\sin\theta)^2}{2} \qquad \text{(Eq. 10)}$$

$$\text{Prob}_{quant}(A_{DP}) = \frac{(\cos\theta-\sin\theta)^2}{2} \qquad \text{(Eq. 11)}$$

The rate of "success" is optimal if $\sin\theta = \cos\theta$ ($\theta = +\pi/4$). In this case, Prob (A_{CP}) = 1 and Prob (A_{DP}) = 0. Classical probabilities are obtained with $\theta = 0$; in this case, Prob (A_{CP}) = 1/2 and Prob (A_{DP}) = 1/2. Note that there is no signal when $\theta = 0$ because concordant pairs are associated with "inactive" labels (no signal) and discordant pairs are associated with active labels (no signal). When $\theta \neq 0$, the two bases are said to be noncommuting.

In conclusion, the relationship between "expected" and observed results can be modeled as the consequence of the superposition of the possible cognitive states of the experimenter. The passage from classical to quantum-like logic rests on a unique parameter (angle θ).

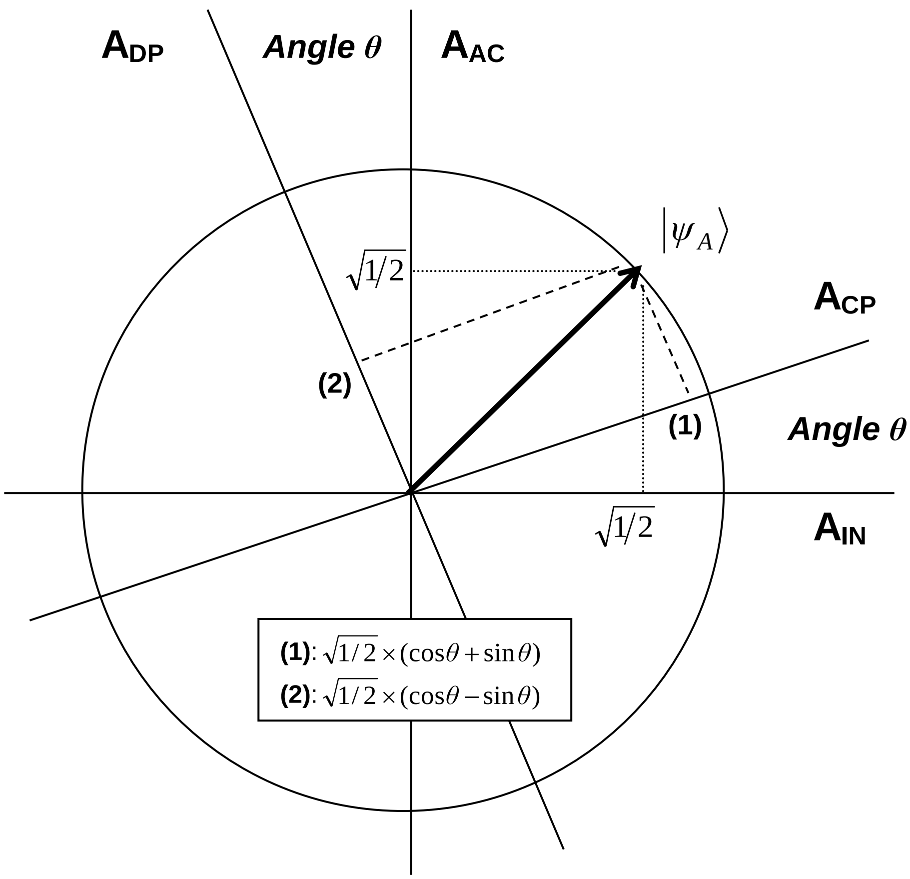

Figure 2. Relationship between the cognitive states for "expected" results and observed results. This figure summarizes the relationship between the two observables, namely the cognitive states for "expected" results (A_{IN}/A_{AC}) and for observed results (A_{CP}/A_{DP}). The state vector of A can be described according to two orthogonal bases A_{IN}/A_{AC} or A_{CP}/A_{DP}. The probabilities for A to be associated with IN, AC, CP, or DP is obtained by squaring the projection of Ψ_A on the corresponding axis (probability amplitude) and by squaring the value. The probability to be associated with IN or AC is fixed and equal to 1/2; the probability to be associated with CP or DP depends on the value of θ. For example, the concordance between expected results and observed results is optimal for $\theta = +\pi/4$. When $\theta = 0$, the observables are said commuting and noncommuting when $\theta \neq 0$.
Abbreviations: IN, "inactive" expected value; AC, "active" expected value; CP, concordant pair ("expected" result associated with observed value); DP, discordant pair ("expected" result not associated with observed value).

4.2 *Second step*: Why are the observables noncommuting?
In the first step, we have seen that $\theta \neq 0$ allows describing a relationship between the two observables. We have to explain however why $\theta \neq 0$ (noncommuting observables). To understand how noncommuting observables could emerge from formalism, we consider now that the experimenter obtains information on the state of the experimental device either "directly" or through other sources such as the interaction with another observer (Figure 1). Interaction must be understood as the "measurement" of the actual state of *A* by *B* and the actual state of *B* by *A*. The following demonstration rests on the following propositions: 1) The information gained on the outcome of an experiment is through macroscopic environment; 2) The macroscopic environment is submitted to microscopic fluctuations (related to thermal fluctuations, electromagnetic waves, etc); 3) Different cognitive states that gain information on the outcome of the same experiment must agree on this outcome (intersubjective agreement).

We first define two experimenters, Alice and Bob with cognitive states *A* and *B*, respectively, who perform experiments together. The observables are supposed to be initially commuting, that is $\theta = 0$ (i.e. there is no relationship between the observables). The state vectors that describe the cognitive states *A* and *B* separately with $\theta = 0$ are (see Appendix 1):

$$\left|\psi_A\right\rangle = \frac{\left|A_{CP}\right\rangle + \left|A_{DP}\right\rangle}{\sqrt{2}} \qquad \text{(Eq. 9a for } A \text{ with } \theta = 0)$$

$$\left|\psi_B\right\rangle = \frac{\left|B_{CP}\right\rangle + \left|B_{DP}\right\rangle}{\sqrt{2}} \qquad \text{(Eq. 9b for } B \text{ with } \theta = 0)$$

The tensor product of the two state vectors describes the cognitive states *A* and *B* together:

$$\left|\psi_A\right\rangle \otimes \left|\psi_B\right\rangle = \left(\frac{\left|A_{CP}\right\rangle + \left|A_{DP}\right\rangle}{\sqrt{2}}\right) \otimes \left(\frac{\left|B_{CP}\right\rangle + \left|B_{DP}\right\rangle}{\sqrt{2}}\right) \qquad \text{(Eq. 12)}$$

$$= \frac{\left|A_{CP}\right\rangle\left|B_{CP}\right\rangle}{2} + \frac{\left|A_{CP}\right\rangle\left|B_{DP}\right\rangle}{2} + \frac{\left|A_{DP}\right\rangle\left|B_{CP}\right\rangle}{2} + \frac{\left|A_{DP}\right\rangle\left|B_{DP}\right\rangle}{2}$$

When they compare their observation of the same experiment, Alice and Bob agree that their observations fit. For example, if Alice reports that she observed a concordant pair, Bob must also observe a concordant pair (intersubjective agreement). As a consequence, the states $\left|A_{CP}\right\rangle\left|B_{DP}\right\rangle$ and $\left|A_{DP}\right\rangle\left|B_{CP}\right\rangle$ are not possible states. The vector that describes *A* and *B* becomes:

$$\left|\psi_{AB}\right\rangle = \frac{\left|A_{CP}\right\rangle\left|B_{CP}\right\rangle}{\sqrt{2}} + \frac{\left|A_{DP}\right\rangle\left|B_{DP}\right\rangle}{\sqrt{2}} \qquad \text{(Eq. 13)}$$

(Total probability is equal to 1 and probability amplitudes of the state vectors in Eq. 9 have therefore been divided by $\sqrt{2}$).

Because $\left|A_{CP}\right\rangle\left|B_{CP}\right\rangle$ and $\left|A_{DP}\right\rangle\left|B_{DP}\right\rangle$ define an orthogonal basis, one could suggest that classical probabilities would be sufficient to calculate probabilities. In the "real world", however, the experimental device and the observers are not isolated but influenced by microscopic random fluctuations of various origins. In classical physics, these microscopic fluctuations induce small variations around the mean value of a measurement. We will explore the consequences of these fluctuations in the quantum-like modeling. If we take into account the random microscopic fluctuations, Eq. 9 must be modified. We first complete Eq. 9a and Eq. 9b with positive or negative ε random numbers << 1/2.

$$\left|\psi_A\right\rangle = \sqrt{1/2+\varepsilon_1}\left|A_{CP}\right\rangle + \sqrt{1/2-\varepsilon_1}\left|A_{DP}\right\rangle \qquad \text{(Eq. 14)}$$

$$\left|\psi_B\right\rangle = \sqrt{1/2+\varepsilon_2}\left|B_{CP}\right\rangle + \sqrt{1/2-\varepsilon_2}\left|B_{DP}\right\rangle \qquad \text{(Eq. 15)}$$

The portions of environment corresponding to *A* and *B* are different; therefore, the random microscopic fluctuations associated with *A* and *B* are independent. The state vector that describes both *A* and *B* is therefore:

$$\left|\psi_{AB}\right\rangle = \frac{\sqrt{1/2+\varepsilon_1}\sqrt{1/2+\varepsilon_2}}{\sqrt{\Delta}}\left|A_{CP}\right\rangle\left|B_{CP}\right\rangle + \frac{\sqrt{1/2-\varepsilon_1}\sqrt{1/2-\varepsilon_2}}{\sqrt{\Delta}}\left|A_{DP}\right\rangle\left|B_{DP}\right\rangle \qquad \text{(Eq. 16)}$$

$$\text{Prob}_{quant}(AB_{CP}) = \frac{(1/2+\varepsilon_1)(1/2+\varepsilon_2)}{\Delta} \qquad \text{(Eq. 17)}$$

(with $\Delta = (1/2+\varepsilon_1)\times(1/2+\varepsilon_2)+(1/2-\varepsilon_1)\times(1/2-\varepsilon_2)$ since total probability must be equal to 1).

The successive probabilities associated with *A* and *B* are computed step by step, each step corresponding to one infinitesimal random fluctuation. Thus, after the first random microscopic fluctuation, the probability associated with concordant pairs for the two cognitive states are $\text{Prob}_{quant}(A_{CP}) = (1/2 + \varepsilon_1)$ and $\text{Prob}_{quant}(B_{CP}) = (1/2 + \varepsilon_2)$ (Eq. 14 and Eq. 15). The intersubjective agreement must be guaranteed and the *common probability* $\text{Prob}_{quant}(AB_{CP})_1$ is calculated according to Eq. 17. After the next random microscopic fluctuations (ε_3 for *A* and ε_4 for *B*), $\text{Prob}_{quant}(AB_{CP})_2$ associated with *A* and *B* is calculated. At each computing step, the common $\text{Prob}_{quant}(AB_{CP})_n$ is updated and reinjected for the calculation of $\text{Prob}_{quant}(AB_{CP})_{n+1}$.

The evolution of $\text{Prob}_{quant}(AB_{CP})$ after a series of random microscopic fluctuations is computed in Figure 3. We see that *only two positions are stable*. Even with tiny random changes of probabilities at each step ($[-0.5; 0.5] \times 10^{-15}$), a transition occurs after several iterations that model fluctuations of the environment. One of two different outcomes are obtained: either $\text{Prob}_{quant}(AB_{CP}) = 1$ (i.e. all pairs are concordant) or $\text{Prob}_{quant}(AB_{CP}) = 0$ (i.e. all pairs are discordant). In both cases, signal is selected/filtered from background noise and order is introduced. Thus, suppose that "expected" results are ↓↓↓↓↑↑↑↑. Before transition, the observed results are ↓↓↓↓↓↓↓↓ (i.e., no signal; 50% of concordant pairs and 50% of discordant pairs). After transition, the observed results are ↓↓↓↓↑↑↑↑ (100% of concordant pairs) or ↑↑↑↑↓↓↓↓ (0% of concordant pairs). Note that modeling with Alice alone does not lead to transition of $\text{Prob}_{quant}(A_{\text{CP}})$ toward 1 or 0.

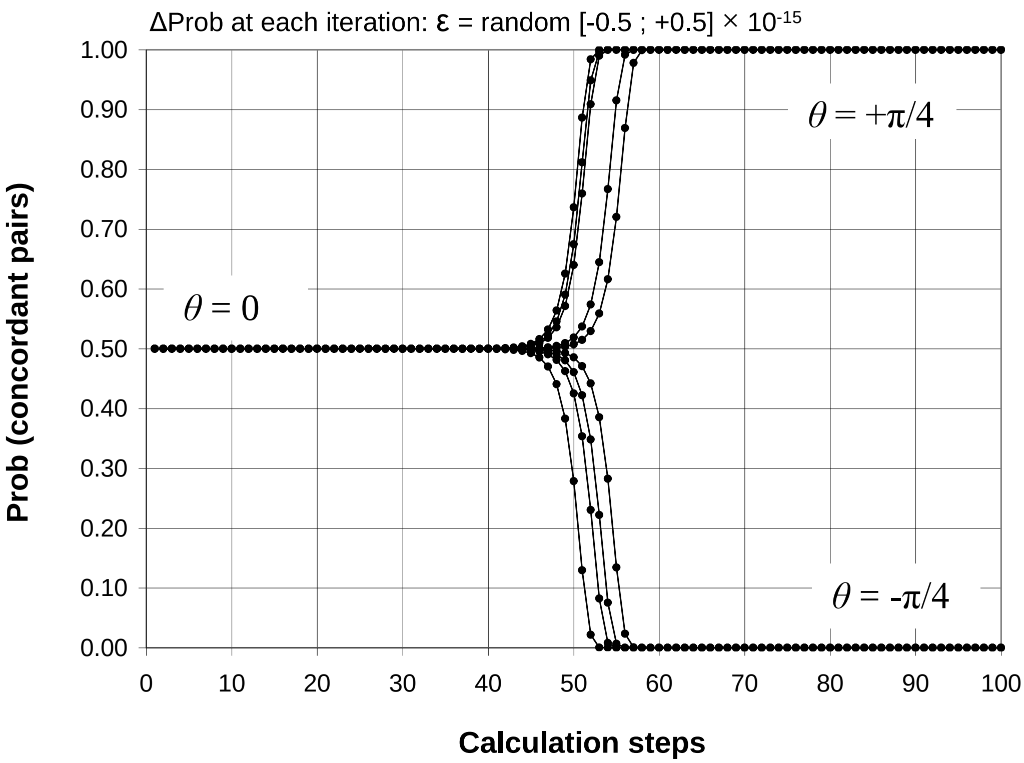

Figure 3. Consequence of the interaction of two cognitive states for the same experiments.
Cognitive states gain information on the outcome of an experiment always through the macroscopic environment. The macroscopic environment is submitted to tiny fluctuations in the interval. The experimenter obtains information on the state of the experimental device either "directly" or through other sources such as the interaction with another observer Nevertheless agreement between these different sources must be respected. It can be demonstrated that only two positions are stable: "expected" results and observed results are either always concordant ($\theta = +\pi/4$) or always discordant ($\theta = -\pi/4$). See text for details on calculations. Eight examples of computing of the probability to observed concordant pairs are shown in this figure (at each iteration, a very small elementary change of probability of concordant pairs is applied in this computer simulation: from –0.5 to +0.5 × 10^{-15}).

Therefore, taking into account both fluctuations of the environment and intersubjective agreement forces the observables (AB_{IN}/AB_{AC} and AB_{CP}/AB_{DP}) into *a noncommuting relationship*.

4.3 *Third step*: How asymmetry is introduced in favor of "expected" results?

As depicted in the previous section, two stable states were obtained after transition (with θ = +π/4 or θ = -π/4) (Figure 3). Nothing in the formalism allows favoring one of the two solutions. Nevertheless, in practice, asymmetry is actually introduced by the biological model. Indeed, when the biological model is "at rest" (between two measurements), the state "↓" (no signal) is observed because the experimental conditions are equivalent to an "inactive" sample. Therefore one can consider that an "inactive" sample with the outcome "↓" is inserted between each measurement. After transition, the relationships of "labels" and their respective outcomes must be either all concordant or all discordant. Since the association of "↓" with inactive sample is a concordant pair, the asymmetry introduced by the biological system at rest permits only the solution corresponding to θ = +π/4 (Figure 3).

5. THE STUMBLING BLOCK OF BENVENISTE'S EXPERIMENTS EXPLAINED

We now have the tools to describe the stumbling block of Benveniste's experiments, namely the disturbance observed in some blind experiments. Any description or interpretation of Benveniste's experiments must be able to take into account this puzzling phenomenon that prevented the success of experiments designed as proof-of-concept. Simply put, when Bob or Eve controlled the experiments made by Alice (Figure 1) using blind designs and then assessed the rate of "success", the results were quite different: statistically significant concordance of "expected" and observed labels with Bob and concordance not better than random with Eve.

We can summarize the issue in a concise manner. Suppose that the "expected" results are ↓↓↓↓↑↑↑↑ in that order, i.e. we expect 8 outcomes: 4 with no signal and 4 with signal. With the controller Bob who participates to the blind experiment by assessing the rate of "success", the results are: ↓↓↓↓↑↑↑↑, i.e. complete "success" with this series of samples (100% of concordant pairs). With Eve replacing Bob, the results become ↓↑↑↓↑↑↓↓, i.e. not better than random (50% of concordant pairs and 50% of discordant pairs). Signal is nevertheless observed after control by Eve, but not at the correct place (i.e. "expected" place). The fact that a signal is nevertheless present is an experimental fact that has been repeatedly observed but that remained unexplained according to classical logic. The presence of signal at unexpected places was interpreted by Benveniste's team as "jumps" of biological activity between samples due to various external disturbances. The idea of local cause ("memory of water") was not called into question at this time by Benveniste's team.

When an "outside" controller (Eve in Figure 1) assesses the rate of "success", she compares the successive items of two lists: labels ("expected" results) and experimental outcomes (observed results). For Eve, the cognitive state of the experimenter is superposed. However, when Eve compares "expected" results and observed results, *the information she has on the "expected" results must be taken into account* for the calculation of the probability for A to be associated with concordant pairs. This is formally equivalent to a "which-path" measurement in quantum physics. The "path" information must be taken into account for the calculation of the probability of "success" or "failure"; therefore classical probabilities (conditional probabilities) apply:

$$\mathrm{Prob}_{class}(A_{CP}) = \mathrm{Prob}(A_{IN}) \times \mathrm{Prob}(A_{CP} \mid A_{IN}) + \mathrm{Prob}(A_{AC}) \times \mathrm{Prob}(A_{CP} \mid A_{AC}) \quad \text{(Eq. 18)}$$

$$\mathrm{Prob}_{class}(A_{DP}) = \mathrm{Prob}(A_{AC}) \times \mathrm{Prob}(A_{DP} \mid A_{AC}) + \mathrm{Prob}(A_{IN}) \times \mathrm{Prob}(A_{DP} \mid A_{IN}) \quad \text{(Eq. 19)}$$

According to Eq. 7 and Eq. 8, $\mathrm{Prob}(A_{CP} \mid A_{AC}) = \mathrm{Prob}(A_{DP} \mid A_{IN}) = \sin^2\theta = 1/2$ (for $\theta = +\pi/4$). This means that the probability of signal is the same for both "inactive" and "active" labels (signal is associated either with "inactive" labels in discordant pairs or with "active" labels in concordant pairs).

We now consider the general case of an experiment with a proportion $p = \mathrm{Prob}(A_{IN})$ of "inactive" labels and a proportion $q = \mathrm{Prob}(A_{AC})$ of "active" labels ($p + q = 1$). In this case, the conditional probability of signal or no signal is q or p, respectively:

$\mathrm{Prob}(A_{DP} \mid A_{IN}) = \mathrm{Prob}(A_{CP} \mid A_{AC}) = q$ for signal,

$\mathrm{Prob}(A_{CP} \mid A_{IN}) = \mathrm{Prob}(A_{DP} \mid A_{AC}) = p$ for no signal.

We can now calculate:

$$\mathrm{Prob}_{class}(A_{CP}) = p^2 + \boldsymbol{q^2} \quad \text{(Eq. 20)}$$

$$\mathrm{Prob}_{class}(A_{DP}) = qp + \boldsymbol{pq} \quad \text{(Eq. 21)}$$

There are two components in each of these two equations: one is related to "inactive" labels and the other is related to "active" labels. The terms in bold letters in these equations are those as

sociated with signal. The probability of observing a signal in experiments with an "outside" controller like Eve is equal to $pq + q^2 = q \times (p + q) = q$ (Figure 4). The probability of observing a signal remains the same, without or with control by Eve, and is equal to q. The chief difference is that without Eve's control the samples with a signal are *at the expected places* and with Eve's control, they are *positioned at random*.

	“Inactive” labels						*“Active” labels*			
“Expected” results according to labels	○	○	○	○	○	○	●	●	●	●
	Prob (●) = q									
Observed results <u>without</u> “outside” controller*	○	○	○	○	○	○	●	●	●	●
	Prob (●) = q									
Observed results <u>with</u> “outside” controller*	○	●	○	○	●	○	○	●	○	●
	Prob (●) = (1 – q) × q if “inactive”						*Prob (●)= q^2 if “active”*			
	Prob (●) = q									

○: No signal (background noise); ●: Signal.

* “Outside” controller is personified by Eve in Figure 1; for Eve, the cognitive state *A* of the experimenter Alice is in a *superposed state*. As an “outside” controller who participates to blind experiment, Eve assesses if “signal” (●) is at the correct (i.e. “expected”) places. This is formally equivalent to a “wave function collapse” of the cognitive state *A*, and classical probabilities apply. When Alice and Eve meet, Eve communicates to Alice the places (labels) where a signal is present and they both agree, *despite the presence of signal*, that the experiment is a “failure” because the places observed with signal are not better than random.

Figure 4. Description of the seemingly “jumping” activities from one sample to another. The quantum-like modeling predicts that random concordance between “expected” results and observed results are obtained when the experiments are checked by an “outside” controller (Eve in Figure 1). Benveniste’s team reasoned into a classic frame and interpreted these “failed” experiments as “jumping of biological activity” from one sample to another. See text for details on calculations.

In conclusion, in the quantum-like formalism, the cognitive state of Alice is superposed for Eve; in contrast, for Bob the cognitive state of Alice is not superposed (they are both on the same “branch” of the reality). The consequence is an apparent causal relationship between labels and outcomes if Eve does not control the experiments. This relationship is broken, however, if Eve controls the experiments. The quantum-like modeling easily describes the apparent “jumps” of signal that disturbed so much the interpretation of Benveniste’s experiments.

6. ARE ALL EXPERIMENTAL MODELS SUITABLE TO EVIDENCE QUANTUM-LIKE CORRELATIONS OF COGNITIVE STATES?

To observe quantum-like correlations between “expected” and observed results, the formalism suggests that two conditions are necessary: 1) small random fluctuations of θ around zero and 2) “compliance” of the experimental model, thus allowing transition from mean $\theta = 0$ to $\theta = +\pi/4$ (or $\theta = -\pi/4$). Therefore, the question is: With which experimental models could quantum-like correlations between “expected” results and observed results be established?

Suppose an experimental model based on radioactive decay. Nucleus disintegration is not influenced by fluctuations of the environment. As a consequence, such a model would not be suitable. A beam splitter that randomly reflects or transmits incident photons is submitted to tiny random environmental noise. The probability for a photon to be transmitted is submitted to infinitesimal variations around a mean value. Condition #1 is thus fulfilled. However, these variations remain centered on the mean value because the random fluctuations are not sufficiently large to change the fixed average rate of transmission. The same reasoning applies for the spin of an electron measured in a Stern-Gerlach apparatus; the intensity of the random fluctuations is too small to change the fixed orientation of the magnets. Although submitted to external fluctuations, these devices are not “compliant”.

Therefore, what was so special in Benveniste’s experimental models? Although this is obvious, we must underscore that Benveniste’s experiments were performed in the context of a laboratory dedicated to biological sciences. The experimental models used in these experiments resulted in a selection among other ones that were assayed for optimal evidence of correlations between “expected” and observed results. Indeed, many biological models fulfill the conditions required by the formalism: 1) they are submitted to environment fluctuations (e.g. thermal fluctuations) and 2) many molecules in living systems are submitted to Brownian motion. Movements of molecules in solution confer a large plasticity to these systems. The mean values of a parameter can vary (under some range) thus fulfilling also condition #2. Moreover, biological systems are generally asymmetric with a "resting" state (See Section 4.3); this is not the case with the above physical system.

In conclusion, models such as biological models, which are both randomly influenced by the fluctuations of environment and composed of elements with many degrees of freedom, could be sufficiently compliant to evidence quantum-like correlations.

7. DISCUSSION

It appears that a crucial issue in the present quantum-like modeling is as follows: *Who* is the first to compare "expected" results and observed results of a series of experiments? In other words, *who is aware* of the rate of "success"? The fact that the order of the assessments (outside observer first vs. inside observer first) leads to different results is a property of noncommuting observables.

Our modeling gives logic to the paradoxical results that messed up Benveniste every time he seemed near to succeed with proof-of-concept experiments. How a simple modification of experimental conditions (inside vs. outside assessment of rate of "success") could have such consequences remained incomprehensible according to the logic of the classical experimental sciences. The apparent causal relationship between observables (interpreted as "success") and the "spreading" of the signal into "inactive" samples (interpreted as "failure") are both simply described by the formalism. The emergence of a signal from the background noise of the biological system is also easily explained. Overall, this formalism fits the corpus of the experimental data gained by Benveniste's team over the years [2, 13, 15, 23]. Moreover, in this modeling, no physico-chemical explanation such as "memory of water" is necessary.

The formalism proposed in this article is observer-centered. What an observer perceives cannot be directly experienced by another observer. By definition, the "qualia" of an observer belong to personal experience and only language in its different forms (or direct observation of the state of the observer) allows transmitting information on perception from one observer to another. Acquiring information on perceptions of an observer is actually a "measurement". In the quantum-like modeling, the outcome does not preexist to the "measurement"; the act of questioning/measuring literally creates the answer (but *which* answer is produced cannot be controlled). This indeterminacy for Eve on what Alice "really" perceives concerning the relationship of two observables is central in our modeling (Figure 1). The perception of one observer is formalized by a vector, which is the sum of the possible perceptions of the "reality". For one observable, there is no difference for the classic versus the quantum-like approaches because, mathematically speaking, $(x + 0)^2 = x^2 + 0^2$ (the square of the sum is equal to the sum of the squares in this case). For two observables, however, the classic and quantum-like approaches diverge because two pathways with probability amplitudes x and y lead to the same outcome and therefore in the general case, $(x + y)^2 \neq x^2 + y^2$; the difference between the two sides of this equation is the "interference term".

The fact that different cognitive states interact with one another through the macroscopic world (which is submitted to infinitesimal fluctuations) with the constraint of intersubjective agreement has important consequences: the observables are forced into a noncommuting relationship. Therefore, the correlations between "expected" results and observed results in Benveniste's experiments could be understood as the consequence of quantum-like interferences of the possible cognitive states of the experimenters/observers.

The formalism used in this article is reminiscent of Bayesian logic. Indeed, the probabilities of the two observables, "expected" results and observed results, could be equated to *a priori* probabilities and *a posteriori* probabilities, respectively. Probabilities are updated according to the "reality" shared by the observers as defined by intersubjective agreement. In quantum Bayesianism, the quantum state is not a property of the external world, but of the observer: quantum states are thus states of knowledge of each observer [24]. Therefore, for a given event, there are as many wave functions as there are observers. After sharing the outcomes of measurements and accordingly modifying their respective cognitive states, a coherent modeling of the reality, common to all observers, emerges [22].

This quantum-like modeling has similarities with modelings of quantum cognition on information processing by human brain for decision making, judgment, memory, etc. [19]. Until now however the objective of the modeling in quantum cognition was to describe psychological processes. Our modeling is the first to our knowledge to propose the use of a quantum-like formalism to describe the perception of macroscopic events outside human brain. The decision to study some observables and to explore their possible relationships is subjective and is dependent on our capacity to discriminate between our perceptions coming from the "outside" world and to describe "objects". Despite the subjective nature of the observables, the formalism shows that they are forced into a noncommuting relationship in a manner reminiscent of a decoherence process. In other words, the formalism describes a *subjective* "potential" that is the consequence of the interaction of the cognitive state with the *objective* macroscopic world (exactly as any quantum entity interacts with a macroscopic device). This "potential" is necessary but is not sufficient. Indeed, nothing guarantees that the macroscopic objects will be perceived according to these constraints. The formalism itself suggests that experimental devices with many freedom degrees submitted to random fluctuations appear more suitable for establishing quantum-like correlations because they are possibly more compliant. Biological models are more likely to fulfill these requirements.

Demonstrating causal relationships is a daily exercise for many bench scientists with their experimental models. Therefore one could expect that such quantum-like correlations would be more frequently reported. It is well known that some experiments, more particularly in biology, are not reproduced by other teams and conversely that some teams are more "gifted" than other ones in getting "successful" results. Of course, trivial explanations must be first identified. Nevertheless, it is also possible that quantum-like correlations sometimes happen without the knowledge of the experimenters. A control/blinding of the experiments in conditions that Benveniste himself defined (even though for other purposes) could allow detecting such quantum-like correlations.

8. CONCLUSION

This observer-centered quantum-like modeling offers a new framework for Benveniste's experiments, which remained paradoxical to date. There are lessons to be drawn from this episode of the history of science and we propose theoretical tools for apprehending similar experimental situations.

9. APPENDIX

The cognitive state *A* is described as a superposition of the eigenvectors of the first observable (cognitive states *A* indexed with labels *IN* and *AC*):

$$\left|\psi_A\right\rangle = \frac{\left|A_{IN}\right\rangle + \left|A_{AC}\right\rangle}{\sqrt{2}} \qquad \text{(Eq. 1)}$$

We then develop the eigenvectors of the first observable (A_{IN}/A_{AC}) on the eigenvectors of the second observable (A_{CP}/A_{DP}):

$$\left|A_{IN}\right\rangle = \mu_{11}\left|A_{CP}\right\rangle + \mu_{12}\left|A_{DP}\right\rangle \qquad \text{(Eq. 2)}$$

$$\left|A_{AC}\right\rangle = \mu_{21}\left|A_{CP}\right\rangle + \mu_{22}\left|A_{DP}\right\rangle \qquad \text{(Eq. 3)}$$

Therefore, we can express $\left|\psi_A\right\rangle$ as a superposed state of $\left|A_{CP}\right\rangle$ and $\left|A_{DP}\right\rangle$:

$$\left|\psi_A\right\rangle = \frac{(\mu_{11}+\mu_{21})}{\sqrt{2}}\left|A_{CP}\right\rangle + \frac{(\mu_{12}+\mu_{22})}{\sqrt{2}}\left|A_{DP}\right\rangle \qquad \text{(Eq. 4)}$$

The probability of each state is the square of the corresponding probability amplitude:

$$\text{Prob}_{quant}(A_{CP}) = \frac{(\mu_{11}+\mu_{21})^2}{2} \qquad \text{(Eq. 5)}$$

$$\text{Prob}_{quant}(A_{DP}) = \frac{(\mu_{12}+\mu_{22})^2}{2} \qquad \text{(Eq. 6)}$$

As $\mu_{11}^2+\mu_{12}^2=1$, $\mu_{21}^2+\mu_{22}^2=1$, and $\text{Prob}_{quant}(A_{CP}) + \text{Prob}_{quant}(A_{DP}) = 1$, it can be calculated that $\mu_{11}^2=\mu_{22}^2$, $\mu_{12}^2=\mu_{21}^2$, and $\mu_{11}\mu_{21}=-\mu_{22}\mu_{12}$. Therefore, the solutions for the different probability amplitudes μ_{ij} correspond to two rotation matrixes M1 and M2:

$$\text{M1} = \begin{pmatrix}\mu_{11} & \mu_{12}\\ \mu_{21} & \mu_{22}\end{pmatrix} = \begin{pmatrix}\mu_{11} & -\mu_{21}\\ \mu_{21} & \mu_{11}\end{pmatrix} = \begin{pmatrix}\cos\theta & -\sin\theta\\ \sin\theta & \cos\theta\end{pmatrix}$$

or

$$\text{M2} = \begin{pmatrix}\mu_{11} & \mu_{12}\\ \mu_{21} & \mu_{22}\end{pmatrix} = \begin{pmatrix}\mu_{11} & \mu_{21}\\ -\mu_{21} & \mu_{11}\end{pmatrix} = \begin{pmatrix}\cos\theta & \sin\theta\\ -\sin\theta & \cos\theta\end{pmatrix}$$

We choose the counterclockwise rotation matrix (M1); note that these two solutions differ only for the sign of θ. In Figure 2, the state Ψ_A can be described with one or other basis (A_{IN}/A_{AC} or A_{CP}/A_{DP}) in the vector space. The passage from one basis to the other is obtained by a rotation with an angle equal to θ. When θ is different from zero, the two observables described by these two bases are said to be noncommuting.

We can now write Eq. 2 and Eq. 3 using trigonometric notation:

$$|A_{IN}\rangle = \cos\theta|A_{CP}\rangle - \sin\theta|A_{DP}\rangle \quad \text{(Eq. 7)}$$

$$|A_{AC}\rangle = \sin\theta|A_{CP}\rangle + \cos\theta|A_{DP}\rangle \quad \text{(Eq. 8)}$$

It follows that:

$$|\psi_A\rangle = \frac{(\cos\theta + \sin\theta)}{\sqrt{2}}|A_{CP}\rangle + \frac{(\cos\theta - \sin\theta)}{\sqrt{2}}|A_{DP}\rangle \quad \text{(Eq. 9)}$$

$$\text{Prob}_{quant}(A_{CP}) = \frac{(\cos\theta + \sin\theta)^2}{2} \quad \text{(Eq. 10)}$$

$$\text{Prob}_{quant}(A_{DP}) = \frac{(\cos\theta - \sin\theta)^2}{2} \quad \text{(Eq. 11)}$$

$\text{Prob}_{quant}(A_{CP}) = 1$ (concordance of pairs is maximal) if $\cos\theta = \sin\theta$ ($\theta = +\pi/4$).

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