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ORIGINAL PAPER

"Memory of Water" Without Water: The Logic of Disputed Experiments

Francis Beauvais

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Abstract The "memory of water" was a major international controversy that remains unresolved. Taken seriously or not, this hypothesis leads to logical contradictions in both cases. Indeed, if this hypothesis is held as wrong, then we have to explain how a physiological signal emerged from the background and we have to elucidate a bulk of coherent results. If this hypothesis is held as true, we must explain why these experiments were difficult to reproduce by other teams and why some blind experiments were so disturbing for the expected outcomes. In this article, a third way is proposed by modeling these experiments in a quantum-like probabilistic model. It is interesting to note that this model does not need the hypothesis of the "memory of water" and, nevertheless, all the features of Benveniste's experiments are taken into account (emergence of a signal from the background, difficulties faced by other teams in terms of reproducibility, disturbances during blind experiments, and apparent "jumps of activity" between samples). In conclusion, it is proposed that the cognitive states of the experimenter exhibited quantum-like properties during Benveniste's experiments.

Keywords Memory of water · Scientific controversy · Quantum-like probabilities · Quantum cognition

> *Where would elementary principles such as the law of mass action be if Benveniste is proved correct?*
>
> (Maddox 1988b)

F. Beauvais (✉)
91, Grande Rue, 92310 Sèvres, France
e-mail: beauvais@netcourrier.com

1 Introduction

Scientific controversies often reveal the functioning of science and sometimes lead to paradigm changes (Kuhn 1962). Thus, the "memory-of-water" controversy exposed the role of leading scientific journals and the peer-review system in the filtering of ideas from emergent research fields (Schiff 1998). This specific topic has been widely commented upon and details could be found elsewhere (Maddox 1988a; Maddox et al. 1988; Schiff 1998; Benveniste 2005; Beauvais 2007). For many scientists, the affair with the journal *Nature* marked the end of the "memory-of-water" controversy. Indeed, the hypothesis that a fluid such as water could retain, even if temporarily, information from large molecules after serial dilutions beyond the limit of Avogadro was judged highly implausible (Teixeira 2007). Moreover, other teams encountered difficulties to reproduce the effects with high dilutions with either the same experimental protocol or other biological systems; these reasons led to a disinterest in an idea that was considered at one time as a "new area for biology" if it could be confirmed (Benveniste 2005).

After 1988, Benveniste and his team continued to explore the new research domain that they thought to have discovered. After the disputed basophils, two biological models with promising results were successively developed: the isolated rodent heart (Langendorff model) and the coagulation model. In parallel, after high dilutions, Benveniste proposed other methods to "imprint" biological information into water. Thus, in 1992, he reported that a specific electromagnetic radiation emitted from a solution containing a biologically-active molecule could be transmitted to water via an electronic amplifier (Benveniste et al. 1992; Aïssa et al. 1993; Benveniste et al. 1994; Aïssa et al. 1995). Finally, in 1996, he described the storage of this "biological information" on a hard disk via the sound card of a computer; the stored information could then be "played" to water to transmit this specific "information" (Benveniste et al. 1996; Benveniste et al. 1997; Benveniste et al. 1998).

Close examination of the whole "memory-of-water" saga supports the idea that the controversy has not been closed satisfactorily (Beauvais 2007). Indeed, substantiated arguments were made from both sides. On one side, the a priori impossibility for writing "bits" in water was far from absurd and the proponents of "memory of water," despite promising results, have not been able to offer convincing proofs to the contrary. On the other side, the effects that were related to the "memory of water" were reported by a laboratory with an excellent reputation. Benveniste himself was a reputed senior director of INSERM, the French medical research organization, and he was a member of the scientific establishment. He was one of the discoverers of the platelet-activating factor, a new inflammatory molecule discovered in the 1970s, and he had everything to lose with such extraordinary claims. This research extended on for approximately 20 years and involved successive experimenters who were experts in the management of different biological models. Therefore, suggesting trivial explanations, such as artifact, fake, or incompetence cannot explain the whole story.

2 Why Did Benveniste's Experiments Fail to Convince?

The initial program of Benveniste's team was to assess a causal relationship between water samples, which were supposed to have been "informed" by different processes and the corresponding biological outcomes. Although the initial program was a failure, significant correlations were observed in these experiments.

The hypothesis of the "memory of water" was supported by experiments that were, at first sight, similar to classical pharmacological experiments. However, odd results were repeatedly observed during the "public demonstrations" that Benveniste organized to convince other scientists about the importance of his research (Table 1). The aim of these public demonstrations was to establish a definitive proof of concept for "electronic transmission" and "digital biology" with other scientists as witnesses. During these demonstrations, scientists who were interested in these experiments participated in the production of the experimental samples by using the electronic tools devised by Benveniste's team for the "transmission of biological activity." The samples received a code number from the participants and the samples were assessed in Benveniste's laboratory. The protocols and results of these public blinded demonstrations have been previously described in detail (Beauvais 2007).

An unexpected phenomenon that was an obstacle for the establishment of a "definitive" proof repeatedly occurred. Indeed, after the unblinding of the masked experiments, an effect on the biological system was frequently found associated with the "control" tubes, whereas some of the samples supposed to be "active" were without effect. Benveniste generally interpreted these mismatches as "jumps of activity" between the samples owing to the electromagnetic nature of the specific

Table 1 The antagonistic *pro* and *con* arguments of the "memory-of-water" controversy and their peaceful coexistence in a quantum-like model

Classical view		Quantum-like view
Yes, "memory of water" exists[a]	No, "memory of water" does not exist	
Arguments Emergence of signal from the background Numerous coherent results Success with blind experiments (type-2 observer[b])	*Arguments* Not compatible with our knowledge of physics of water Reproductions of experiments by other teams generally failed Blind experiments (type-1 observer[b]) failed	Description of the experiments with a quantum-like probabilistic model taking into account the experimental context "Success" and "failure" of the experiments are described as the two facets of the same phenomenon No need of "memory-of-water" hypothesis
Paradox		No paradox

[a] "Memory of water" is the hypothesis that specific biological information could be "imprinted" in water samples in the absence of the original biological molecule. Highly diluted solutions of biologically active compounds or other methods ("electronic transmission" and "digital biology") were used

[b] Blind experiments with type-1 and type-2 observers: see text

"molecular signal." The logical consequence of this interpretation was trying to protect the "informed" water samples and their controls from external influences, such as electromagnetic waves. Despite additional precautions and further improvements of the devices, this weirdness nevertheless persisted and "jumps" could not be prevented (Benveniste 2005; Beauvais 2007, 2008, 2012; Thomas 2007).

At this stage, one could conclude that the initial hypotheses were "falsified" and that the concepts of "memory of water," "electronic molecular transmission," and "digital biology" were illusions. Benveniste, however, clung to the idea that a variation of the biological parameters was nevertheless observed during these experiments, a phenomenon that was not explained by current scientific knowledge. For example, the experimental outcomes were correlated after two successive measurements on the same biological system or after measurements on two experimental devices (Beauvais 2007).

Therefore, Benveniste's team constructed an automatic robot analyzer to perform coagulation experiments with minimal intervention of the experimenter, which was suspected to interfere, by unknown reasons, with the device.

In 2001, the United States Defense Advanced Research Projects Agency (DARPA) that was amazed by Benveniste's theories decided to investigate the automatic robot analyzer and assess if the digital signals recorded on a hard disk could be the source of specific biological effects. In the article that summarized their study, the experts reported that some effects supporting the concepts of "digital biology" were observed. However, they did not admit that the concepts of "digital biology" were valid, but that an unknown "experimenter effect" could explain the results. The experts concluded that a theoretical framework was necessary before trying to apprehend these phenomena (Jonas et al. 2006).

In a previous article, we analyzed a large set of experiments obtained by Benveniste's team in the 1990s with the Langendorff model including "public demonstrations" (Beauvais 2012). Comparing the results obtained in different blinding conditions, we concluded that the results of these experiments were related to experimenter-dependent correlations. Although these results did not support the initial "memory of water" hypothesis, the signal that emerged from the background noise remained puzzling. We proposed a model in which the emergence of a signal (i.e., a change of biological parameter) from the background noise could be described by the entanglement of the experimenter with the observed system. However, entanglement is a notion that is borrowed to quantum physics and decoherence of any macroscopic system was an obstacle to the general acceptance of such an interpretation. In a second article, we showed that Benveniste's experiments and quantum interference experiments of single particles had the same logical structure. This parallel allowed elaborating a more complete formalism of Benveniste's experiments and we proposed to see Benveniste's experiments as the result of quantum-like probability interferences of cognitive states (Beauvais 2013).

The purpose of this article is to present an original framework based on a quantum-like description of Benveniste's experiments. Biological systems will not be detailed and will be considered as black boxes with inputs (sample labels) and outputs (biological outcomes); only the logical aspects and the underlying mathematical structures of these experiments will be taken into account. Some of the ideas presented here have been previously published, but the present article offers a synthesis and takes a closer look at specific issues raised by the quantum-like formalism that were not addressed before (Beauvais 2012, 2013).

3 The Logic of Benveniste's Experiments and Single-Particle Interference Experiments

In Benveniste's experiments and single-particle interference experiments, a quantum object (photon) or quantum-like object (cognitive state of the experimenter) interact with macroscopic devices for measurement/observation. Therefore, we drew a parallel between Benveniste's experiments and single-particle interference experiments in a Mach–Zehnder interferometer (Table 2; Fig. 1).

A Mach–Zehnder interferometer has the advantage of possessing only two detectors and not a screen as the two-slit Young's experiment. As seen in Fig. 1 (upper drawing), 50 % of light emitted from a source is transmitted by a beam splitter (BS1) in path T and 50 % is reflected in path R (Scarani and Suarez 1998). In BS2, the two beams are recombined and 50 % of light is transmitted to detector D1 and 50 % to detector D2. If light is considered a wave, it can be demonstrated that waves from the two paths are constructive when they arrive in D1 and are destructive in D2. This is indeed what experiments show: only detector D1 clicks after light detection. This result is in favor of the wave nature of light. Indeed, if light is considered as a collection of particles, then they should be recorded randomly into D1 or D2 (with a probability of 1/2 either D1 or D2). However, if light intensity is decreased in order that particles are emitted one by one, the interference pattern persists (only detector D1 clicks). Each particle behaves as if it

Table 2 Parallel between the single-particle interference experiment with the Mach–Zehnder interferometer and Benveniste's experiments

	Interferometer experiment	Benveniste's experiments[a]
First "path"	Path T	A_{IN}
Second "path"	Path R	A_{AC}
λ_1^2	Prob (path T)	Prob (A_{IN})
λ_2^2	Prob (path R)	Prob (A_{AC})
Superposition (quantum probabilities)	Path T and path R	A_{IN} and A_{AC}
Outcome 1	100 % detector D1	100 % "concordant" pairs[b]
Outcome 2	0 % detector D2	0 % "discordant" pairs[c]
No superposition (classical probabilities)	Path T or path R	A_{IN} or A_{AC}
Outcome 1	50 % detector D1	50 % "concordant" pairs[b]
Outcome 2	50 % detector D2	50 % "discordant" pairs[c]

A cognitive state of the experimenter, *IN* "inactive" labels, *AC* "active" labels, ↓ background, ↑ signal, *T* transmission, *R* reflection

[a] For an experiment with optimal correlations between labels and biological outcomes (and with $\lambda_1^2 = \lambda_2^2$)

[b] A_{IN} with $A_{\downarrow}$ or A_{AC} with $A_{\uparrow}$

[c] A_{IN} with $A_{\uparrow}$ or A_{AC} with $A_{\downarrow}$

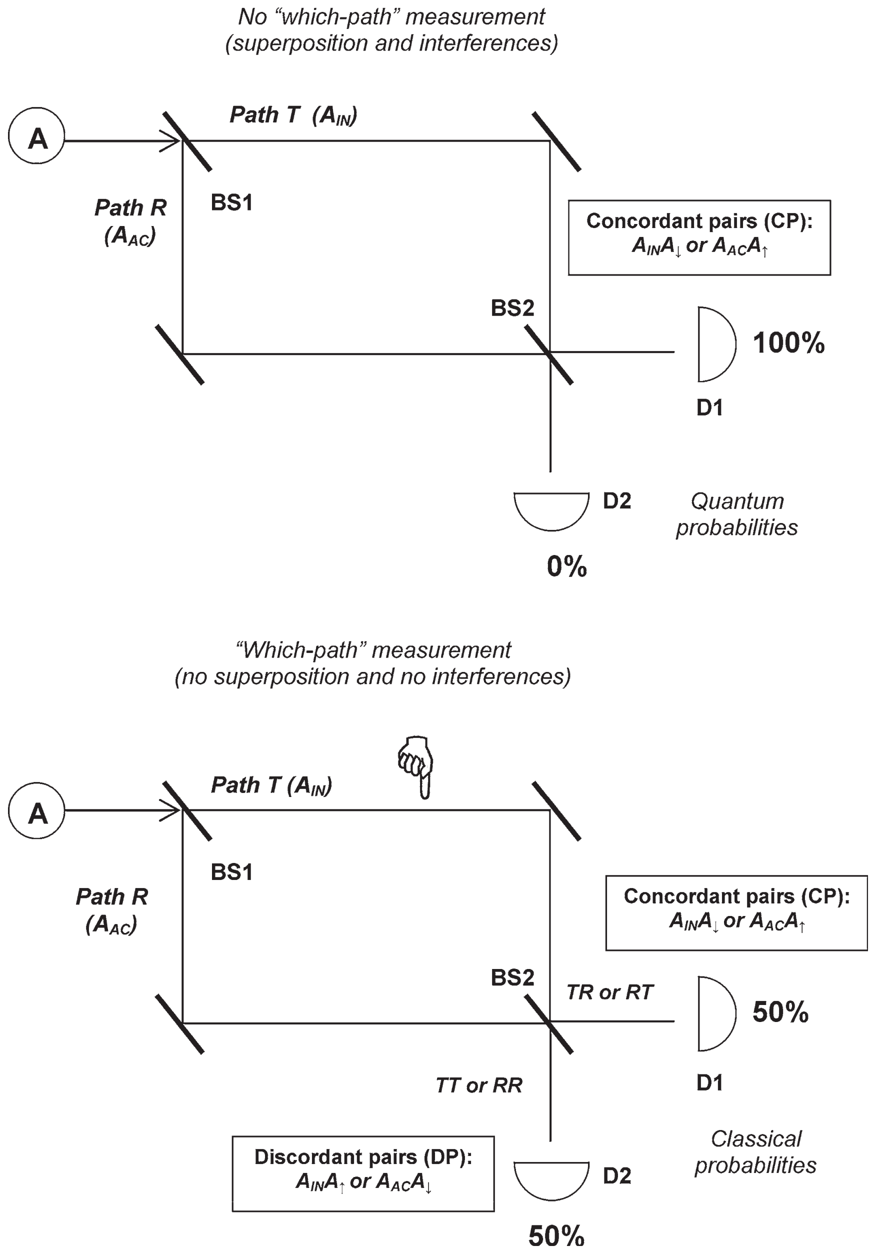

Fig. 1 Experiments of single-particle interference have the same logical structure as Benveniste's experiments. When a unique particle interferes with itself, interferences are constructive in the detector D1 and destructive in the detector D2. Therefore, only detector D1 clicks (upper drawing). If one evidences by measurement the path of the particle (R or T), then both detectors click with a probability of 0.5 for each (classical probability apply because information on the path must be taken into account) (*lower* drawing). In Benveniste's experiments, significant correlations of the labels and outcomes (*IN* with "↓" and *AC* with "↑"; concordant pairs) were observed in the open-label experiments (or after blinding by a type-2 observer) (*upper* drawing). In case of blinding by a type-1 observer, correlations vanished and the association between labels and outcomes were broken and were randomly distributed in concordant and discordant pairs (*lower* drawing)

would interfere with itself. This counterintuitive (i.e., nonclassical) behavior disappears if the information on the initial path (T or R) is obtained by measurement: then D1 or D2 click randomly with a probability of 1/2 for each detector (classical probabilities apply in this case) (Fig. 1; lower drawing).

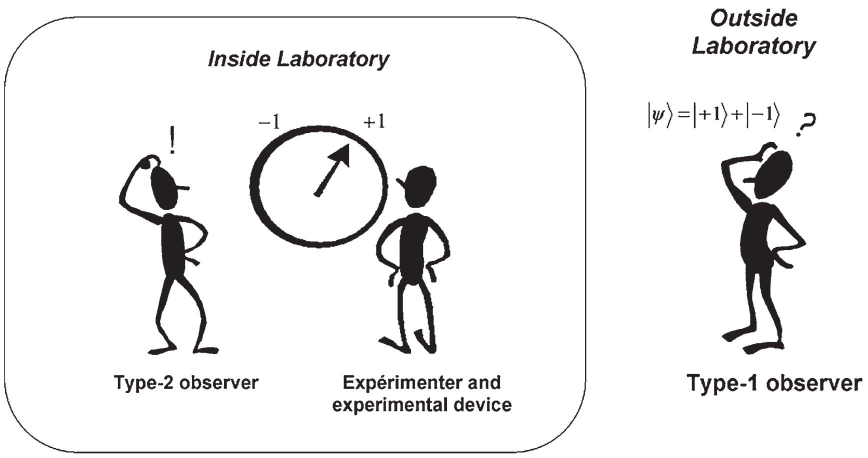

Fig. 2 Roles of type-1 and type-2 observers. The role of the type-1 and type-2 observers was to check the results of Benveniste's experiments in the blind experiments. These observers replaced the initial label of all the experimental samples by a code number. The type-2 observer was inside the laboratory where he/she could interact with the experimenter and the experimental system. The type-1 observer was outside the laboratory, and he did not interact with the experimenter or experimental device and had no information on the on-going measurements. When all the samples had been tested, the results of the biological effects were sent to the type-1 observer and the two observers could assess the rate of concordant pairs by comparing the two lists: biological effects (background or signal) and corresponding labels under code number ("inactive" and "active" samples)

Therefore, the logic of the two experimental situations (Benveniste's experiments and one-particle interference experiment) is comparable. In Benveniste's experiments, "active" samples were expected to be associated with a change in the experimental biological system (we name it a "signal") whereas "inactive" samples were expected to be associated with background. According to the context of the experiment (detection or not of the "initial path," i.e., sample labels), either only concordant pairs (equivalent to only detection in D1) or both concordant/discordant pairs (i.e., equivalent to random detection by D1 and D2) were obtained (Fig. 2; Table 2).

4 The Quantum Probabilities in Brief

In the classical world, the probabilities P1 and P2 of two incompatible events E1 and E1 add (for example, head or tail after coin toss):

$$\text{Prob}_{\text{class}}\ (\text{E1 or E2}) = \text{P1} + \text{P2}$$

This is not the case for quantum probabilities where *probability amplitudes* add; probability is obtained by the squaring of the sum of probability amplitudes. If we define the complex numbers a and b (probability amplitudes), such as $\text{P1} = a^2$ and $\text{P2} = b^2$, then:

$$\text{Prob}_{\text{quant}}\ (\text{E1 or E2}) = (a + b)^2 = \text{P1} + \text{P2} + \text{"interference term."}$$

Therefore, in quantum probabilities, the probability amplitudes of two events can interfere constructively or destructively (as, for example, in the interference pattern on the screen of the two-slit Young's experiment).

In quantum logic, the term "observable" is used to designate a "physical variable." To each observable (for example, the outcome of Schrödinger's cat experiment) corresponds a set of possible pure states obtained after measurement (dead cat; alive cat). Before measurement, the quantum system is said to be in a superposed state of all possible pure states. Vectors in a vector space called Hilbert's space represent the states. Thus, before measurement, the state of the Schrödinger's cat in this vector space is:

$$|Cat\rangle = \frac{1}{\sqrt{2}}|dead\rangle + \frac{1}{\sqrt{2}}|alive\rangle$$

In this equation, each pure state is associated to a probability amplitude $\left(\frac{1}{\sqrt{2}}; \frac{1}{\sqrt{2}}\right)$ and the probability to obtain a pure state after measurement is calculated by squaring the probability amplitude (1/2; 1/2). The quantum formalism involves that, before measurement, the quantum object is in an undetermined state (superposed state), which is not a mixture of the different possible pure states. Moreover, there are no "hidden variables" that predetermine the future outcome after measurement.

5 The Quantum-Like Formalism of Benveniste's Experiments

5.1 Open-Label Experiments

In open-label experiments, the experiments are performed without blinding; the experimenter assesses the rate of concordant pairs by associating the changes of a biological parameter with the "labels" of the samples to be assessed. Samples are said to be "active" (*AC*) if a change of biological parameter ("signal" or "↑") is expected and "inactive" if a change of the biological parameter that is not different from the background ("↓") is expected.

The cognitive state *A* is described in a superposed state for the first observable:

$$|\psi_A\rangle = \lambda_1|A_{IN}\rangle + \lambda_2|A_{AC}\rangle \quad \text{for each sample} \tag{1}$$

In Eq. 1, that describes the cognitive state *A* with regard to the label of a given sample, A_{AC} is the cognitive state *A* associated with the "active" label (and A_{IN} is associated with the "inactive" sample). This equation means that the probabilities for *A* to be associated with an "inactive" or "active" label for this sample are λ_1^2 and λ_2^2, respectively.

The second observable is the concordance of pairs with A_{CP} for concordant pairs and A_{DP} for discordant pairs. The observable is said to be concordant if A_{IN} is associated with $A_\downarrow$ (*A* is associated with background, i.e., no change of biological parameter) or if A_{AC} is observed with $A_\uparrow$ (*A* is associated with the signal, i.e., change of biological parameter). Otherwise, the observable is said to be discordant (A_{IN} is associated with $A_\uparrow$ and A_{AC} is associated with $A_\downarrow$).

We introduce the possibility for the observables to be noncommuting. Technically speaking, this means that two bases to describe any vector in the vector subspace where A is described exist. When the two bases are confounded, the observables commute (classical probabilities are therefore only a special case of quantum probabilities).

The four vectors $|A_{IN}\rangle$, $|A_{AC}\rangle$, $|A_{CP}\rangle$ and $|A_{DP}\rangle$ are four unitary vectors; the two pairs $|A_{IN}\rangle/|A_{AC}\rangle$and $|A_{CP}\rangle/|A_{DP}\rangle$ form two bases of the vector subspace. We can express one basis as a function of the other basis with four coefficients named μ_{11}, μ_{12}, μ_{21}, and μ_{21}:

$$|A_{IN}\rangle = \mu_{11}|A_{CP}\rangle + \mu_{12}|A_{DP}\rangle \tag{2}$$

$$|A_{AC}\rangle = \mu_{21}|A_{CP}\rangle + \mu_{22}|A_{DP}\rangle \tag{3}$$

Therefore, $|\psi_A\rangle$ can be expressed as a superposed state of $|A_{CP}\rangle$and$|A_{DP}\rangle$:

$$|\psi_A\rangle = (\lambda_1\mu_{11} + \lambda_2\mu_{21})|A_{CP}\rangle + (\lambda_1\mu_{12} + \lambda_2\mu_{22})|A_{DP}\rangle \tag{4}$$

The quantum probability (Prob_{quant}) of A_{CP} is the square of the probability amplitude of this state:

$$\mathrm{Prob}_{quant}(A_{CP}) = |\lambda_1\mu_{11} + \lambda_2\mu_{21}|^2 \tag{5}$$

Similarly, $\mathrm{Prob}_{quant}(A_{DP})$ is calculated:

$$\mathrm{Prob}_{quant}(A_{DP}) = |\lambda_1\mu_{12} + \lambda_2\mu_{22}|^2 \tag{6}$$

Since $\mu_{11}^2 + \mu_{12}^2 = 1$, $\mu_{21}^2 + \mu_{22}^2 = 1$, and Prob_{quant} (A_{CP}) + Prob_{quant} $(A_{\mathrm{DP}}) = 1$, it means that the matrix for change of basis is a rotation matrix. Two rotations matrixes with opposite directions are solutions. We choose the matrix that allows the correct association of A_{IN} with $A_\downarrow$ and A_{AC} with $A_\uparrow$:

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

Therefore, we can replace the probability amplitudes in the equations calculated above:

$$|A_{IN}\rangle = \cos\theta|A_{CP}\rangle - \sin\theta|A_{DP}\rangle \tag{7}$$

$$|A_{AC}\rangle = \sin\theta|A_{CP}\rangle + \cos\theta|A_{DP}\rangle \tag{8}$$

$$|\psi_A\rangle = (\lambda_1\cos\theta + \lambda_2\sin\theta)|A_{CP}\rangle + (\lambda_2\cos\theta - \lambda_1\sin\theta)|A_{DP}\rangle \tag{9}$$

$$\mathrm{Prob}_{quant}(A_{CP}) = |\lambda_1\cos\theta + \lambda_2\sin\theta|^2 \tag{10}$$

$$\mathrm{Prob}_{quant}(A_{DP}) = |\lambda_2\cos\theta - \lambda_1\sin\theta|^2 \tag{11}$$

We can easily see that the rate of concordant pairs is maximal for $\lambda_1 = \sin\theta$ (and consequently $\lambda_2 = \cos\theta$):

$$\mathrm{Prob}_{quant}(A_{CP}) = |\lambda_1\cos\theta + \lambda_2\sin\theta|^2 = \left|\lambda_1^2 + \lambda_2^2\right|^2 = 1 \tag{12}$$

$$\mathrm{Prob}_{quant}(A_{DP}) = |\lambda_2\cos\theta - \lambda_1\sin\theta|^2 = |\lambda_2\lambda_1 - \lambda_1\lambda_2| = 0 \tag{13}$$

In this case, all pairs (samples labels and biological outcomes) associated with the cognitive state A are concordant.

5.2 Angle θ and Emergence of Signal from the Background

The quantum-like formalism allows describing the results of Benveniste's experiments without the notion of the "memory of water" or its avatars, such as "digital biology." In the present model, changing the value of the angle θ allows the passage from the logic of classic physics to quantum logic. The logic of classic physics appears as a particular case ($\theta = 0$) of a generalized probability theory (with any θ value). If θ is equal to zero, then the observables commute:

$$|A_{IN}\rangle = 1 \times |A_{CP}\rangle - 0 \times |A_{DP}\rangle = |A_{CP}\rangle \tag{2}$$

$$|A_{AC}\rangle = 0 \times |A_{CP}\rangle + 1 \times |A_{DP}\rangle = |A_{DP}\rangle \tag{3}$$

Therefore, with $\theta = 0$, A_{IN} is always associated with A_{CP} and A_{AC} is always associated with A_{DP}. In other words, concordant pair for the *IN* label is the background, and the discordant pair for the *AC* label is also the background: only the background is associated with the cognitive state A if $\theta = 0$.

These results mean that $\theta \neq 0$ is necessary not only for the concordant pairs, but also for the emergence of the signal. The state $A_{\uparrow}$ must exist in the background of all the possible states of A, even with a low probability. The superposition of the states and the noncommuting observables allow the emergence of $A_{\uparrow}$.

Some questions however remain. Thus, the origin of the noncommuting observables remains unknown. Moreover, we chose one direction for the rotation matrix to associate the "inactive" label with the background on one hand and the "active" label and the background on the other hand. However, the other rotation matrix with the angle θ in the opposite direction was also allowed by the formalism ("inactive" label with signal and "active" signal with background). How asymmetry could be introduced in this formalism remains undefined. These questions will be explored in a future article.

In the next sections, we discuss how the other characteristics of Benveniste's experiments (such as "jumps of activity") are also described by the quantum-like formalism.

5.3 Definition of Type-1 and Type-2 Observers

As explained above, some observers checked the results of Benveniste by using a blind procedure. After samples had received a code number, the experimenter did not know which sample (inactive or active) was tested and the outcome of the experiment could not be unconsciously influenced. Since it appeared that the outcomes (rate of concordant pairs) varied according to the circumstances of the blinding in Benveniste's experiments, we will first precisely describe the roles and characteristics of the different observers.

The definitions of the observers are based on the "Wigner's friend," a thought experiment proposed by Wigner (1983). In this thought experiment, Wigner imagines that a quantum experiment with two possible outcomes is performed in his laboratory by his friend; Wigner is outside the laboratory for the duration of the experiment (Fig. 2). At the end of the experiment, from the point of view of Wigner who has no information on the experiment's outcome, his friend and the complete chain of measurements are in an undetermined state (superposed state). When Wigner enters the laboratory, he learns the outcome of the experiment. Therefore, from his point of view, the quantum wave "collapses" at this moment. However, from the point of view of Wigner's friend, the "collapse" occurred when he looked at the measurement apparatus at the end of the experiment and he never felt himself in a superposed state. On the contrary, he felt that one and only one of the two possible outcomes occurred with certainty. Therefore, according to this thought experiment, two valid but different descriptions of the reality coexist: there is a "collapse" of the quantum wave at different times according to the information that the observers get on the quantum system.

This interpretation of a quantum measurement, however, is now generally considered out-of-date. Wigner himself subsequently adopted the theory of decoherence when this theory was proposed in the 1970s. Decoherence occurs when a quantum system interacts with its environment in a way that is thermodynamically irreversible. Consequently, the different elements of the wave function in the quantum superposition cannot interfere and the interferences become negligible. Therefore, quantum decoherence has the appearance of a wave collapse. However, in contrast with the Wigner's thought experiment, no conscious observer is necessary in the decoherence theory.

It is important to note that we do not endorse Wigner's interpretation for the quantum measurement (in fact, we are agnostic on this issue). This well-known thought experiment simply allows a precise and immediately understandable definition of the different observers/participants in Benveniste's experiments. Indeed, the type-1 observer and type-2 observer are respectively at the same positions as Wigner and Wigner's friend in the thought experiment (Fig. 2).

5.4 Blinding by Type-1 or Type-2 Observers into Practice

In blind experiments, the type-1 and type-2 observers replaced the initial labels of the samples to be tested by a code number. The type-1 and type-2 observers were at their respective places as defined before (Fig. 2). When Benveniste's team completed all the measurements with samples, the results were sent to the type-1 observer (generally by fax or e-mail). The type-1/type-2 observers compared the two lists: biological effects (background or signal) and labels ("inactive" and "active" samples); then, she/he could assess the rate of concordant pairs (i.e., "inactive" with the background and "active" with the signal).

5.5 Quantum Formalism with Blinding by a Type-2 Observer

In case of blind experiments by a type-2 observer with cognitive state O, Eq. 1 is modified:

$$|\psi_O\rangle = \lambda_1|O_{IN}\rangle + \lambda_2|O_{AC}\rangle$$
$$|\psi_{AO}\rangle = \lambda_1|A_{IN}\rangle|O_{IN}\rangle + \lambda_2|A_{AC}\rangle|O_{AC}\rangle \quad (1\,bis)$$

Finally, we obtain:

$$|\psi_{AO}\rangle = (\lambda_1 \cos\theta + \lambda_2 \sin\theta)|A_{CP}\rangle|O_{CP}\rangle + (\lambda_2 \cos\theta - \lambda_1 \sin\theta)|A_{DP}\rangle|O_{CP}\rangle \quad (4\,bis)$$

Therefore, this experimental situation is formally not different from open-label experiments described above since the cognitive states of both the experimenter (A) and type-2 observer (O) are on the same "branch" of the state vector (Eq. 1 *bis*; Fig. 2). The type-2 observer can be considered as an integral part of the experiment as the biological system or any automatic device for blinding.

5.6 Quantum Formalism with Blinding by a Type-1 Observer

When a blind experiment is performed by a type-1 observer, he/she assesses the rate of concordant pairs by comparing labels and biological outcomes. This experimental situation is then formally comparable to a "which-path" *measurement* in the Mach–Zehnder interferometer experiment and therefore, *classical probabilities* apply. Indeed, *the information gained by the type-1 observer on the label has to be taken into account* for the calculation of the probability for A to be associated with the concordant pairs:

$$\mathrm{Prob}_{class}(A_{CP}) = \mathrm{Prob}(A_{IN}) \times \mathrm{Prob}(A_{CP}|A_{IN}) + \mathrm{Prob}(A_{AC}) \times \mathrm{Prob}(A_{CP}|A_{AC}) \tag{14}$$

with $\mathrm{Prob}(A_{CP}|A_{IN}) = \cos^2\theta$ and $\mathrm{Prob}(A_{CP}|A_{AC}) = \sin^2\theta$, then:

$$\mathrm{Prob}_{class}(A_{CP}) = \lambda_1^2 \cos^2\theta + \lambda_2^2 \sin^2\theta \tag{15}$$

Prob_{class} (A_{DP}) is calculated similarly:

$$\mathrm{Prob}_{class}(A_{DP}) = \lambda_2^2 \cos^2\theta + \lambda_1^2 \sin^2\theta \tag{16}$$

The important point is that Prob_{quant} $(A_{\mathrm{CP}}) \neq \mathrm{Prob}_{class}$ (A_{CP}) in the general case (compare Eqs. 10 and 16). In the squaring of the sum of probability amplitudes, there is an additional term 2 $\lambda_1\lambda_2$ cos θ sin θ, which is typical of all the quantum mechanical interference effects.

The calculations for the different classical and quantum probabilities are summarized in Fig. 3. Quantum probabilities are calculated as the square of the sum of probability amplitudes and classical probabilities (in case of measurement/observation of the first observable by the type-1 observer) are obtained as the sum of the squares of all probability amplitudes.

5.7 Consequence of the Formalism: "Jumps" of Activity

As we have seen, the apparent "jumps of activity" between the samples was a strange phenomenon that poisoned Benveniste's experiments, particularly, during public demonstrations (Table 3). The design of these experiments involved blinding by a type-1 observer, and in our quantum-like probabilistic model, this phenomenon is simply explained.

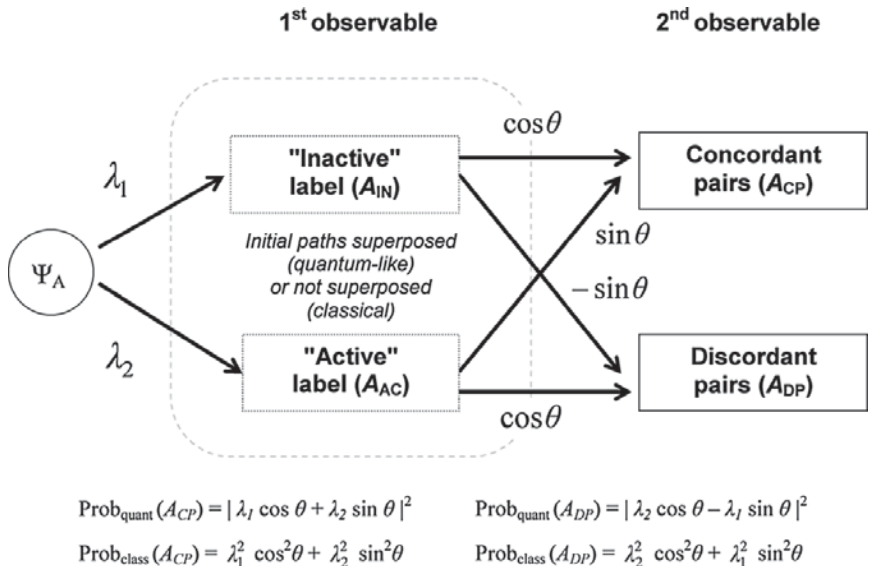

Fig. 3 Design of a quantum-like experiment (application to Benveniste's experiments). The quantum-like object (cognitive state A of the experimenter) is "measured" through two successive noncommuting observables ($\theta \neq 0$), which are mathematical operators. The first observable ("labels") splits the state of the cognitive state A into two orthogonal (independent) states ("inactive" and "active" labels). Each of these two states is split by the second observable ("concordance of pairs") into two new orthogonal states, concordant pairs and discordant pairs. If the events inside the box are not measured or observed, the system is in a superposition of states. If the events inside the box are measured, then, classical probabilities apply because we have to take into account the information obtained on the path (consequently, there is no superposition of the initial "path"). The probabilities for the concordance of pairs are different according to the quantum or classic probabilities. Indeed, quantum probabilities are calculated as the square of sum of the probability amplitudes of paths. Classical probabilities are calculated as the sum of squares of the probability amplitudes of paths. Interferences of the two initial paths (in area with dashed line) are possible with the probability amplitudes (quantum probabilities) but not with probabilities (classical probabilities)

If we suppose that the number of "inactive" samples (labels IN) and "active" samples (labels AC) are equal (i.e., $\lambda_1^2 = \lambda_2^2 = 0.5$) and that the concordance is optimal (i.e., $\cos\ \theta = \lambda_1$ and $\sin\ \theta = \lambda_2$), we can calculate the respective probabilities according to Eqs. 10, 11, 15, and 16.

For open-label experiments (or with blinding by a type-2 observer),

$$\mathrm{Prob}_{quant}(A_{CP}) = |\lambda_1 \cos\theta + \lambda_2 \sin\theta|^2 = 1$$
$$\mathrm{Prob}_{quant}(A_{DP}) = |\lambda_2 \cos\theta - \lambda_1 \sin\theta|^2 = 0$$

For experiments with blinding by a type-1 observer,

$$\mathrm{Prob}_{class}(A_{CP}|A_{IN}) = \cos^2\theta = 0.5$$
$$\mathrm{Prob}_{class}(A_{CP}|A_{AC}) = \sin^2\theta = 0.5$$

These calculations indicate that in the open-label experiments (or with blinding by a type-2 observer), A_{IN} is always associated with $A_{\downarrow}$ and A_{AC} is always associated with $A_{\uparrow}$. In contrast, after blinding with a type-1 observer, $\mathrm{Prob}_{class}\ (A_{CP}) = 0.5$ and $\mathrm{Prob}_{class}\ (A_{DP}) = 0.5$.

Therefore, for a participant in these blind experiments with a type-1 observer, the proportion of samples with the AC labels associated with the signal decreases from

Table 3 Summary of the quantum-like probabilistic model describing Benveniste's experiments in different experimental contexts

	Patterns of results		
Expected results[a]	↓↓↓↓↑↑↑↑	↓↓↓↓↑↑↑↑	↓↓↓↓↑↑↑↑
Observed results	↓↓↓↓↑↑↑↑	↓↓↑↑↓↑↓↑	↓↓↓↓↓↓↓↓
Description	Signal present at expected places	Signal present but at random places	No signal
Conclusion according to classic logic	Success	Failure ("jumps of activity" between samples)	Failure
Conclusion according to quantum logic	$\theta \neq 0$ with interferences of quantum states	$\theta \neq 0$ without interferences of quantum states	$\theta = 0$
Probability of concordant pairs[a]	$\left\lvert \frac{1}{\sqrt{2}}\cos\,\theta + \frac{1}{\sqrt{2}}\sin\,\theta \right\rvert^2 = 1$	$\frac{1}{2}\cos^2\theta + \frac{1}{2}\sin^2\theta = \frac{1}{2}$	$\frac{1}{2}$
Corresponding experimental situations	Benveniste's experiment without blinding by a type-1 observer[b]	Benveniste's experiment with blinding by a type-1 observer	Results as predicted by classical probabilities[c]

↓ Background, ↑ signal

[a] Experiments with $\lambda_1^2 = \lambda_2^2 = 0.5$ (i.e., numbers of "inactive" and "active" labels are equal); we suppose that sin $\theta = \lambda_2$ for the first two columns (quantum interferences are maximal in the first column)

[b] Open-label experiment or experiment blinded by a type-2 observer

[c] Such results (i.e., no signal with all samples) were generally obtained by other scientific teams that tried to reproduce Benveniste's experiments

100 to 50 % and the proportion of samples with the *IN* labels associated with the signal increases from 0 to 50 %. It is as if the "biological activity" (signal) "jumped" from some samples with the *AC* label to samples with the *IN* label (Table 3).

This is a chief consequence of the quantum-like formalism that easily describes this phenomenon without supposing ad hoc hypotheses involving uncontrolled "external" causes or artifacts.

5.8 "Success" and "Failure" in Benveniste's Experiments

Quite different results are obtained in the Mach–Zehnder interferometer experiment (or in the two-slit Young's experiments) based on the decision to measure the initial path or not. In one case (interference pattern), light behaves as a wave and in the other case (no interference pattern), it behaves as a collection of particles. In Benveniste's results, the experimental context also appeared to play an important role (blinding by a type-1 observer vs. a type-2 observer) (Beauvais 2007, 2008, 2012, 2013). According to the blinding conditions, different results were obtained that were considered as "successes" or "failures" (Table 3). In the two-slit experiment, observing interferences on the screen or not, according to the experimental context, is not considered as a success or a failure: both results are necessary to describe the physics of light. In Benveniste's experiments also, the "successes" and "failures" were the two faces of the same coin. Results of the blinding with the type-1 observer played the same role as the measurement of the path entered by the particle in the single-particle interference experiments.

6 Quantum-Like Formalism and Decoherence

Decoherence is an obstacle to the general acceptance of any quantum or quantum-like model that deals with macroscopic phenomena. In our quantum-like model, it is important to note that we borrow only some notions from the quantum logic, such as Hilbert's space, vector superposition, and noncommuting observables. However, there is no term equivalent to the Planck constant and no Schrödinger equation. The cognitive state itself is an abstract "object," which is involved in measurement/observation processes involving nonphysical observables. Thus, labels take the meaning that the experimenter decides (samples are considered as physically the same in the formalism). Definition of a concordant pair is also arbitrary and assessing pair concordance requires information processing for "interpretation." Therefore, the formalism deals not with the events themselves, but with the relationships between these events. For all these reasons, the superposition of the different possible states of the cognitive state is supposed to be not exposed to a decoherence process (except in the case of a blind experiment with a type-1 observer).

Such an approach has never been proposed for these experiments but there are comparable uses of notions from the quantum physics in other domains. Thus, Walach proposed to use a "generalized" version of the quantum theory by weakening some constraints of the original quantum formalism. Therefore, the theory is applicable in more general contexts than in the original quantum physics (Walach and von Stillfried 2011). In quantum cognition, which is an emerging research field, the cognitive mechanisms and information processing in the human brain are modeled by using some notions from the formalism of quantum physics. This approach allowed addressing problems, that were until now considered paradoxical, and has been applied to human memory, decision making, personality psychology, etc. (see, for example (Bruza et al. 2009) for the special issue of *Journal of Mathematical Psychology* in 2009).

7 Conclusions

Our description of Benveniste's experiments can be summarized with only two equations, whose general form is $a^2 + b^2$ and $|a + b|^2$. Only one parameter (the angle θ) is necessary for the passage from classical ($\theta = 0$) to quantum-like ($\theta \neq 0$) probabilities.

We understand now why Benveniste's experiments were the ideal ground for a controversy. Indeed, as soon as one tried to "measure/observe" the initial "path" (namely, the cognitive state A associated with sample labels), correlations between the effects and supposed causes vanished. Nevertheless, a signal persisted and that was the reason why Benveniste's team pursued its technical quest for the best experimental device and the crucial experiment. Moreover, other teams (for which—in our interpretation—observables were commuting) could not confirm these experiments and their results were as expected according to the logic of classical physics.

In conclusion, the use of a quantum-like probabilistic model allows describing all the characteristics of Benveniste's experiments and brings a new light on this major controversy. We propose that the outcomes of these experiments were related to quantum-like interferences of the cognitive states of the experimenter.

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