Quantum-Like Interferences of Experimenter's Mental States: Application to "Paradoxical" Results in Physiology

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ABSTRACT

Objectives: "Memory of water" experiments (also known as Benveniste's experiments) were the source of a famous controversy in the contemporary history of sciences. We recently proposed a formal framework devoid of any reference to "memory of water" to describe these disputed experiments. In this framework, the results of Benveniste's experiments are seen as the consequence of quantum-like interferences of cognitive states. **Design:** In the present article, we describe retrospectively a series of experiments in physiology (Langendorff preparation) performed in 1993 by Benveniste's team for a public demonstration. These experiments aimed at demonstrating "electronic transmission of molecular information" from protein solution (ovalbumin) to naïve water. The experiments were closely controlled and blinded by participants not belonging to Benveniste's team. **Results:** The number of samples associated with signal (change of coronary flow of isolated rodent heart) was as expected; this was an essential result since, according to mainstream science, no effect at all was supposed to occur. However, besides coherent correlations, some results were paradoxical and remained incomprehensible in a classical framework. However, using a quantum-like model, the probabilities of the different outcomes could be calculated according to the different experimental contexts. **Conclusion:** In this reassessment of an historical series of "memory of water" experiments, quantum-like probabilities allowed modeling these controversial experiments that remained unexplained in a classical frame and no logical paradox persisted. All the features of Benveniste's experiments were taken into account with this model, which did not involve the hypothesis of "memory of water" or any other "local" explanation.

Key Words: memory of water, quantum-like probabilities, quantum cognition, entanglement, contextuality, non-local interactions

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> *"One explanation might be that the data had been generated by a hoaxer in [Benveniste's] laboratory."* (Maddox 1988)

Introduction

Some words – such as "memory of water" – have the remarkable property to induce rapid and strong physiological reactions in readers, especially if they are also science editors. No doubt that classical Pavlovian conditioning is at work (Reiff *et al.*, 1999). The present article should not induce any hypertensive response since I will describe a series of Benveniste's experiments without reference to modification of water structure whatsoever. Indeed, I proposed recently to model these controversial experiments with some notions inspired from the generalized probability theory that is the core of quantum physics (Beauvais, 2012; 2013). Strictly speaking, the possibility of "memory of water" was not definitely dismissed; it is always difficult to prove that something does not exist. Nevertheless, all difficulties encountered by Benveniste

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(reproducibility, disturbances after blinding) were described in this quantum-like model, which did not require the hypothesis that water had been "structured" or "informed".

The controversy with the journal *Nature* and its editor has been extensively discussed (de Pracontal, 1990; Schiff, 1998; Benveniste, 2005; Beauvais, 2007; Thomas, 2007; Beauvais, 2012). The above quote of J. Maddox, the editor of *Nature* during the "Benveniste's affair", is a good indicator of the state of mind of some scientists faced with the puzzling results on the effects of high dilutions reported in the *Nature*'s article (Davenas *et al.,* 1988). Less known are the experiments performed by Benveniste's team after publication of the controversial article in 1988. Thus, a large series of blind experiments with the same basophil model was performed under the supervision of statisticians and statistically significant results were obtained in favor of the effects of high dilutions confirming both the results of 1988 in *Nature* and other results previously published with the same biological model (Davenas *et al.,* 1987; Benveniste *et al.,* 1991). Nevertheless, Benveniste abandoned basophils and searched for other models that were less disputed.

One of the biological systems that were routinely used in Benveniste's laboratory – namely the isolated perfused rodent heart preparation (Langendorff preparation) – was shown to respond to high dilutions of various pharmacological compounds (Hadji *et al.,* 1991; Benveniste *et al.,* 1992). The Langendorff heart preparation is a classical model of physiology, which allows recording pharmacological effects of biological compounds or pharmacological drugs on different parameters of a rodent heart maintained alive. In early experiments with high dilutions, coronary flow appeared to be the most sensitive parameter. This biological model had the advantage to be more objective than basophil counting, which depends on the judgment and skill of the experimenter. Moreover, with the Langendorff preparation, the biological effects of high dilutions were directly observed in the series of tubes that collected the effluent from coronary arteries. Therefore, in contrast with the basophil model, the effects of high dilutions could be shown in real time to scientists interested by this research who visited the laboratory.

In 1992, Benveniste reported that he was able to transmit the "molecular information" contained in an aqueous solution by placing a tube containing a biologically active compound in an electric coil at the entry of a low-frequency amplifier; the "biological information" was said to be transmitted to naïve water contained in another tube placed in a second electric coil wired at the amplifier output. In a further refinement (1995), the "molecular signal" was digitized and stored on the hard disk of a personal computer and could then be "replayed" in a second time to naïve water. Benveniste coined then the term "digital biology". In the last version (1997), the coil was directly fixed on the perfusion column of the Langendorff system and therefore the system could be piloted from the computer without injection of the samples of "informed" water into the perfusion circuitry. The results obtained with these successive devices were published as posters and abstracts at congresses (Aïssa *et al.,* 1993; Benveniste *et al.,* 1994; Aïssa *et al.,* 1995; Benveniste *et al.,* 1996; Benveniste *et al.,* 1997; Benveniste *et al.,* 1998). If true, these "discoveries" were ground-breaking, but they received great skepticism (Schiff, 1998; Beauvais, 2007).

In order to convince other scientists that his controversial research was well-founded, Benveniste organized regular public demonstrations during years 1992–1998. During these demonstrations, experimental samples were produced and blinded by participants (Beauvais, 2007). The samples were then assessed on the Langendorff system. The initial objective of these demonstrations has however never been achieved because an unexpected phenomenon occurred repeatedly. Indeed, after unblinding of the masked experiments, a "signal" was frequently found with "control" tubes whereas some samples supposed to be "active" were without effect. Benveniste generally interpreted these failures as "jumps of activity" between samples and as a logical consequence he concluded that "informed" water samples should be protected from external influences, particularly electromagnetic waves. Despite additional precautions and further improvements of the devices, this weirdness nevertheless persisted and was an obstacle for the establishment of a definitive proof of concept (Benveniste, 2005; Beauvais, 2007; Thomas, 2007; Beauvais, 2008; 2012).

The purpose of the present article is first to describe in detail such a demonstration that comprised a series of experiments made in parallel; these experiments were blinded and closely controlled by observers not belonging to Benveniste's team. The aim of these experiments was to demonstrate "electromagnetic transmission of biological activity" to naïve water. In a second time, we will see how the results of these experiments that remain inexplicable in a classical framework, are easily described in a quantum-like model without reference to "memory of water".

Methods

The protocol of the experiments of May 13th 1993

The public demonstration described in this article included four parallel independent blind experiments starting on May 13th 1993. For this purpose, a written protocol precisely described the experiments and defined the role of each participant. After completion of all measurements, the raw data were presented to the participants before unblinding. An internal report reported the results and included all data and original records.

This series of experiment was designed and proposed to Benveniste by Michel Schiff who was a former physicist who turned next to psychology and social sciences (Schiff *et al.,* 1978). He was amazed by the "memory of water" controversy and had no *a priori* opinion on the debate on "memory of water". Schiff proposed to Benveniste to spend time in his laboratory to get information on this research; in exchange he could bring help, particularly for design of experiments, statistical analysis and supervision of experiments. Schiff joined Benveniste's laboratory half-time during years 1992–1993; he reported his experience in a book (Schiff, 1998). The purpose of the demonstration was to convince the participants that it was possible, according to the title of the internal report, "to dissociate molecular information from its support and to transmit it to naïve water".

The electronic devices have been described in details elsewhere (Thomas *et al.,* 2000); it was composed of a low-frequency amplifier with a coil wired at input (for pharmacological solution) and a coil wired at output (for "imprinting" of naïve water). The biological model was the Langendorff preparation, which allows maintaining alive a rodent heart while pharmacological agents are injected into the circuitry to modify some physiological parameters (Beauvais, 2007; 2012). Change of coronary flow was the main biological parameter that was recorded with this system in Benveniste's experiments on "memory of water".

On May 13th 1993, the participants to these experiments met in a laboratory at Paris. Four parallel experiments of "electronic transmission" were performed by four teams; each team was composed of two participants who were not members of Benveniste's laboratory. An original method for blinding of sample labels was used so that nobody knew the original label until unblinding. The molecule to be transmitted was ovalbumin and rats of which hearts were used for measurements had been sensitized to ovalbumin.

The successive tasks of each two-participant team (one participant performed the experimental handlings and the other was a witness) were the following: choice of ten plastic tubes containing distilled water from a stock and choice of ten padded envelopes from a stock; one tube was placed in each envelope. One envelope was chosen and the respective tube was placed on the output coil of the low-frequency amplifier (a tube containing ovalbumin at 10 μmol/L was always present on the input coil). After 15 min, the "transmitted" tube was placed again into the envelope with a self-adhesive label attached inside the envelope. The nine other tubes of naïve water were left untouched and the ten envelopes were mixed for randomization. Then all tube received labels with code: each tube was extracted from envelope (without looking inside), received a self-adhesive label and an identical label was placed on the envelope (outside); the labels were 1 to 10 for experience #1, 11 to 20 for experience #2; 21 to 30 for experience #3 and 31 to 40 for experience #4. All envelopes were given to a bailiff who kept them until unblinding. Before and after each "ovalbumin transmission", one open-label transmission was also performed by a member of Benveniste's team (positive controls).

The 40 blinded tubes and the 8 open-label positive controls were then transported to Benveniste's laboratory at Clamart, in the inner suburbs of Paris. The content of all samples was assessed from May 13 to 17 on the Langendorff device: for homogeneity of results, each series was tested on the same heart (one heart per series). For each of the four experiments, one open-label water sample (negative control), one open-label sample of "transmitted" ovalbumin (positive control) and the ten blinded samples were assessed; the last sample was a sample of ovalbumin at 0.1 µmol/L (positive control at "classical" concentration).

After a first measurement of all samples, the tubes received a new code and another round of measurements was undertaken. This interim blinding was performed by Schiff and another member of Benveniste's laboratory not involved in these experiments.

The quantum formalism in brief

In quantum physics, all the knowledge on a physical object is summarized by a state vector $|\psi\rangle$. For a system S with two possible states S_1 and S_2 (e.g., disintegrated and non-disintegrated states of a radioactive atom), the state of the system S is described by the following state vector:

$$|\psi_S\rangle = a|S_1\rangle + b|S_2\rangle$$

This equation means that before measurement the quantum object is in a "superposed" state described by the sum of two state vectors. It is important to note that the indetermination of the state of the system before measurement is total (there is no "hidden variables"). After measurement ("reduction of the quantum wave"), the probability P1 to observe S_1 is a^2 and the probability P2 to observe S_2 is b^2.

In classical probability theory, probabilities add. Thus, if P1 and P2 are the probabilities associated to two mutually exclusive events S_1 and S_2, the probabilities for either event to occur is Prob (S_1 or S_2) = P1 + P2. In contrast, in quantum probability theory, *probability amplitudes* add and probabilities are calculated as the square of probability amplitudes. Thus, if a and b are the probability amplitude associated to two events S_1 and S_2 (with P1 = a^2 and P2 = b^2), then:

Prob (S_1 or S_2) = $(a + b)^2$ = P1 + P2 + *interference term.*

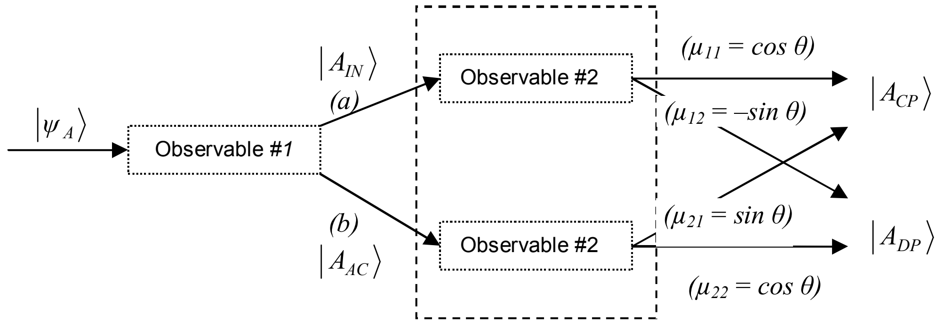
The interference term is added or subtracted to classical probabilities according to sign to give quantum probabilities.

The notion of non-commutable observables is another key concept of quantum probabilities. Physical "observables" are mathematical "operators" and for each operator there is a spectrum of possible results, which are named the "eigenvectors" of the operator (they constitute an orthogonal basis in the vector space). When an operator is applied to a state vector, the vector is split into different components, which are the eigenvectors of the operator (Figure 1). If the original state vector to be observed is an eigenvector of the operator, then it is not affected (this means that the value of the parameter to be measured was already fixed before measurement). Two observables are said to commute with each other when they share eigenvectors (the shared eigenvectors are not affected by the measure of the other observable). As a consequence, the outcomes will be different according to the order of the measurements. When two observables are not commutable, the set of eigenvectors of one observable (orthogonal basis) can be expressed as a linear combination of the set of eigenvectors of the other observable; in other words, there are two different bases for the same vector space.

Type-1 and type-2 observers in quantum-like model

The point of view of the different types of participants/observers must be precisely defined. We will now refer to an "inside" observer as a type-2 observer and an "outside" observer as a type-1 observer.

The emphasis placed on the different points of view of observers is reminiscent of the thought experiment named "Wigner's friend" proposed in the early 1960s by the physicist Eugene Wigner (Figure 2) (D'Espagnat, 2005; Wikipedia, 2013). Actually, "Wigner's friend" was an extension of another famous thought experiment, namely Schrödinger's cat. Wigner's friend is supposed to perform a measurement on a macroscopic system (Schrödinger's cat) linked to a microscopic quantum system (radioactive atom), which is in a superposed state before measurement. Wigner remains outside the laboratory and he has no information on the state of his friend. At the end of the experiment, from the point of view of Wigner's friend, the cat is either dead *or* alive ("collapse" of the quantum wave from a superposed state). From the point of view of Wigner, the cat is in a superposed state of the two possible outcomes: cat dead *and* alive (with Wigner's friend in the corresponding state). If Wigner enters the laboratory or has information on the result of the experiment ("collapse" of the quantum wave), he learns that the cat is dead *or* alive and his friend is in the corresponding state. This is the "measurement problem": we have two valid but different descriptions of the reality with apparent "collapse" of the quantum wave at different times according to the different observers.



$$P_{II}(A_{CP}) = |a\cos\theta + b\sin\theta|^2 \qquad P_{II}(A_{DP}) = |b\cos\theta - a\sin\theta|^2$$

$$P_I(A_{CP}) = a^2\cos^2\theta + b^2\sin^2\theta \qquad P_I(A_{DP}) = b^2\cos^2\theta + a^2\sin^2\theta$$

Figure 1. Design of an experiment exhibiting quantum-like interferences (application to Benveniste's experiments). The quantum object (cognitive state *A* of the experimenter) is symbolized by the state vector $|\psi_A\rangle$ and is measured through two successive observables, which are mathematical operators. The first observable ("labels") splits the state $|\psi\rangle$ into two orthogonal states (denoted $|A_{IN}\rangle$ and $|A_{AC}\rangle$). Each of these two states is split by the second observable ("concordance of pairs") into two new orthogonal states, $|A_{CP}\rangle$ and $|A_{DP}\rangle$. It is assumed that the observables do not commute. If the events inside the box are not measured/observed, the system is in a superposition of states, which is not equal to a mixture of the two states. The consequence of superposition is that quantum probabilities to observe $|A_{CP}\rangle$ or $|A_{DP}\rangle$ are different compared with classic probability. Indeed, quantum probabilities (P_{II}) are calculated as the *square of sum* of probability amplitudes of paths; classical probabilities (P_I) are calculated as the *sum of squares* of probability amplitudes of paths.

In Benveniste's experiments, the type-1 observer ("outside") is the equivalent of Wigner whereas type-2 observer ("inside") is the equivalent of Wigner's friend (Figure 2). The type-2 observer is on the same "branch of reality" of the experimenter with experimental device (i.e., Schrödinger cat); the type-1 observer considers that the type-2 observer (or the experimenter) is in a superposed state (until he interacts with him).

Statistical analysis

The raw data were obtained from the internal report of Schiff and Benveniste and the analysis of the results was reassessed. The biological parameter that was recorded during these experiments was the coronary flow recorded for 15 min (one time point per min). When a signal was recorded, the flow change was maximal at 3–4 min after injection of sample into perfusion circuitry and flow returned to basal value before 10 min. The area under the curve (AUC) method was used to present the results in this article. The mean and standard deviations of background were calculated with the nine samples (in each of the four experiments) that did not significantly change the coronary flow. The experimental result obtained with each sample was expressed as the number of standard deviations of background from mean background. Another method was used to summarize the results in the internal report of Schiff and Benveniste; the results were sufficiently clear-cut to lead to identical conclusions for identification of samples associated to signal and background in each experiment.

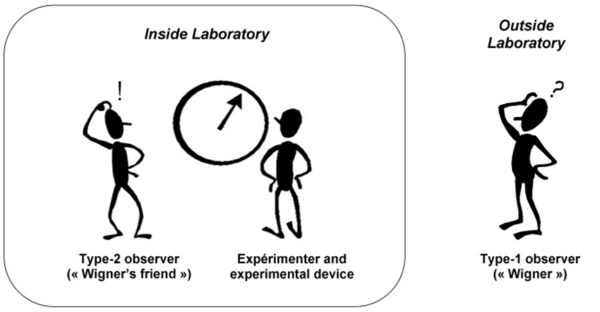


Figure 2. Type-1 observer (Wigner) and type-2 observer (Wigner's friend). In this thought experiment, two points of view are successively considered. From the point of view of Wigner who has no information on experiment outcome, the chain of measurement including his friend is in an undetermined state at the end of the experiment (superposed state). There is "collapse of the quantum wave" when Wigner enters the laboratory and learns the outcome of the experiment. From the point of view of Wigner's friend, "collapse" occurs when he looks at the measurement apparatus at the end of the experiment and he never feels himself in a superposed state; on the contrary he feels that one of the outcomes has occurred with certainty. Therefore two valid but different descriptions of the reality coexist in this thought experiment with apparent "collapse" of the quantum wave at different times according to information that observers get on quantum system. In Benveniste's experiment, we make a parallel with Wigner (type-1 observer) and Wigner's friend (type-2 observer) to define the point of view of the different participants/observers.

Results

Results of the four experiments and interpretation by Benveniste's team

The results of the two rounds of measurements in the four parallel experiments are described in Table 1 and Table 2. As "expected", a signal corresponding to one sample *and only one* emerged from background in each 10-samples series in first round of measurements: label #8 in first experience, label #17 in second experience; label #21 in third experience and label #34 in fourth experience. This is not a trivial comment since, according to mainstream science, no effect at all was supposed to occur.

Table 1. Results of the Benveniste's experiments of May 13th, 1993: first round of measurements after blinding by type-1 observers.

Exp. #1		Exp. #2		Exp. #3		Exp. #4	
Label #	Result	Label #	Result	Label #	Result	Label #	Result
Blind samples: in each series, 9 "inactive" labels (water) and 1 "active" label (Ova. tr.)							
1	-0.5	11	1.5	**21**	**13.2**	31	0.6
2	-1.2	12	-1.3	22	-0.5	32	0.6
3	-0.8	13	-0.6	23	-1.0	33	0.6
4	0.2	14	-0.6	24	-0.5	**34**	**10.8**
5	2.0	15	-0.6	25	0.1	35	0.6
6	-0.8	16	-0.6	26	-1.0	36	-0.9
7	-0.1	**17**	**21.4**	27	0.6	37	1.0
8	**16.0**	18	0.8	28	2.2	38	0.6
9	0.6	19	1.5	29	-0.5	39	-1.7
10	0.6	20	0.1	30	0.6	40	-1.3
Open-label samples							
Water [a]	-0.5	Water	-1.3	Water	0.6	Water	-0.2
Ova. tr. [b]	8.1	Ova. tr.	9.0	Ova. tr.	19.5	Ova. Tr.	14.5
Ova. [c]	43.7	Ova.	37.2	Ova.	27.9	Ova.	20.2

Results are expressed as the number of standard deviations of background from mean background (see Methods section). Results corresponding to "emergent signal" are in bold characters in grey boxes.

[a] Negative control of water (no "transmission")

[b] Positive control: water "informed" with ovalbumin (Ova.) "transmitted" (tr.) through electronic device

[c] Positive control: ovalbumin at "classical" concentration (0.1 µmol/L).

After the second round of measurements, again a signal corresponding to one sample and only one emerged from background in each experiment. As indicated in Table 2, the four samples that were associated with signal for the second round were the same than for the first round despite interim blinding. This was an important result for Benveniste's team, since it strongly suggested that all series were successful.

Table 2. Results of the Benveniste's experiments of May 13th, 1993: second round of measurement after interim blinding by type-2 observers (in-house blinding).

Exp. #A (Exp. #1)		**Exp. #B** (Exp. #3)		**Exp. #C** (Exp. #4)		**Exp. #D** (Exp. #2)	
Label #	Result	Label #	Result	Label #	Result	Label #	Result
Blind samples: in each series, 9 "inactive" labels (water) and 1 "active" label (Ova. tr.)							
A (6) [a]	-	B (30)	1.8	D (32)	0.3	C (14)	1.6
E (8)	**25.1**	F (25)	0.0	H (31)	1.1	G (11)	1.6
O (3)	1.3	N (27)	0.0	J (35)	1.1	I (16)	0.4
Q (2)	-1.3	**P (21)**	**11.6**	M (38)	-0.5	K (13)	-0.5
U (4)	0.0	W (28)	0.0	S (39)	1.1	L (18)	0.0
V (7)	-1.3	AB (29)	-0.9	T (40)	-1.4	R (19)	-0.9
AA (1)	1.3	AG (26)	-1.8	Z (33)	-1.4	X (15)	-0.9
AD (9)	0.0	AH (22)	0.9	AE (36)	-0.5	Y (20)	-0.9
AF (5)	0.0	AI (24)	0.0	**AK (34)**	**11.7**	**AC (17)**	**4.1**
AM (10)	0.0	AJ (23)	0.0	AN (37)	0.3	AL (12)	-0.5
Open-label samples							
Water [b]	0.0	Water	2.7	Water	1.1	Water	0.0
Ova. tr. [c]	9.3	Ova. tr.	8.9	Ova. tr.	19.1	Ova. tr.	6.6
Ova. [d]	-	Ova.	20.6	Ova.	23.1	Ova.	7.4

Results are expressed as the number of standard deviations of background from mean background (see Methods section).
Results corresponding to "emergent signal" are in bold characters in grey boxes.
[a] Number between parentheses is label # from Table 1.
[b] Negative control of water (no "transmission")
[c] Positive control: water "informed" with ovalbumin (Ova.) "transmitted" (tr.) through electronic device
[d] Positive control: ovalbumin at "classical" concentration (0.1 µmol/L).

On May 19, all participants had a meeting at the same location as previously in Paris to assist to the unblinding of the experiments. Results were first presented and then envelopes were opened by the bailiff for unblinding. Labels that were "expected" to be associated with signal were revealed: #8, #18, #26 and #34. Therefore, experiments #1 and #4 were successes and experiments #2 and #3 missed the target.

These results were considered as illogical by Benveniste's team. Indeed, this was a half-success: two experiments had signal at the expected place; but why the target was missed in the two series of measurements despite coherent results after interim in-house blinding was baffling. Schiff calculated the probabilities of different scenarios supposing an experimental artifact (internal report). The first hypothesis was that the artifact was located in the measurement device (Langendorff preparation) supposing a discontinuous functioning in an all-or-nothing manner. The second hypothesis was that contamination of some tubes would be responsible of all-or-nothing effects. In both cases (random false positive results or random contamination), the probabilities were very low and these hypotheses were rejected. Schiff concluded that only trivial errors (such as label mistakes between transport of tubes after blinding and first measurement) could explain these weird results. No objective data however supported this conclusion. It is important to note that these hypothetical scenarios rested on the assumption that "something" was present in water samples. This is what could be named a "local" interpretation.

Benveniste concluded that the experimental devices needed to be improved and he continued his endless technical pursuit for the decisive experiment. Among other improvements, he developed what he named "digital biology" to reduce the possible contaminations or electromagnetic interferences. However, the spontaneous "jumps" of activity between "active" and "inactive" samples and other weirdness persisted (Beauvais 2007).

In the next parts of the text, we will describe these experiments using quantum-like probabilities.

The quantum-like formalism applied to Benveniste's experiments

Definitions

The purpose of the experiments performed by Benveniste was to assess the rate of concordant pairs, namely "inactive" samples (*IN*) with background noise ("↓") and "active" samples (*AC*) with signal ("↑"). In other words, we must quantify the correlation between "expected" results and observed results.

We define $P_I(A_{CP})$ as the probability for the cognitive state (named *A*) of the experimenter to be associated with concordant pairs (*CP*) according to *classical probabilities*; $P_{II}(A_{CP})$ is the same probability according to *quantum probabilities*. $P_I(A_{DP})$ and $P_{II}(A_{DP})$ are the respective P_I (classical) and P_{II} (quantum) probabilities for discordant pairs (*DP*).

We describe the experimental situation from the point of view of an external observer that knows the initial state of the system and does not perform any measurement / observation.

Open-label or type-2 blinding

The state vector of the cognitive state *A* of the experimenter is described in terms of the eigenvectors of the first observable (cognitive states *A* indexed with labels *IN* and *AC*):

$|\psi_A\rangle = a|A_{IN}\rangle + b|A_{AC}\rangle$ for each sample in each series.

The probabilities a^2 and b^2 associated with the states A_{IN} and A_{AC} are the proportions of samples with *IN* and *AC* labels, respectively.

We develop the eigenvectors of the first observable on the eigenvectors of the second observable (concordance of pairs). We postulate that the cognitive states *A* indexed with "labels" and the cognitive states *A* indexed with "concordance of pairs" are non-commutable observables:

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

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

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

$$|\psi_A\rangle = (a\,\mu_{11} + b\,\mu_{21})|A_{CP}\rangle + (a\,\mu_{12} + b\,\mu_{22})|A_{DP}\rangle$$

The probability of A_{CP} is the square of the probability amplitude associated with its state:

$$P_{II}(A_{CP}) = |a\,\mu_{11} + b\,\mu_{21}|^2$$

Type-1 blinding

If a type-1 observer has blinded the labels, the context of the experiment changes. In this case, one observable (labels) is measured /observed by the type-1 observer and not by the experimenter as above; this is formally equivalent to a which-path measurement in single-particle experiment. The cognitive state *A* cannot interfere with itself (there is no superposition of $|A_{IN}\rangle$ and $|A_{AC}\rangle$) and classical probabilities apply for calculation of the probability of concordant pairs (Figure 1):

$$P_I(A_{CP}) = P(A_{IN}) \times P(A_{CP}|A_{IN}) \; + \; P(A_{AC}) \times P(A_{CP}|A_{AC})$$

With $P(A_{CP}|A_{IN}) = \mu_{11}^2$ and $P(A_{CP}|A_{AC}) = \mu_{21}^2$, then: $P_I(A_{CP}) = a^2\,\mu_{11}^2 + b^2\,\mu_{21}^2$

Similarly, $P_I(A_{DP}) = a^2\,\mu_{12}^2 + b^2\,\mu_{22}^2$.

We note that, in the general case, the probability for *A* to be associated with concordant pairs is dependent on the experimental context (open-label/type-2 blinding vs. type-1 blinding) since we find $P_I(A_{CP}) \neq P_{II}(A_{CP})$. The difference is due to the interference term.

Simplification of the formalism equations

Since $\mu_{11}^2 + \mu_{12}^2 = 1$, $\mu_{21}^2 + \mu_{22}^2 = 1$ and $P_{II}(A_{CP}) + P_{II}(A_{DP}) = 1$, we can easily calculate that $\mu_{11}\mu_{21} = -\mu_{22}\mu_{12}$, $\mu_{11}^2 = \mu_{22}^2$ and $\mu_{12}^2 = \mu_{21}^2$.

Thus, we can write:

$$|A_{IN}\rangle = \mu_{11}|A_{CP}\rangle - \mu_{21}|A_{DP}\rangle$$

$$|A_{AC}\rangle = \mu_{21}|A_{CP}\rangle + \mu_{11}|A_{DP}\rangle$$

We note that the matrix for change of basis is a rotation matrix; counterclockwise rotation has been chosen for appropriate concordance (experimenter's choice) between labels (*IN*/*AC*) and biological outcomes (background/signal):

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

Therefore,

$$|\psi_A\rangle = (a\cos\theta + b\sin\theta)|A_{CP}\rangle + (b\cos\theta - a\sin\theta)|A_{DP}\rangle$$

The formulas of $P_{II}(A_{CP})$ and $P_I(A_{CP})$ become (Table 3 and Figure 1):

$$P_{II}(A_{CP}) = |a\cos\theta + b\sin\theta|^2$$

$P_I(A_{CP}) = a^2\cos^2\theta + b^2\sin^2\theta$ with $P_I(A_{CP}|A_{IN}) = \cos^2\theta$ and $P_I(A_{CP}|A_{AC}) = \sin^2\theta$

The formulas of $P_{II}(A_{DP})$ and $P_I(A_{DP})$ are similarly calculated:

$$P_{II}(A_{DP}) = |b\cos\theta - a\sin\theta|^2$$

$P_I(A_{DP}) = b^2\cos^2\theta + a\sin^2\theta$ with $P_I(A_{DP}|A_{IN}) = \sin^2\theta$ and $P_I(A_{DP}|A_{AC}) = \cos^2\theta$

In a previous paper, this model allowed describing Benveniste's experiments without any reference to "memory of water", "electronic transmission", "digital biology" or any other "local" explanation (Beauvais, 2013). Just supposing superposed states and non-commutable observables, the quantum-like model described the main characteristics of Benveniste's experiments: emergence of signal from background, different outcomes according to type-1 or type-2 blinding and apparent "jumps of activity" between samples. We remind briefly these issues using the quantum-like model.

Emergence of signal from background

If θ = 0, then the observables are commutable:

$$|A_{IN}\rangle = \cos\theta \times |A_{CP}\rangle - \sin\theta \times |A_{DP}\rangle = 1 \times |A_{CP}\rangle - 0 \times |A_{DP}\rangle = |A_{CP}\rangle$$

$$|A_{AC}\rangle = \sin\theta \times |A_{CP}\rangle + \cos\theta \times |A_{DP}\rangle = 0 \times |A_{CP}\rangle + 1 \times |A_{DP}\rangle = |A_{DP}\rangle$$

In this case, the two observables share their eigenvectors: $|A_{IN}\rangle = |A_{CP}\rangle$ and $|A_{AC}\rangle = |A_{DP}\rangle$. The observation of concordant pairs is always associated with label *IN* (i.e., *IN* always associated with "↓") and the observation of discordant pairs is always associated with label *AC* (i.e., *AC* always associated with "↓"). In other words, no signal is observed when the observables are commutable (θ = 0) since only background is associated with both *IN* and *AC* labels. Therefore, non-commutable observables are necessary for signal emergence. The signal must be one of the possible states of the system, even with a low probability. Thanks to entanglement, the probability of signal increases. In a previous article, we proposed that the relationship between different cognitive states (A_{IN} with $A_{\downarrow}$ and A_{AC} with $A_{\uparrow}$), which are summarized in θ value, results of associative processes related to cognition mechanisms (Beauvais, 2013).

Table 3. Summary of the quantum-like model describing Benveniste's experiments.

	Non-commutable observables (θ ≠ 0)		Commutable observables (θ = 0)
	With interference term (superposition)	Without interference term (no superposition)	
Presence of signal	Yes [a]	Yes [b]	No [c]
Concordance of labels and outcomes [d]	High [e]	Low	NA
Probability of concordant pairs: $P(A_{CP})$	$\lvert a\cos\theta + b\sin\theta\rvert^2$	$a^2\cos^2\theta + b^2\sin^2\theta$	a^2
Probability of discordant pairs: $P(A_{DP})$	$\lvert b\cos\theta - a\sin\theta\rvert^2$	$b^2\cos^2\theta + a^2\sin^2\theta$	b^2
Corresponding experimental situations	Open-label or blinding by type-2 observer	Blinding by type-1 observer	Unqualified or untrained experimenter

NA: not applicable

[a] $P_{II}(A_{\uparrow}) = a^2 \times P_{II}(A_{DP}) + b^2 \times P_{II}(A_{CP})$; a^2 is the proportion of "inactive" labels (*IN*) and b^2 is the proportion of "active" labels (*AC*)

[b] $P_I(A_{\uparrow}) = \sin^2\vartheta$

[c] Observables are commutable with $\cos\vartheta = 1$ and $\sin\vartheta = 0$; then $P(A_{\uparrow}) = 0$ and $P(A_{\downarrow}) = 1$ (only background is associated with *A*; there is no signal)

[d] Concordant pairs : A_{IN} associated with $A_{\downarrow}$ or A_{AC} associated with $A_{\uparrow}$

[e] For $\sin\vartheta = b$ (and consequently $\cos\vartheta = a$), the quantum interference is maximal with $P_{II}(A_{CP}) = 1$ and $P_{II}(A_{DP}) = 0$.

Outcomes after type-1 blinding or type-2 blinding

We note first that open-label experiments or experiment after blinding with type-2 observer are not formally different since experimenter *A* and type-2 observer *O* are on the same "branch" of the reality described by the state vector (Figure 1) (Beauvais 2013):

$$|\psi_{AO}\rangle = (a\cos\theta + b\sin\theta)|A_{CP}\rangle|O_{CP}\rangle$$
$$+(b\cos\theta - a\sin\theta)|A_{DP}\rangle|O_{CP}\rangle$$

With the above formulas, we calculate now the outcomes of experiments by supposing that the number of "inactive" samples (labels *IN*) and "active" samples (labels *AC*) are equal ($a^2 = 0.5$ and $b^2 = 0.5$); we suppose that quantum-like correlations are optimal ($\cos\theta = a$ and $\sin\theta = b$):

$$P_{II}(A_{CP}) = |a\cos\theta + b\sin\theta|^2 = 1$$

$$P_{II}(A_{DP}) = |b\cos\theta - a\sin\theta|^2 = 0$$

$$P_I(A_{CP}|A_{IN}) = \cos^2\theta = 0.5$$

$$P_I(A_{CP}|A_{AC}) = \sin^2\theta = 0.5$$

Therefore, after blinding with type-2 observer (or in open-label experiments), all samples with *IN* labels are associated with background and all samples with *AC* label are associated with signal. In contrast, after blinding with type-1 observer, $P_I(A_{CP}) = 0.5$ and $P_I(A_{DP}) = 0.5$. In other words, in type-1 blind setting, the proportion of samples with *AC* labels associated with signal decreases from 100% to 50% and the proportion of samples with *IN* labels associated with signal increases from 0% to 50%. Therefore, everything happens as if "biological activity" (signal) "jumped" from some samples with *AC* label to samples with *IN* label. These apparent "jumps" of activity between samples were precisely a blocking issue in the demonstrations aimed to provide a proof of concept on the reality of the biological effects related to "memory of water". Therefore, our quantum-like model easily describes these "disturbances" without supposing additional hypotheses involving "external" causes or experimental artifacts.

Numerical application

We are now able to apply these calculations to the historical series of Benveniste's experiments described in this article; in each series, one unique sample with "active" label had to be "guessed" out of ten (i.e., $a^2 = 0.9$ and $b^2 = 0.1$). With the open-label samples or after type-2 blinding, the probability of concordant pairs was maximal; therefore, for all experiments (including type-1 experiments), we take $\sin\theta = b$.

In experiments of May 13th 1993, two "successes" out of four (50%) were observed; the 95% confidence interval of this proportion is [0.068–0.932] (Clopper-Pearson confidence interval for a binomial parameter).

According to the formalism, after type-1 blinding, the probability for a sample (regardless label) to be associated with signal is random and is therefore $b^2 = 0.1$; among series of ten samples, the probability to draw a series with one and only one signal is 0.29 (binomial law). Therefore, the theoretical probability to "draw" the "good" sequence (a 10-sample series with signal at the same place as *AC* label) is 0.29 × 0.1 = 0.029; this value is excluded of the 95% confidence interval calculated above. However, we must consider that some parts of any blind experiment are nevertheless open-label: in the present case, one active sample and nine inactive samples in each series was defined by the protocol and was available information. Therefore, statistics must be applied on the subgroup of permutations of ten samples with one and only one signal. The theoretical probability for "success" (one unique signal at the expected place) is then 0.1 (and not 0.029 as above). This value is now included in the calculated 95% confidence interval.

More than accuracy of calculation, the important point is that, after type-1 blinding, probability for "success" is strongly decreased. Moreover, taking into account all information available to the experimenter allows better fitting with the quantum-like model.

Discussion

The "public demonstration" of Benveniste's experiments described in the present article was performed with a wealth of precautions rarely achieved in usual research. Many witnesses were involved and in-house blinding was superimposed to blinding by "outside" participants. It is important to emphasize again that a signal was found associated to four samples out of forty; this result was important and remains unexplained in the present knowledge of science. However, only two signals were at the "expected" place. Therefore, the demonstration was a "half-success"; totally convincing results were paradoxically not achieved although the test of in-house blinding was passed with complete success.

The main problem in the "memory of water" experiments is not so much the lack of explanation on the origin of these phenomena, but the absence of a *logical framework*. Indeed, faced with the results of Benveniste's experiments, there is an unavoidable dilemma if we interpret them in a classical frame. Indeed, if we assume – as Benveniste did – that "something" was present in samples with "active" labels (hypothesis of "memory of water"), we are then unable to explain why these experiments failed more frequently than expected after type-1 blinding (two out of four experiments in the data presented in this article). If we tempt to explain the "jumps of activity" as artifacts (random triggering of the measurement apparatus or random contamination), probability calculations do not support such hypothesis. Of course, we can also tempt to dismiss the hypothesis of "memory of water" and its avatars, but we are unable to explain the emergence of a signal from background and a bulk of coherent results (such as the significant correlations that persisted after type-2 blinding).

A third possibility is to change the logical framework and to use a generalized probability theory (that includes classical probability theory as a limit theory). In this later case, emergence of signal and presence/absence of correlations according to experimental context are simply described without additional *ad hoc* hypotheses. The passage from classical to quantum logic requires only non-null value for the parameter θ. The alternate way proposed by quantum-like formalism is obviously not intuitive. Nevertheless, if we accept an effort of abstraction, a couple of simple equations can give a formal framework to these poorly understood experiments and quantitative statistical modeling can be performed.

In this quantum-like framework, there is no paradox; "successes" and "failures" appear then as the two faces of the same coin. In the paradigmatic two-slit experiment of Young, observing "waves" (interference pattern on the screen) is not considered as a success whereas observing "particles" (no interference pattern after which-path measurement) is not considered as a failure. In the quantum-like model of Benveniste's experiments, we can decide to observe either "waves" (high rate of correlated pairs in open-label or type-2 blind settings) or "particles" (low rate of correlated pairs in type-1 blind setting) (Beauvais 2013). "Waves" and "particles" are two complementary aspects of the same quantum (or quantum-like) object. Table 4 summarizes the "successes" and "failures" of Benveniste's experiments according to the different experimental contexts.

Table 4. Contextuality in Benveniste's experiments: three different patterns of results are observed according to experimental context.

	Experimental context		
	Open-label or blinding by type-2 observer	Blinding by type-1 observer	Unqualified or untrained experimenter
Expected results [a]	↓↓↓↓↑↑↑↑	↓↓↓↓↑↑↑↑	↓↓↓↓↑↑↑↑
Observed results	↓↓↓↓↑↑↑↑	↓↓↑↑↓↑↓↑	↓↓↓↓↓↓↓↓
Probability of concordant pairs	1	1/2	1/2
Description of results	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	θ ≠ 0 with superposition of quantum states (interferences)	θ ≠ 0 without superposition of quantum states (no interferences)	θ = 0 (classical probabilities apply)

[a] Experiments with equal number numbers of "inactive" and "active" labels and with maximal quantum interferences ($a^2 = b^2 = 0.5$ and $\sin\theta = b$).

This quantum-like model is in the spirit of quantum cognition, an emerging research field that proposes to model cognitive mechanisms and information processing in human brain by using some notions from the formalism of quantum physics such as contextuality or entanglement. Using quantum-like probabilities allowed addressing problems that appeared paradoxical in a classical frame. These new tools have been applied to human memory, decision making, personality psychology, etc (see for example the special issue of *Journal of Mathematical Psychology* in 2009) (Bruza *et al.*, 2009).

Conclusions

The "paradoxical" results of a series of Benveniste's experiments performed in 1993, which were closely controlled and blinded by observers not belonging to Benveniste's team, were reassessed. Using a quantum-like model, the probabilities of the different outcomes were calculated according to experimental context and no logical paradox persisted. All the features of Benveniste's experiments were taken into account with this model, which did not involve the hypothesis of "memory of water" or any other "local" explanation.

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Author disclosure statement

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