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RESEARCH ARTICLE

Description of Benveniste's Experiments Using Quantum-Like Probabilities

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Abstract—Benveniste's experiments (also known as "memory of water" or "digital biology" experiments) remain unresolved. In some research areas, which have in common the description of cognition mechanisms and information processing, quantum-like statistical models have been proposed to address problems that were "paradoxical" in a classical frame. Therefore, the outcomes of the cognitive state of the experimenter were calculated for a series of Benveniste's experiments using a quantum-like statistical model (i.e. a model inspired by quantum physics and taking into consideration superposition of quantum states, non-commutable observables, and contextuality). Not only were the probabilities of "success" and "failure" of the experiments modeled according to their context, but the emergence of a signal from background was also taken into account. For the first time, a formal framework devoid of any reference to "memory of water" or "digital biology" describes all the characteristics of these disputed results. In particular, the difficulties encountered by Benveniste (reproducibility of the experiments, disturbances after blinding) are simply explained in this model without additional ad hoc hypotheses. It is thus proposed that we see Benveniste's experiments as the result of quantum-like probability interferences of cognitive states.

Keywords: Memory of water—quantum cognition—quantum-like probabilities—entanglement—experimenter effect—contextuality—nonlocal interactions

"There is no objective explanation of these observations."
John Maddox (1988a)

The Everlasting Story of the "Memory of Water"

The above quote of John Maddox, a former Editor of the journal *Nature*, is from the Editorial of the 30 June 1988 journal issue containing an article that shortly after became famous as the starting point of the "memory of water" controversy (Davenas et al. 1988). Actually, the story of the "memory of water" began in the early 1980s. Due to industrial contracts with two homeopathic firms, scientists from Unit 200 of INSERM (the French biomedical and public health research institution), led by Jacques Benveniste, assessed with biological models the effects of solutions obtained according to the principles of homeopathy. After serial ten-fold or hundred-fold dilutions, the probability of finding a biologically active molecule becomes close to zero in high dilutions. However, in some experiments with white blood cells containing polymorphonuclear basophils, a variation in basophil counts was observed repeatedly, thus suggesting that high dilutions had an effect on cells. Initially skeptical about homeopathy and its principles from another age, Benveniste began to revise his opinion.

After several years of extensive experimental work, Benveniste convinced himself that trivial explanations such as contamination could not explain these odd results, and he decided to bring them to the attention of the scientific community. A long negotiation then began with the journal *Nature* in June 1986. Successive versions of an article were written, including new experiments requested by the reviewers. In its last version, the manuscript described experiments in which highly diluted immunoglobulins decreased the counts of basophils stained by a classical method and counted under a microscope. Meanwhile, two articles on the high dilutions were published by Benveniste's team in other scientific journals (Davenas, Poitevin, & Benveniste 1987, Poitevin, Davenas, & Benveniste 1988). However, *Nature*'s Editor and reviewers of the manuscript continued to express their skepticism regarding the idea of a "biological effect without molecules."

Unexpectedly, at the end of May 1988, John Maddox, the Editor of *Nature*, decided to publish the article for the next month provided that Benveniste accept an investigation into his laboratory (Davenas et al. 1988). Strangely, this investigation would take place after publication of the article. Details on the survey performed in Benveniste's laboratory and on the whole story of the "memory of water" can be found elsewhere (de Pracontal 1990, Alfonsi 1992, Kaufmann 1994, Schiff 1998, Benveniste 2005, Beauvais 2007).

Maddox himself was a former theoretical physicist, and none of the investigators was a specialist in the research done in Benveniste's laboratory or more generally had a background in biology. Indeed, the trio of investigators formed by Maddox had an a priori: They were certain that Benveniste acted in good faith, but that someone was playing tricks without his knowledge. The other investigators were Walter Stewart, an American chemist disputed in academic circles for his investigations on cases of scientific fraud, and the stage magician James Randi, star of many entertainment shows in the United States (and also debunker of pseudo-science). The role of Randi (as he himself said later) was to inconspicuously monitor the members of Benveniste's laboratory (Beauvais 2007). On the third day of the inquiry, Randi had to go to the evidence: He did not observe any suspicious behavior. In addition, the experiments performed during these three days (including one blind experiment) confirmed the results of the published article.

Consequently, for the next two days, the investigators decided to organize a new series of experiments, and they involved themselves in the experiments that they were supposed to control: Stewart not only blinded the experimental samples but also pipetted the cell suspensions containing stained basophils, which were then counted under a microscope by two members of Benveniste's team. Despite repeated remarks on the poor quality of some cell samples, the investigators insisted that these counts be completed "for statistics" (Beauvais 2007). The results obtained with these latter experiments did not support the alleged effect of high dilutions. A few weeks later *Nature* published a report concluding that the results claimed in the article were a "delusion" and were the consequence of both observer bias and ignorance of statistical laws (Maddox 1988b, Maddox, Randi, & Stewart 1988). For many people, the report from *Nature* was the last word on the story of the "memory of water." In the years following this harmful episode, Benveniste continued his research in this disputed area with a reduced team, using other biological systems and developing new devices as described in the next section.

From High Dilutions to "Digital Biology"

After the episode in 1988, some authors, including Benveniste's team, attempted to reproduce the results of the *Nature* paper and published negative (Ovelgonne, Bol, Hop, & van Wijk 1992), ambiguous (Hirst, Hayes, Burridge, Pearce, & Foreman 1993), or positive results (Benveniste, Davenas, Ducot, Cornillet, Poitevin, & Spira 1991, Belon, Cumps, Ennis, Mannaioni, Sainte-Laudy, Roberfroid, & Wiegant 1999, Brown & Ennis 2001); see also the review in Ennis (2010). Meanwhile, Benveniste's team explored other biological models that were hoped to be more persuasive than the basophil model. The most notable results were obtained first with the isolated heart model and some years later with an in vitro coagulation model.

The results with the isolated heart model (using Langendorff apparatus) are very helpful to understand Benveniste's issues with "reproducibility." Less famous than the basophil experiments, these results nevertheless were published as abstracts and posters at international congresses from 1991 to 1999. Moreover, during the period 1992–1997, Benveniste and his team regularly organized “public demonstrations” where scientists were invited to blind experimental samples or files to convince themselves of the reality of the alleged phenomena. These demonstrations were carefully designed with a written protocol, and, after completion, the participants received a detailed report with raw data. Therefore, valuable data that could be analyzed were available.

All these experiments have been described in detail elsewhere (Beauvais 2007). In the present article, biological systems will be considered simply as black boxes with inputs and outputs. Indeed, the aim of the article is to describe the logical aspects and the underlying mathematical structures of these experiments.

Briefly, the Langendorff apparatus allows for the maintaining of a rodent heart while different parameters (beat rate, coronary flow, muscular tension) are recorded continuously; the variations related to the addition of pharmacological agents are studied. Benveniste’s team focused on the flow rate of the coronary arteries, which initially appeared to respond significantly to high dilutions. After each run, the intensity of flow change allowed discriminating “active” samples (10% or more of maximal variation of basal flow) from “inactive” samples (below 10% variation, i.e. not different from background noise).

The advantage of the isolated heart model (Langendorff apparatus) over the basophil model was the possibility of showing in real time the biological effect of high dilutions to scientists visiting the laboratory. Indeed, the changes of baseline flow (20%–30%) were easily seen in the series of tubes that collected (one tube per minute) the physiological solution from coronary circulation. However, the recurrent criticism of contamination of samples containing high dilutions was not discarded.

In 1992, Benveniste alleged that a low-frequency amplifier allowed the “electromagnetic transfer” of the “activity” from a biologically active solution (inserted in an electric coil) to naïve water. Interestingly, this device could use water in a sealed vial. Therefore, explaining the observed effects by contamination was less relevant. New “progress” was accomplished in 1996 when Benveniste used a personal computer with a sound card to “record” and to store as a digital file the “activity” of a solution placed into the electric coil. The “replay” was performed in naïve water put inside an electric coil wired at the output of the sound card. Positive results comparable with those observed with high dilutions were obtained.

For Benveniste, this was a new era for biology and medicine, and he coined the expression “digital biology.” These new experiments, however, encountered more skepticism (if possible) than the previous high-dilution experiments. Further progress was achieved by positioning the electric coil (which diffused the "electromagnetic information") directly around the column of physiological liquid that perfused the isolated heart. With this modification, the experiment could be piloted directly from the computer, without an intermediary water sample. The electromagnetic field of the electric coil became the unique link between the computer and the apparatus. The contamination argument seemed to be definitively discarded.

Despite these successive improvements, however, an issue literally poisoned the demonstrations aimed to provide "proof" of the reality of the "memory of water." As explained in the next section, this issue was more particularly evidenced after blinding of the experimental samples during the "public demonstrations."

Contextuality as the Central Issue: In-House Blinding vs. Blinding by Outside Observer

All participants in these experiments, including Benveniste himself, acknowledged that besides the very impressive, convincing, and "clean" experiments, other experiments cast doubt on the reality of the alleged phenomena (Benveniste 2005, Thomas 2007, Beauvais 2008, Poitevin 2008). This was particularly evident after blinding of samples—not for in-house blinding, which led to statistically significant correlations, but for blinding during public demonstrations with "outside" observers. Even the early experiments with basophils were not free from blinding disturbances. Thus, the usual large and regular waves of biological activity related to high dilutions and routinely obtained by some teams became unnoticeable during large-scale blind experiments (Benveniste, Davenas, Ducot, Cornillet, Poitevin, & Spira 1991, Belon, Cumps, Ennis, Mannaioni, Sainte-Laudy, Roberfroid, & Wiegant 1999). With the Langendorff apparatus and with the coagulation model, the blinding issue became a central concern. Moreover, a phenomenon that was already suggested by basophil experiments became obvious: "Better" results were obtained with some "gifted" experimenters (Beauvais 2007).

Initially, it was proposed that uncontrolled parameters in the environment, such as electromagnetic waves or quality of water, were probably responsible for these discrepancies. Indeed, detecting a weak signal amid a noisy background could be the reason for poor results. In retrospect, however, it now appears that the difficulties of reproducibility were unusual. This was particularly obvious during the "public demonstrations" that Benveniste organized to convince other scientists that the phenomenon he described was not imaginary. These demonstrations were usually performed in two steps. First, negative and positive samples were produced (e.g., high dilutions, samples of "informed water" or digital files) and were blinded (the initial label was replaced by a code) by an observer not belonging to Benveniste's team. It is important to emphasize that some negative and positive samples were kept open. Second, the samples were brought back to Benveniste's laboratory where the team tested all samples (blind and open-label) on the biological system. Note also that the samples kept open were nevertheless frequently blinded by a member of the team before being given to the experimenter dedicated to the testing. When all measurements were made, the results of the experiments were sent to the outside scientists who assessed the concordance of observed results with expected results.

In these demonstrations, the mean biological effects after repeated experiments (on several biological preparations) were usually clear-cut, and active samples were easily distinguished from inactive samples. However, the results of blind samples were almost always at random and did not fit the expected results: Some samples with "control" labels were clearly active on the biological system whereas some samples with "active" labels had no significant effect. Table 1 describes an example of an experiment involving a participating outside observer.

In a first approach, it could be hypothesized that active samples had been "erased" by an external disturbing influence. However, it is more difficult to explain the mechanisms that transformed inactive samples into specific "active samples." And even if we assume the hypothesis of a "noisy" environment, how do we explain the open samples (positive and negative samples), which were prepared, transported, and tested at the same time and in the same conditions as blind samples, giving systematically "correct" results (i.e. expected correlations between supposed causes and biological outcomes)?

After each failure of public demonstration, Benveniste's team improved the experimental setting, and either open-label or in-house blind experiments confirmed that "good" results were obtained with the new device or with the modified experimental design. Nonetheless, despite the successive technical improvements of the different experimental systems, the weirdness persisted.

To avoid any interference with the environment (including the experimenter), Benveniste's team constructed an automatic robot analyzer based on a new promising biological model, the coagulation system. After filling it with consumables, the whole process was automatic, from the random choice of files (to be "played" to naïve water) to the printing of the results. At this time, Benveniste's "digital biology" attracted the attention of the Defense Advanced Research Projects Agency (DARPA), of the US Department of Defense responsible for the development of new technology. In 2001, a multidisciplinary team was commissioned by DARPA to study these

TABLE 1
Example of Random Correlations between Labels and Biological Outcomes in an Experiment Involving a Participating Outside Observer (Type-1 Observer)

Experimental Samples [a]	Biological Outcome	Unblinding of Blind Files	Expected Biological Outcome
Blind files			
File #1	Signal	*IN* #2	No
File #2	Background	*IN* #3	Yes
File #3	Signal	*AC* #3	Yes
File #4	Background	*IN* #1	Yes
File #5	Signal	*IN* #1	No
File #6	Signal	*IN* #3	No
File #7	Background	*AC* #1	No
File #8	Background	*AC* #1	No
File #9	Signal	*AC* #1	Yes
File #10	Signal	*AC* #2	Yes
Open files [b]			
IN #A	Background	-	Yes
IN #B	Background	-	Yes
AC #C	Signal	-	Yes
AC #D	Signal	-	Yes
"Classical" positive control	Signal	-	Yes

[a] For this experiment of "digital biology" (an avatar of "memory of water") performed in September 1997, 10 blind files and 4 open-label files of digital recordings of different samples were produced in a foreign laboratory and then blinded by the participating outside observer (type-1 observer) (Beauvais 2007, 2012). Five "active" (*AC*) labels and five "inactive" (*IN*) labels were blinded; two *IN* and two *AC* labels were kept open. The 4 open-label files were nevertheless in-house blinded before measurements. In Benveniste's laboratory, experiments were performed with each file and the associated biological outcome was recorded: either "background" ("↓") (i.e. outcome below cutoff at 10) or signal ("↑") (i.e. outcome above cutoff). The biological device was a Langendorff apparatus, which allowed measuring the variations of an isolated rodent heart. After completion of the measurements in Benveniste's laboratory, the results were sent to the participating outside observer who assessed the number of concordant pairs (*IN* with↓ and *AC* with↑) and discordant pairs (*IN* with ↑ and *AC* with ↓). This experiment is representative of many other "public" experiments detailed elsewhere (Beauvais 2007). Despite repetitive measurements for each file and coherence of the results for each file, blind files were associated randomly with "signal" (biological outcome >10) and "background" (biological outcome <10). In contrast, expected results were obtained with the in-house blind files. Even though such an experiment dismisses the hypothesis of "memory of water" or "digital biology," the presence of signal remained puzzling.

[b] Labels kept open by the participating outside observer (type-1 observer), but nevertheless in-house blinded (type-2 observer) before measurement.

TABLE 2
Concordant and Discordant Pairs in Different Experimental Conditions in Benveniste's Experiments with the Langendorff Apparatus

Experimental Situations		Number of Experimental Points	Outcome ↓ (Background)	Outcome ↑ (Signal)	P-Value [a]
Open-label experiments [b]					
	Label *IN*	N=372	**93% (CP)**	7% (DP)	$<1 \times 10^{-83}$
	Label *AC*	N=202	11% (DP)	**89% (CP)**	
Experiments blinded by type-2 observer					
	Label *IN*	N=118	**91% (CP)**	9% (DP)	$<1 \times 10^{-26}$
	Label *AC*	N=86	15% (DP)	**85% (CP)**	
Experiments blinded by type-1 observer					
	Label *IN*	N=54	57% (CP)	43% (DP)	0.25
	Label *AC*	N=54	44% (DP)	56% (CP)	

Summary of results presented in Beauvais (2012).
Bold type numbers are statistically significant concordant pairs.
CP, concordant pairs; DP, discordant pairs; *IN*, "inactive" labels; *AC*, "active" labels.
[a] Chi-square test.
[b] See also Figure 1.

potentially interesting experiments. After completion of the experiments performed in part with the help of Benveniste's team, the experts concluded they could not confirm that an effect related to "digital biology" was involved, while they did confirm the importance of the experimenter for the outcome. Indeed, they suggested that unknown "experimenter effects" could explain these unusual results, but that a theoretical framework was necessary to understand them. They added: "Without such a framework, continued research on this approach to digital biology would be at worst an endless pursuit without likely conclusion, or at best premature" (Jonas et al. 2006).

The Different Experimental Situations with or without Correlations

In our previous reappraisal of Benveniste's experiments, we defined three experimental situations (open-label, in-house blinding, and blinding by a participating outside observer) that led to "success" or "failure" (Beauvais 2012). Table 2 summarizes the results of this reappraisal.

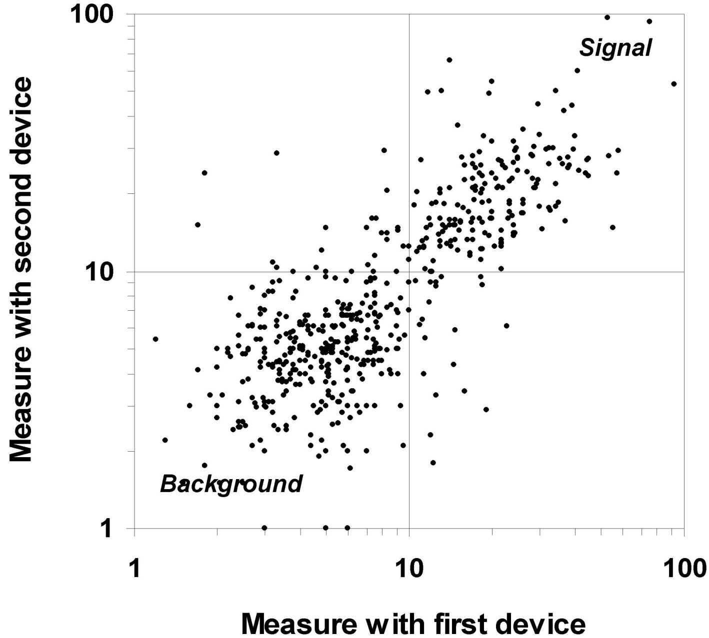

Figure 1. Correlations of measurements on two parallel devices.
These plots (574 pairs of measures) summarize a systematic analysis of large-scale experiments performed from 1992 to 1996 by Benveniste's team (Beauvais 2012). The limit between background and signal was set at 10. For these experiments each measurement was performed in duplicate on two devices (this was done to guarantee results). Note that the probability of obtaining a signal (resp. background) for a second measure was high if a signal (resp. background) was obtained for the first measure. Even if "memory of water" is dismissed, we have to explain 1) how a signal emerged and 2) how a correlation was obtained.

The open-label experiments led to "correct" correlations between labels ("inactive" or "active") and device outcomes (background or signal). For open-label experiments, background was observed in 93% of the cases with "inactive" label, and signal was observed in 89% of the cases with "active" label (Table 2 and Figure 1).

In-house blind experiments, i.e. blinding performed by an "inside" observer, also led to significant correlation. The "inside" observer will now be named *type-2 observer*. For experiments blinded by a type-2 observer, background was observed in 91% of the cases with "inactive" label, and signal was observed in 85% of "active" label cases.

The difference of effect between "inactive" and "active" samples was statistically very significant in these two experimental situations (no blinding, or blinding by type-2 observer) (Table 2). Therefore, these experiments were usually considered as successes; it was as if a causal relationship existed between the alleged causes and the outcomes.

The crucial issue was observed when the blinding of the samples was performed by a participating outside observer (e.g., the public demonstration described in Table 1). The participating outside observer will now be named *type-1 observer*. When all measurements had been carried out by the experimenter on the Langendorff apparatus, the results were sent by Benveniste's team to the type-1 observer who held the code of the blinded samples and who compared the two series (biological outcomes and labels of the corresponding samples). In this situation, the biological outcomes (signal or background) were distributed at random according to the initial label ("inactive" or "active" samples) (Table 2). For these experiments, background was observed in 57% of "inactive" labels and signal in 56% of "active" labels. These experiments were thus usually considered as failures; the alleged relationship between labels and outcomes appeared broken.

In summary, correlations were evidenced either in open-label experiments or in experiments blinded by a type-2 observer; in sharp contrast, in blind experiments involving a type-1 observer, the correlations vanished. Nevertheless, in all cases, a signal emerged from background.

Benveniste's Experiments Free of the Memory-of-Water Hypothesis

In our previous article, we analyzed the experiments with the Langendorff system, and we concluded that they did not support the hypothesis of the "memory of water" (Beauvais 2012). We did not reach this conclusion because the known physical properties of water did not support memory in this liquid as argued by some authors (Teixeira 2007), but simply because a subset of results from Benveniste's experiments themselves dismissed this hypothesis.

In a first step, we analyzed a set of experiments obtained by Benveniste's team in the 1990s. We quantified the relationship between "expected" effects (i.e. labels of the tested samples) and apparatus outcomes, and we defined the experimental conditions to observe significant correlations. We observed that the results were amazingly identical despite the various "stimuli" thought to induce a signal (high dilutions, direct "electromagnetic transfer" from a biological sample, "electromagnetic transfer" from a stored file, and transfer of the "biological activity" of homeopathic granules to water). Moreover, a diversity of electronic devices was used, particularly electric coils with various technical characteristics. In other words, the dynamic range of the "measure apparatus" used to evidence "informed water" seemed to be exceptionally large for the "input" but was nevertheless associated with a monotonous response for the "output." What appeared to be the "cause" of the outcome was the "label" of the sample ("inactive" or "active") and not the specific physical process that had supposedly "informed" the water.

We concluded that the results of these experiments were related to experimenter-dependent correlations, which did not support the initial "memory of water" hypothesis. Nevertheless, the fact that a signal emerged from background noise remained puzzling.

Therefore, in a second step, we described Benveniste's experiments according to the relational interpretation of quantum physics (Beauvais 2012). This interpretation allowed for the elaboration of a first quantum approach of Benveniste's experiments: The emergence of a signal from background noise was described by the entanglement of the experimenter with the observed system.

Although our hypothesis did not definitely dismiss the possibility of "memory of water," the experimenter-dependent entanglement was an attractive alternative interpretation of Benveniste's experiments. However, quick decoherence of any macroscopic system is an obstacle to the general acceptance of such an interpretation.

In the next section, we propose a parallel between Benveniste's experiments and classical interference experiments. This parallel allows for a description of a more complete formalism of Benveniste's experiments.

The Single-Particle Interference Experiment

Single-particle quantum interference is one of the most important phenomena that illustrate the superposition principle and highlight the major difference between quantum and classical physics. The two-slit interferometer of Young can be used for one-particle interference experiments, but the Mach-Zehnder device has the advantage of ending only with two detectors (D1 and D2) and not with a screen (i.e. a great number of detectors) (Scarani & Suarez 1998). Figure 2 (upper drawing) depicts the Mach-Zehnder device. Light is emitted from a monochromatic light source: 50% of the light is transmitted by the beam splitter (BS1) in path T and 50% is reflected in path R. In BS2, the two beams are combined and 50% of the light is transmitted by the beam splitter in detector D1 and 50% in detector D2.

If light is considered a wave, it can be calculated that waves from the two paths are constructive when they arrive in D1 and destructive in D2. Therefore, clicks after light detection are heard only in D1. This is indeed what experiment shows, and it is an argument for the wavy nature of light.

On the contrary, if we consider light a collection of small balls (photons), they should randomly go into path T or R (with a probability of

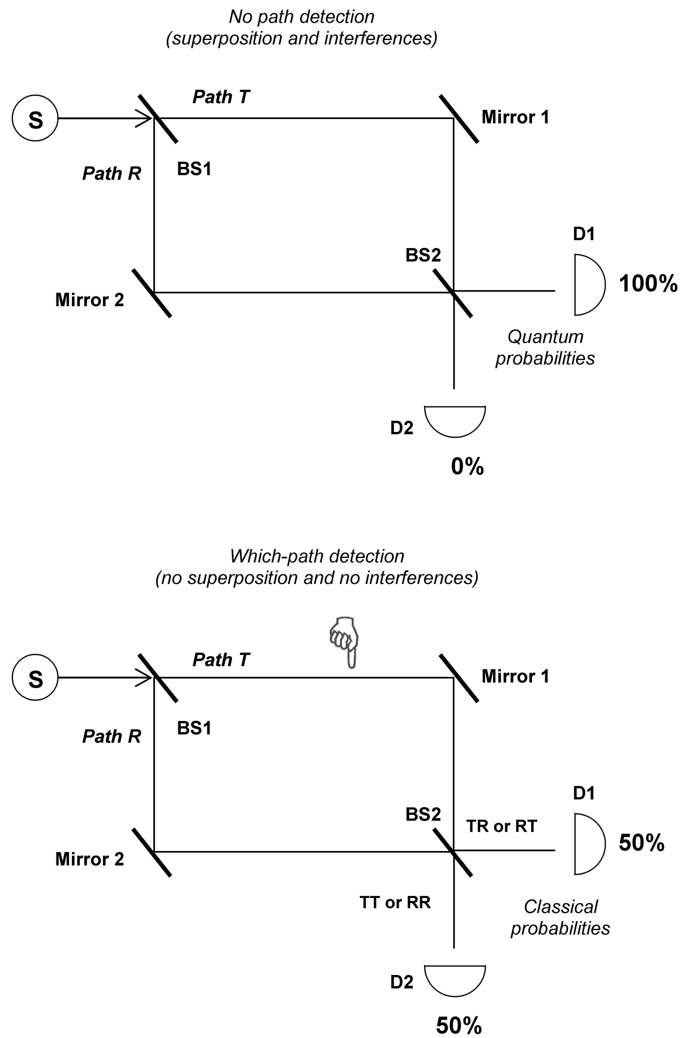

Figure 2. Single-particle interference in a Mach-Zehnder interferometer with or without which-path measurement.

0.5 for each path) and then in BS2 they go into D1 or D2 randomly (again with a probability of 0.5 for D1 or D2). As a consequence D1 should click in 50% of cases and D2 in 50% of cases.

However, if photons are emitted one by one (by decreasing light intensity), the interference pattern persists (100% of clicks in D1). This is a quite counterintuitive result. Even more astonishingly, this unexpected (nonclassical) behavior disappears if the initial path (T or R) is detected by

TABLE 3
Parallelism between Single-Photon Interference Experiment with Mach-Zehnder Interferometer and Benveniste's Experiments

	Interferometer Experiment	**Benveniste's Experiments** [a]
First path	Path T	A_{IN}
λ_1^2	Prob (path T)	Prob (A_{IN})
Second path	Path R	A_{AC}
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]

$\downarrow$, background; $\uparrow$, signal.

A, cognitive state of the experimenter; IN, "inactive" labels; AC, "active" labels; 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 $A_{\downarrow}$.

any means: Then either D1 or D2 clicks, each in 50% of cases (classical probabilities apply) (Figure 2, lower drawing).

We made a parallel between Benveniste's experiments and the one-particle interference experiment, which appeared to have isomorphic underlying mathematical structures. Indeed, according to the context of the experiment, either only concordant pairs (equivalent to detection in D1) or both concordant/discordant pairs (i.e. equivalent to random detection by D1 and D2) were obtained (Figure 3 and Table 3).

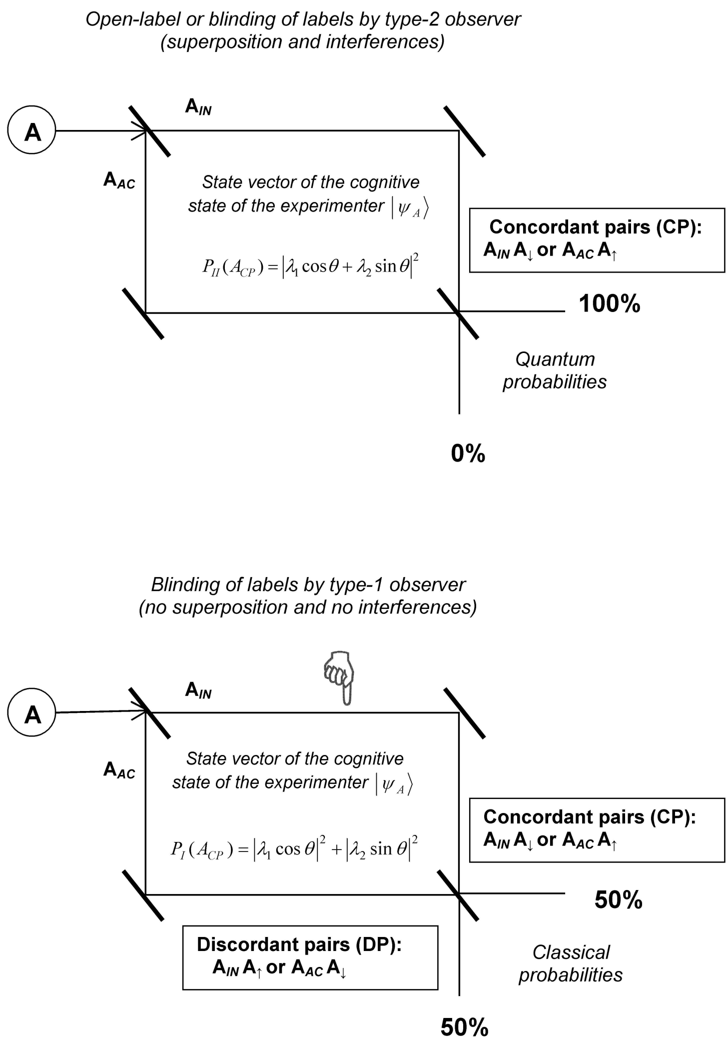

Figure 3. Interpretation of Benveniste's experiments as a consequence of quantum-like interferences (for an experiment with an optimal interference term).

If the sample labels are not blinded or blinded by a type-2 observer, then the cognitive state of A (described by the state vector $|\psi_A\rangle$) is able to interfere with itself (as a single particle interferes with itself) and the rate of correlated pairs is high. If a type-1 observer blinds the sample labels, then the cognitive state of A cannot interfere with itself (there is no superposition) and the rate of correlated pairs is not better than random. In both cases, the signal is observed.

The Quantum Formalism in Brief

The objective of our study is to describe the possible outcomes of the cognitive states of an experimenter in different contexts. Mathematically, a state is represented by a vector in a Hilbert space. Using the quantum formalism, the cognitive state of the experimenter is represented by the state vector $| \psi_A \rangle$, which summarizes all the information on the quantum system.

A key ingredient in the quantum formalism is the principle of superposition. According to this principle, the linear combination of any set of states is itself a possible state. Thus, if $| A_1 \rangle$ and $| A_2 \rangle$ are two possible states of the system, then $| \psi_A \rangle = \lambda_1 | A_1 \rangle + \lambda_2 | A_2 \rangle$ also is a possible state of A (with λ_1 and λ_2 real or complex numbers). This is due to the linearity of the Schrödinger equation: Any linear combination of solutions to a particular equation will also be a solution to it.

Therefore, a physical system exists in all its particular and theoretically possible states. When it is "measured," only one state among the possible states is observed by the experimenter. The quantum formalism states that the probability to observe $| A_1 \rangle$ is the square of the probability amplitude λ_1 associated with this state.

An example of superposition that is directly observable is the interference pattern observed in the two-slit experiment. Interferences are the hallmark of superposed states and are the heart of quantum physics. Quantum interference is the consequence of non-commutable observables, as described in Figure 4.

In a single-photon interference experiment, if one can (even in principle) distinguish the path each photon has taken, then interferences vanish and classical probabilities apply. In the setup depicted in Figure 2, the initial path cannot be distinguished in the upper drawing, and interferences occur; in the lower drawing, paths are distinguished by measurement, and consequently classical probabilities apply (without the interference term).

The formalism of single-particle interference has been widely described and we propose to use it to describe Benveniste's experiments (Table 3 and Figure 3).

Type-1 Observer (Wigner) and Type-2 Observer (Wigner's Friend)

The distinction that we made between the type-1 ("outside") observer and the type-2 ("inside") observer is reminiscent of the thought experiment proposed by the physicist Eugene Wigner in the early 1960s and known as "Wigner's Friend" (D'Espagnat 2005). In this thought experiment, Wigner's friend performs a measurement on a quantum system in a superposed state

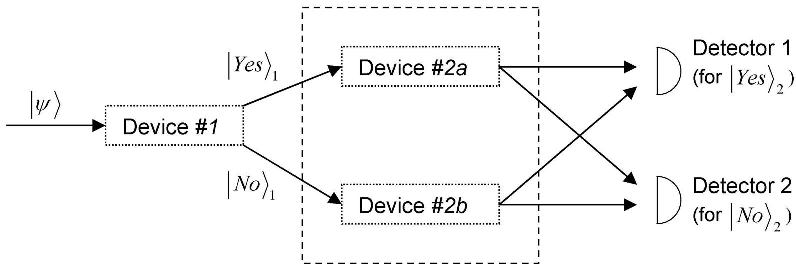

Figure 4. Design of an experiment exhibiting quantum-like interferences. The quantum object is measured through two successive devices named #1 and #2. First, device #1 splits the state $|\psi\rangle$ into two new orthogonal states, denoted $|Yes\rangle_1$ and $|No\rangle_1$. These two states are then fed into two identical devices, #2a and #2b, and each device splits the states into two new orthogonal states, $|Yes\rangle_2$ and $|No\rangle_2$, such that they are recombined at detectors D1 and D2. It is assumed that the observables associated with the first device do not commute with observables associated with the second device. If the events inside the box are not measured, the system is in a superposition of states, which is not equal to either one. The consequence of superposition is that quantum probabilities to observe $|Yes\rangle_2$ (or $|No\rangle_2$) in detector 1 (D1) (with respect to detector 2 (D2)) are different compared with classic probability due to the interference term.

(namely, a Schrödinger's cat); a second experimenter (Wigner) remains outside the laboratory. Inside the laboratory, from the perspective of Wigner's friend, the cat is either dead *or* alive at the end of the experiment ("collapse" of the quantum wave from a superposed state). Outside the laboratory, from the perspective of Wigner, the quantum system and Wigner's friend are described in a superposed state with the two possible outcomes (cat dead *and* cat alive). If Wigner enters the laboratory, he sees the cat (and his friend in the corresponding state) either dead *or* alive ("collapse" of the quantum wave from a superposed state). Therefore, there are two valid—but different—descriptions of the same quantum state with apparent "collapse" of the quantum wave at different times: This is the so-called "measurement problem." For Wigner (the physicist), this discrepancy between the inside and outside perspectives illustrated the role of consciousness, which seems to play a role by "ending" the chain of quantum measurements.

We can make a parallel with on the one hand the type-1 and type-2 observers in Benveniste's experiments, and on the other hand Wigner and his friend, respectively. The type-2 observer (i.e. Wigner's friend) belongs to the same "branch of reality" as Benveniste's experimenter (i.e. Schrödinger's cat) whereas the type-1 observer (i.e. Wigner) considers that the type-2 observer (or the experimenter) is in a superposed state until he interacts with him.

The Quantum-Like Formalism Applied to Benveniste's Experiments

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 probability of A being associated with concordant pairs 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 observer who knows the initial state of the system and does not perform any measurement/observation on it. The state vector of the cognitive state of the experimenter is described in terms of the eigenvectors of the first observable (cognitive states of A indexed with labels *IN* and *AC*):

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

(λ_1^2 and λ_2^2 are the probabilities associated with the states A_{IN} and A_{AC}, 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 of A indexed with "labels" and the cognitive states of 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 $| A_{DP} \rangle$:

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

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

$$P_{II} (A_{CP}) = | \lambda_1\mu_{11} + \lambda_2\mu_{21} |^2$$

$$P_{II} (A_{CP}) = \lambda_1^2 \mu_{11}^2 + \lambda_2^2 \mu_{21}^2 + 2 \lambda_1\lambda_2\mu_{11}\mu_{21}$$

Similarly, $P_{II} (A_{DP})$ is calculated:

$$P_{II} (A_{DP}) = \lambda_1^2 \mu_{12}^2 + \lambda_2^2 \mu_{22}^2 + 2 \lambda_1\lambda_2\mu_{12}\mu_{22}$$

If a type-1 observer has blinded the labels, the context of the experiment changes. This is formally equivalent to a which-path measurement in single-particle interference. Indeed, we have to take into account the path information; therefore, classical conditional probabilities that include path data must be used for calculation of the probability for A to be associated with concordant pairs:

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

with $P(A_{CP} | A_{IN}) = \mu_{11}^2$ and $P(A_{CP} | A_{AC}) = \mu_{21}^2$

$$P_I(A_{CP}) = \lambda_1^2 \mu_{11}^2 + \lambda_2^2 \mu_{21}^2$$

And similarly, $P_I(A_{DP}) = \lambda_1^2 \mu_{12}^2 + \lambda_2^2 \mu_{22}^2$.

We conclude that $P_{II}(A_{CP}) \neq P_I(A_{CP})$ in the general case. In the squaring of the sum, we have obtained an additional term $2 \lambda_1\lambda_2\mu_{11}\mu_{21}$, which is typical of all quantum mechanical interference effects.

Numerical Application with Data from Benveniste's Experiments

Useful Mathematical Formulas

We search the μ values for $P_{II}(A_{CP})=|\lambda_1\mu_{11}+\lambda_2\mu_{21}|^2$ and $P_{II}(A_{DP}) = |\lambda_1\mu_{12}+\lambda_2\mu_{22}|^2$. 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 $\mu_{12}^2 = \mu_{21}^2$.
Then, we can write:

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

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

We note that the matrix for change of basis is a rotation matrix:

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

Therefore,

$$|\,\psi_A\,\rangle \;=\; (\lambda_1\mu_{11} + \lambda_2\mu_{12})\,|\,A_{CP}\,\rangle \;+\; (\lambda_2\mu_{11} - \lambda_1\mu_{12})\,|\,A_{DP}\,\rangle, \quad \text{or}$$

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

The formulas of P_{II} and P_I become:

$$P_{II}(A_{CP}) \;=\; |\lambda_1\cos\theta + \lambda_2\sin\theta|^2 \;= \lambda_1^2\cos^2\theta + \lambda_2^2\sin^2\theta \;+\; 2\lambda_1\lambda_2\cos\theta\sin\theta$$

$$P_{II}(A_{DP}) \;=\; |\lambda_2\cos\theta - \lambda_1\sin\theta|^2 \;= \lambda_2^2\cos^2\theta + \lambda_1^2\sin^2\theta \;-\; 2\lambda_1\lambda_2\cos\theta\sin\theta$$

$$P_I(A_{CP}) \;=\; \lambda_1^2\cos^2\theta + \lambda_2^2\sin^2\theta$$

$$P_I(A_{DP}) \;=\; \lambda_2^2\cos^2\theta + \lambda_1^2\sin^2\theta$$

In a previous article, we presented Benveniste's experiments in different experimental situations. These results, summarized in Table 1, allow for calculating the parameters of the model in different experimental situations, as detailed in the next subsections.

Open-Label Experiments

For the open-label experiments, experimental data were obtained with $P(A_{IN}) = \lambda_1^2 = 0.65$ and $P(A_{AC}) = \lambda_2^2 = 0.35$ (Table 4).

We find $\cos^2\theta = 0.88$ and $\sin^2\theta = 0.12$, indeed:

$$P_{II}(A_{CP}) = |\lambda_1 \cos\theta + \lambda_2 \sin\theta|^2 = |\sqrt{0.65} \times \sqrt{0.88} + \sqrt{0.35} \times \sqrt{0.12}\,|^2 = 0.92\,.$$

$$P_{II}(A_{DP}) = |\lambda_2 \cos\theta - \lambda_1 \sin\theta|^2 = |\sqrt{0.35} \times \sqrt{0.88} - \sqrt{0.65} \times \sqrt{0.12}\,|^2 = 0.08\,.$$

Experiments Blinded by a Type-2 Observer

For experiments blinded by a type-2 observer, experimental data were obtained with

$P(A_{IN}) = \lambda_1^2 = 0.58$ and $P(A_{AC}) = \lambda_2^2 = 0.42$ (Table 4).

We find $\cos^2\theta = 0.88$ and $\sin^2\theta = 0.12$, indeed:

$$P_{II}(A_{CP}) = |\lambda_1 \cos\theta + \lambda_2 \sin\theta|^2 = |\sqrt{0.58} \times \sqrt{0.88} + \sqrt{0.42} \times \sqrt{0.12}\,|^2 = 0.88\,.$$

$$P_{II}(A_{DP}) = |\lambda_2 \cos\theta - \lambda_1 \sin\theta|^2 = |\sqrt{0.42} \times \sqrt{0.88} - \sqrt{0.58} \times \sqrt{0.12}\,|^2 = 0.12\,.$$

Experiments Blinded (or Not) by a Type-1 Observer

For the experiments blinded by a type-1 observer, experimental data were obtained with $P(A_{IN}) = \lambda_1^2 = 0.50$ and $P(A_{AC}) = \lambda_2^2 = 0.50$ (Table 4). Suppose first that we are not aware of the blinding of the experiment by a type-1 observer. We use quantum probabilities and we find $\cos^2\theta = 0.996$ and $\sin^2\theta = 0.004$:

$$P_{II}(A_{CP}) = |\lambda_1 \cos\theta + \lambda_2 \sin\theta|^2 = |\sqrt{0.50} \times \sqrt{0.996} + \sqrt{0.50} \times \sqrt{0.004}\,|^2 = 0.56.$$

$$P_{II}(A_{DP}) = |\lambda_2 \cos\theta - \lambda_1 \sin\theta|^2 = |\sqrt{0.50} \times \sqrt{0.996} - \sqrt{0.50} \times \sqrt{0.004}\,|^2 = 0.44.$$

These results indicate that the interference term is low and we obtain results close to classical probabilities:

$$P_I(A_{CP}) = \lambda_1^2 \cos^2\theta + \lambda_2^2 \sin^2\theta = 0.50 \times 0.996 + 0.50 \times 0.004 = 0.50\,.$$

TABLE 4
Extraction of the Different Parameters from Experimental Results and Use of Quantum Probabilities for Modeling

	EXPERIMENTAL SITUATION		
	Open-Label	**Blinding by Type-2 Observer [a]**	**Blinding by Type-1 Observer [a, b]**
Experimental data [c]			
$P(A_{IN}) = \lambda_1^2$	0.65	0.58	0.50
$P(A_{AC}) = \lambda_2^2$	0.35	0.42	0.50
$P(A_{CP})$	0.92	0.88	0.56
$P(A_{DP})$	0.08	0.12	0.44
Calculated parameters and modeling			
$\mu_{11}^2 = \mu_{22}^2 = \cos^2\theta$	0.88	0.88	0.996
$\mu_{12}^2 = \mu_{21}^2 = \sin^2\theta$	0.12	0.12	0.004
$P_I(A_{CP})$ (classical) [d]	0.61	0.56	0.50
$P_I(A_{DP})$ (classical) [e]	0.39	0.44	0.50
Interference term [f]	0.31	0.32	0.06
$P_{II}(A_{CP})$ (quantum) [g]	0.92 (0.61 + 0.31)	0.88 (0.56 + 0.32)	0.56 (0.50 + 0.06)
$P_{II}(A_{DP})$ (quantum) [h]	0.08 (0.39 – 0.31)	0.12 (0.44 – 0.32)	0.44 (0.50 – 0.06)

$\downarrow$, background; $\uparrow$, signal; CP, concordant pairs; DP, discordant pairs; *IN*, "inactive" labels; *AC*, "active" labels.

[a] For definition of type-1 observer (Wigner) and type-2 observer (Wigner's friend), see text.

[b] For experiments with type-1 observer including both open-label and blind samples, see text.

[c] These experimental data are from experiments described in Table 1 and in Beauvais (2012).

[d] $P_I(A_{CP}) = \lambda_1^2 \cos^2\theta + \lambda_2^2 \sin^2\theta$

[e] $P_I(A_{DP}) = \lambda_2^2 \cos^2\theta + \lambda_1^2 \sin^2\theta$

[f] $2\lambda_1\lambda_2 \cos\theta \sin\theta$

[g] $P_{II}(A_{CP}) = \lambda_1^2 \cos^2\theta + \lambda_2^2 \sin^2\theta + 2\lambda_1\lambda_2 \cos\theta \sin\theta$

[h] $P_{II}(A_{DP}) = \lambda_2^2 \cos^2\theta + \lambda_1^2 \sin^2\theta - 2\lambda_1\lambda_2 \cos\theta \sin\theta$

We have seen, however, that in the same experimental session supervised by a type-1 observer, both blind and open-label samples were included (as in the experiment described in Table 1). To model this case, it is reasonable to suppose that the values of sin θ are the same regardless of label blinding. For probability calculations, we take the values for $\cos^2\theta$ and $\sin^2\theta$ (0.88 and 0.12, respectively) as calculated in the subsections ***Open-Label Experiments*** and ***Experiments Blinded by a Type-2 Observer***:

For open labels,

$$P_{II}(A_{CP}) = |\lambda_1 \cos\theta + \lambda_2 \sin\theta|^2 = |\sqrt{0.50} \times \sqrt{0.88} + \sqrt{0.50} \times \sqrt{0.12}\,|^2 = 0.92 .$$

After blinding by the type-1 observer, classical probabilities apply:

$$P_I(A_{CP}) = \lambda_1^2 \cos^2\theta + \lambda_2^2 \sin^2\theta = 0.50 \times 0.88 + 0.50 \times 0.12 = 0.50 .$$

Therefore, the difference for probability of concordant pairs in open labels vs. blind labels *in the same session with a type-1 observer* is well-described by the proposed formalism: The probability of observing concordant pairs is high with open-label samples (Probability = 0.92), but lower for blind samples (Probability = 0.50) and not better than random in this case.

Comments on the Quantum-Like Formalism Applied to Benveniste's Experiments

Non-Commutable Observables and Emergence of Signal

If $\theta = 0$, 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 particular case, the observation of concordant pairs is always associated with label *IN* (i.e. *IN* is always associated with "↓") and the observation of discordant pairs is always associated with label *AC* (i.e. *AC* is always associated with "↓"). Therefore, *no signal* is observed with commutable observables; only background is associated with both *IN* and *AC* labels.

This shows that non-commutable observables are necessary not only for high rates of concordant pairs, but also for signal emergence. Note also that the signal must be one of the possible states of the system, even one with a low probability. In other words, the signal must be present in the

TABLE 5
Summary of the Quantum-Like Model Describing Benveniste's Experiments

	Non-Commutable Observables ($\theta \neq 0$)		**Commutable Observables ($\theta = 0$)**
	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: $P(A_{CP})$	$\lvert\lambda_1 \cos\theta + \lambda_2 \sin\theta\rvert^2$	$\lambda_1^2 \cos^2\theta + \lambda_2^2 \sin^2\theta$	λ_1^2
Probability of discordant pairs: $P(A_{DP})$	$\lvert\lambda_2 \cos\theta - \lambda_1 \sin\theta\rvert^2$	$\lambda_2^2 \cos^2\theta + \lambda_1^2 \sin^2\theta$	λ_2^2
Corresponding experimental situations	Open-label or blinding by type-2 observer	Blinding by type-1 observer	Unqualified or untrained experimenter

NA, not applicable.

[a] $P_{II}(A_\uparrow) = \lambda_1^2 \times P_{II}(A_{DP}) + \lambda_2^2 \times P_{II}(A_{CP})$

[b] $P_I(A_\uparrow) = \sin^2\theta$

[c] Observables are commutable with $\cos\theta = 1$ and $\sin\theta = 0$; then $P(A_\uparrow) = 0$ and $P(A_\downarrow) = 1$ (only background is observed by A; there is no signal).

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

[e] For $\sin\theta = \lambda_2$ (and consequently $\cos\theta = \lambda_1$), the quantum interference term is maximal with $P_{II}(A_{CP}) = 1$ and $P_{II}(A_{DP}) = 0$.

background; thanks to entanglement, the emergence of the signal is made possible.

"Which-Path" Measurement and Contextuality in Benveniste's Experiments

In the proposed formalism, there is neither success nor failure of the experiments (Table 5). Simply, as in a single-particle interference experiment, we can decide to observe either "waves" or "particles" by modifying the setting of the experiment. In the 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 Benveniste's experiments, the decision to observe "particles" (concordant pairs plus discordant pairs) or "waves" (only concordant pairs) is related to the design of the experiment (Figure 3). If the "cognitive state" of the experimenter is able to interfere with itself (as a single particle interferes with itself), then the probability of "success" is high. In case of blinding by a type-2 observer, quantum probabilities also apply since the respective cognitive states of the experimenter A and of the type-2 observer O are on the same branch of reality (as Wigner's friend observing Schrödinger's cat). Therefore, there is no formal difference for open-label vs. blinding by a type-2 observer. The same outcomes are obtained since the state vector that describes their cognitive states is:

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

If the sample blinding is performed by a type-1 observer, then conditional classical probabilities that take into account the "which path" information apply. In this case, the cognitive state of the experimenter cannot interfere with itself (there is no superposition). When the experimenter and the type-1 observer meet together after a series of blind experiments, they assess the rate of concordant pairs and they both agree that the probability of concordant pairs is low. We have to insist that, even with blinding by a type-1 observer, the signal is present if $\sin\theta \neq 0$.

Cognitive Aspect of the Formalism

The concordance of pairs is optimal for $\cos\theta = \lambda_1$ and $\sin\theta = \lambda_2$; indeed, in this case,

$$P_{II}(A_{CP}) = |\lambda_1 \cos\theta + \lambda_2 \sin\theta|^2 = 1 \quad \text{(Table 5).}$$

The probabilities of concordant pairs were 0.88 and 0.92 for open-label experiments and blind experiments with a type-2 observer, respectively (Table 4). This should not surprise us; it simply indicates that correlations in "real" experiments were not optimal and probabilities of concordant pairs were slightly <1.

Moreover, in a cognitive context, the fact that optimal concordance of pairs is observed when $\cos\theta = \lambda_1$ and $\sin\theta = \lambda_2$ is of particular interest. Indeed, the λ parameters (probability for labels *IN* or *AC*) are related to the experimental protocol, which defines the proportions of labels *IN* and *AC*. In contrast, the angle θ characterizes the relationship between the observables, which become noncommutable if θ is different from zero (see the section **The Quantum-Like Formalism Applied to Benveniste's Experiments**). The probability for the experimenter to observe a high rate of concordant pairs is related to modification of its cognitive state described by the state vector in Hilbert space and summarized by changes of the angle θ. Therefore, it is tempting to link up the angle θ to a previous training and to information on experimental protocol.

It could be suggested that θ fluctuates randomly around zero; the more and more "favorable" values of θ would be progressively selected ("learned") by feedback according to the observed outcomes. In the Mach-Zehnder apparatus, this is equivalent to adjusting settings (e.g., fine-tuning for equal lengths of paths R and T) based on trial and error in order to get all photons in the detector D1 (all photons in phase) (Figure 2).

In summary, we propose that the outcomes of Benveniste's experiments were related to cognitive processes (i.e. establishment of relations between different cognitive states) and that the successive experimenters on Benveniste's team acquired skill by manipulating the biological systems and measurement devices (for example, by performing "classical" experiments).

Note also that a relatively large variation of $\sin^2\theta$ around λ_2^2 leads to "good" results with a high rate of concordant pairs observed by A (Figure 5). Thus, with λ_2^2 set at 0.35, values of $\sin^2\theta$ from 0.10 to 0.75 lead to $P_{II}(A_{CP}) > 0.90$.

Relevance of Quantum-Like Formalism for Describing Macroscopic Events

The conceptual framework of quantum theory is the logical consequence of some simple assumptions. Among them, the assumption of non-commutable observables plays a central role. In this framework, classical probabilities are only a special case of quantum probabilities, one for which all observables commute with each other. Contextuality is another central concept in quantum physics. Thus, according to the experimental device set up by the experimenter, a quantum object could appear as a particle or as a wave: With the use of a two-slit device (or a Mach-Zehnder apparatus), the decision to observe—or not—which path entered the quantum object has a chief consequence on the experiment outcome.

As we have seen, contextuality also had important consequences in Benveniste's experiments: The circumstances of blinding appeared to have crucial consequences. Since interest was focused on the local properties of water (the so-called "memory of water"), little attention was paid to the logical aspects of the experiments. Therefore, the different outcomes according to conditions of blinding were interpreted as difficulties in reproducibility related to "contaminations," "electromagnetic interferences," or other ad hoc explanations.

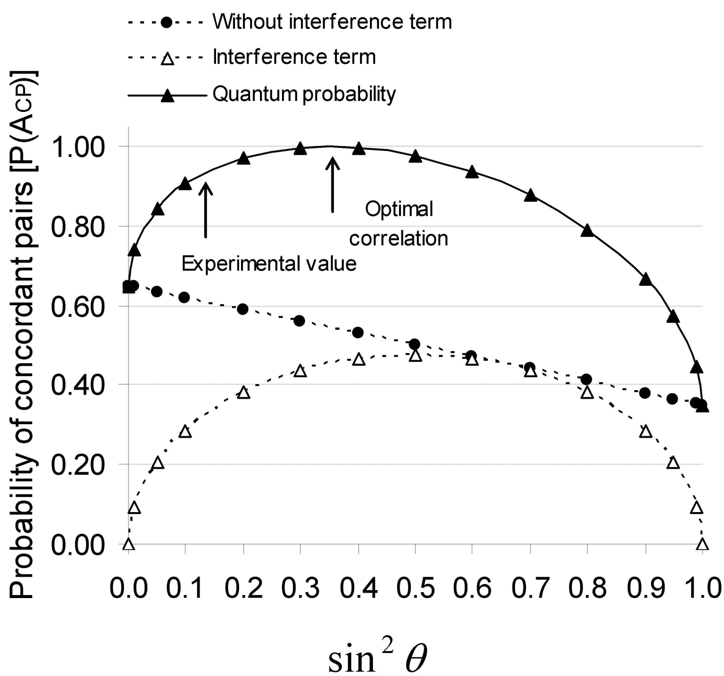

Figure 5. Probability of observing concordant pairs (*IN* with ↓ or *AC* with ↑) as a function of sin² *θ* (in this case λ_1^2 = 0.65 and λ_2^2 = 0.35).
Optimal theoretical value for probability of concordant pairs [P(A_{CP}) = 1] is obtained for $\sin^2\theta = \lambda_2^2$ (here for $\sin^2\theta = 0.35$; experimental value for $P(A_{CP})$ was 0.92 for $\sin^2\theta = 0.12$).

Opposite to this interpretation, we suggested that "successes" and "failures" during these puzzling experiments were the two faces of the same coin. The price to pay for this interpretation was to give up the idea that some modification in the water structure ("memory") was the cause of the biological outcomes observed with "high dilutions" or "digital biology." Note, however, that no convincing and reproducible physical modification of water structure able to induce specific biological phenomena has ever been reported; therefore, the price is not so high.

Faced with the description of Benveniste's experiments using quantum probabilities, different approaches are possible. It could be argued that the application of quantum concepts to these experiments is only metaphorical and that the analogy is simply ad hoc. Another approach—quite the opposite—is in the spirit of strict physicalism where everything can be reduced to physics. Since nothing can be left outside the field of physics, phenomena with a formal quantum description—as those described in this article—are thus quantum phenomena. However, a general acceptance of such an interpretation is generally hampered by the idea that the environment would rapidly destroy macroscopic superpositions.

A third way is possible, as suggested recently by some authors in different research areas. These authors proposed describing some specific parts of the world, whether physical or nonphysical, with a formalism isomorphic to that of standard quantum physics. This can be total isomorphism or more likely partial isomorphism, so that only certain special features of the quantum formalism are used for probability calculation of outcomes. A quantum-like formalism has thus been applied to human memory, information retrieval, decision making, opinion forming, personality psychology, etc. (Busemeyer, Wang, & Townsend 2006, Khrennikov 2006, 2009, Mogiliansky, Zamir, & Zwirn 2009, Pothos & Busemeyer 2009). These research areas have in common the description of cognition mechanisms and information processing in the brain, but this new approach does not rest on the hypothesis that there is something quantum mechanical about the physical brain. The quantum formalism is simply used as a source of alternative new tools (such as contextuality or entanglement) to address problems that remained unresolved in a classical framework. In these studies, the cognitive states of agents were characterized by state vectors in Hilbert space, and, in several experimental models, quantum probabilities had better predictive power than classical probabilities. Thus, some "paradoxical" statistical data, particularly in psychology and cognitive sciences, could be modeled (Atmanspacher, Filk, & Romer 2004, Conte, Todarello, Federici, Vitiello, Lopane, & Khrennikov, 2004, Khrennikov & Haven 2009, Mogiliansky, Zamir, & Zwirn 2009, Pothos & Busemeyer 2009).

In our model, the observables are nonphysical and therefore are not supposed to be exposed to the decoherence process. The first observable is labels, which have the meaning that the experimenter decides (all samples are physically equivalent). The other observable, pair concordance, also requires information processing for "interpretation." The cognitive process that we describe is not a causal action on the physical world, but it allows changing the "point of view" of the experimenter/observer, which is plunged into the world of possibilities described in the Hilbert space.

Finally, it has not escaped our notice that the present interpretation of Benveniste's experiments and the associated mathematical formalism that we propose could be extended to other experimental situations where an apparent "causal" relationship depends on contextual parameters.

Conclusion

The outcomes of the cognitive state of the experimenter were calculated for a series of Benveniste's experiments using a quantum-like statistical model (i.e. a model inspired by quantum physics and taking into consideration superposition of quantum states, non-commutable observables, and contextuality). Not only were the probabilities of "success" and "failure" of the experiments modeled according to their context, but the emergence of a signal from background also was taken into account. For the first time, a formal framework devoid of any reference to "memory of water" or "digital biology" describes all the characteristics of these disputed results. Particularly, the difficulties encountered by Benveniste (reproducibility of the experiments, disturbances after blinding) are simply explained in this model without additional ad hoc hypotheses. It is thus proposed that we see Benveniste's experiments as the result of quantum-like probability interferences of cognitive states.

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