Non-local correlations between separated neural networks

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ABSTRACT

In recent times the interest for quantum models of brain activity has rapidly grown. The Penrose-Hameroff model assumes that microtubules inside neurons are responsible for quantum computation inside brain. Several experiments seem to indicate that EPR-like correlations are possible at the biological level.
In the past year , a very intensive experimental work about this subject has been done at DiBit Labs in Milan, Italy by our research group.
Our experimental set-up is made by two separated and completely shielded basins where two parts of a common human DNA neuronal culture are monitored by EEG.
Our main experimental result is that, under stimulation of one culture by means of a 630 nm laser beam at 300 ms, the cross-correlation between the two cultures grows up at maximum levels.
Despite at this level of understanding it is impossible to tell if the origin of this non-locality is a genuine quantum effect, our experimental data seem to strongly suggest that biological systems present non-local properties not explainable by classical models.

Keywords: neurons, Microelectrode Arrays, EPR, non locality, correlation, coherence

1. INTRODUCTION

The Penrose-Hameroff model [1,2,3] identifies microtubules inside neurons as responsible for quantum effects in brain. A few experiments carried out in the past seem to indicate that EPR[4]-like correlations are possible at a biological level and neural level [5,6,7].

At the Department of Information Technologies , in collaboration with the Stem Cells Research Institute of DIBIT San Raffaele in Milan, a research group was born composed by physicists, computer scientists, biologists and engineers. Our purpose is the study of the collective behavior of human neurons adhering to Microelectrode Arrays (MEAs) [8,9,10,11,12].
The neurons have been cultured starting from human neural stem cells [13,14,15].

One of our interests is exactly the search for quantum processes in neurons.
As literature suggested that a viable method could be the search for non-locality processes between neurons, we set up experiments using two separated and shielded basins filled with cultures of human neurons, stimulating one of them with a laser beam, and looking for non-local effects on the other basin [16].

2. MATERIALS AND METHODS

2.1. The MEAs

Our experimental set up is constituted by two separated and completely shielded basins of human neurons adhering to Microelectrode Arrays (Fig. 1), connected to a PC by means of a signal acquisition card.
Each electrode is connected, by means of a sharp isolated track, to a pad suitable for the external connection.

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The distance between electrodes varies between 100 and 200 μm, whereas the diameter of each electrode is around 10 μm.
On the dish four basins suitable for cell culture have been put, in such a way as to realize more experiments simultaneously.

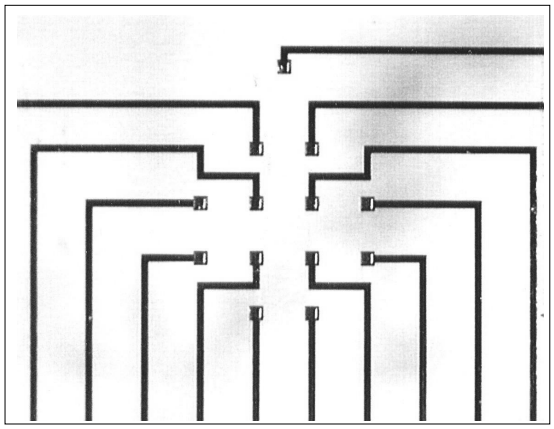

Fig. 1 – Portion of a MEA

From the 96 electrodes some have been chosen as neural input/output, others as ground.
The connection cable between electrodes and the acquisition/stimulation circuit is made by a flat cable with 40 wires shielded against EMI emissions with a suitable copper jacket.

In order to correctly stimulate the neurons it has been necessary to develop a custom constant voltage power supply , which yields the voltage perfectly squared and filtrated: on each signal, a circuit originated voltage pulses with levels suitable to the correct neuron stimulation.

It is possible to vary the wave form of the signal generator, by modifying the negative or the positive voltage. The voltage range is adjustable from a minimum of 5 mV to a maximum of 100 mV. The default voltage (negative and positive) is 35 mV.

The electrical signals are sent through the USB port to the I/O data acquisition card that converts them into TTL logic signals. The signal converted in this way enter the electronic stimulation circuit that transform them into the wave forms and voltage levels compatible with the biological neurons.

In order to avoid electrolysis phenomena due to the direct current through the culture liquid, every generated bit is preceded by a negative pulse which depolarizes the culture electrolyte.

The acquisition card, produced by IOtech , Inc.[17], includes high-resolution, 22-bit A/D converter, and digital calibration, frequency measurements up to 1 MHz , optical isolation from PC for safe and noise-free measurements. It allows programmable inputs from ±31 mV to ±20V full scale and it is expandable up to 80 channels of analog and digital I/O.
The features of the laser diode, produced by Toshiba, are 658 nm wavelength (visible light near IR band) and 2 mW power.

Another circuit has been developed, made up by an oscillator and a direct current generator, in order to drive the laser diode. The circuit keeps steady the current supplied to the laser and produces the modulation pulses.
The laser beam has been modulated in OOK (On Off Key) mode using two different frequencies, as explained below.

2.2 The Experiment

In order to test a possible non-locality effect, the laser beam has been divided into two identical sections by a half-silvered mirror. One of the two rays has been reflected with an angle of 90° by means of an optical 45° prism. In a second time the optical prism has been removed. In this way the laser beam hit only one of the two basins.

The two dishes have been first electrically connected, then separated and electrically insulated.

We produced first 50 electrical stimulations (40 Hz), then a number of light stimulations with the laser diode (Fig. 2)

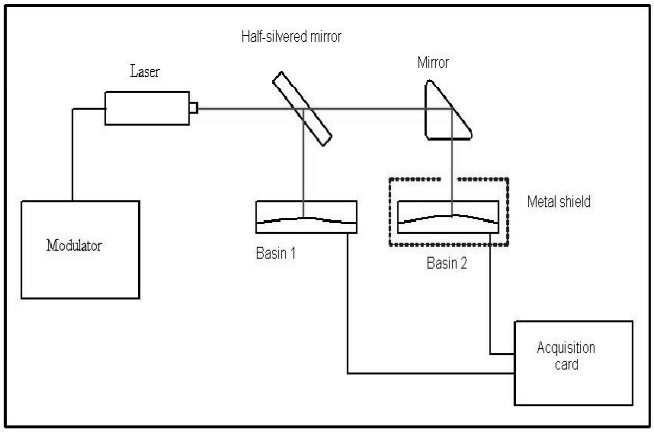

Fig. 2 – The experiment

It is known that 300 ms is the mean value necessary for a cell to react to light stimulation. But in order to test the sensibility of neurons to different exposure times we used two different frequencies, generating both pulses of 300 ms (T1) and of 1 ms (T2) (Fig. 3). We produced 50 T1 pulses and 50 T2 pulses , iterating the process several times.

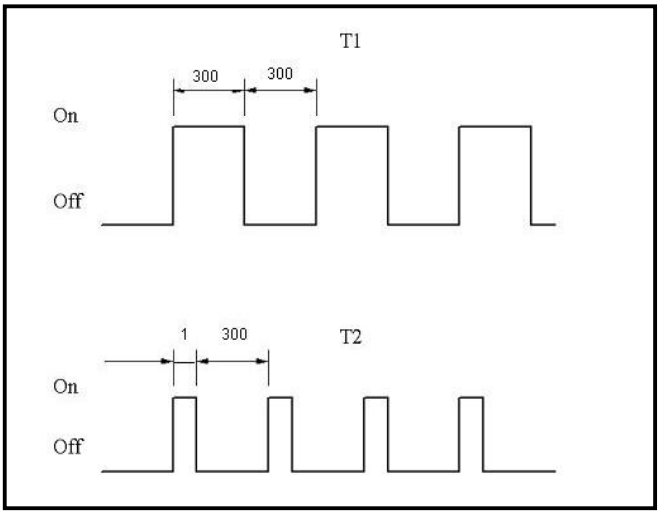

Fig. 3 – Laser frequencies

3. RESULTS

3.1 Signals analysis

During the experiment we recorded several signals emitted before, during and after laser stimulation of one or both basins, with both connected and separated basins.
We analysed the signals in several ways, with particular attention to the correlation/coherence between the signals coming from the two basins.
The most interesting analysis has been carried out on the signals **coming from separated basins, during the T2 stimulation of a single basin**. The coherence between the signals of both basins is shown in Fig. 4.

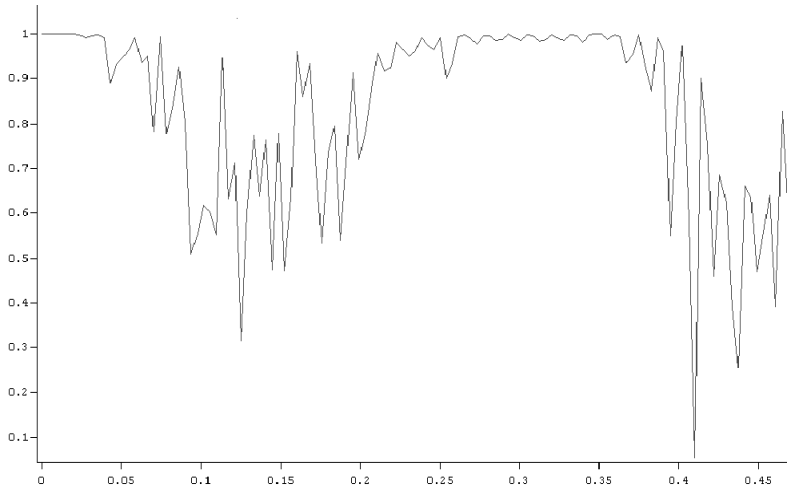

Fig. 4 – Coherence between signals of separated basins

On the basis of this promising result we deepened our analysis on the same signals.
The following graph shows the original signals, and a segment (observations 100 through 150) of the same signals (Fig.5)

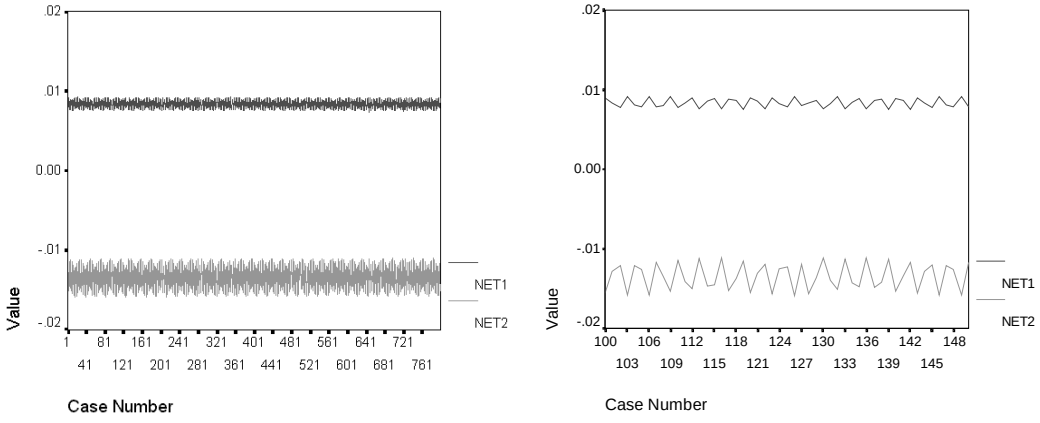

Fig. 5 – The two signals

The table 1 reports the basic descriptive statistics of the two recorded series, showing that the signals show a completely different behavior.

	N	Minimum	Maximum	Mean	Std. Deviation
NET1	800	.00733	.00922	8.350962E-03	5.676923E-04
NET2	800	-.01588	-.01102	-1.3430487E-02	1.623511E-03

Table 1

The signal autocorrelation functions (up to a few lags) are portrayed in Fig. 6.

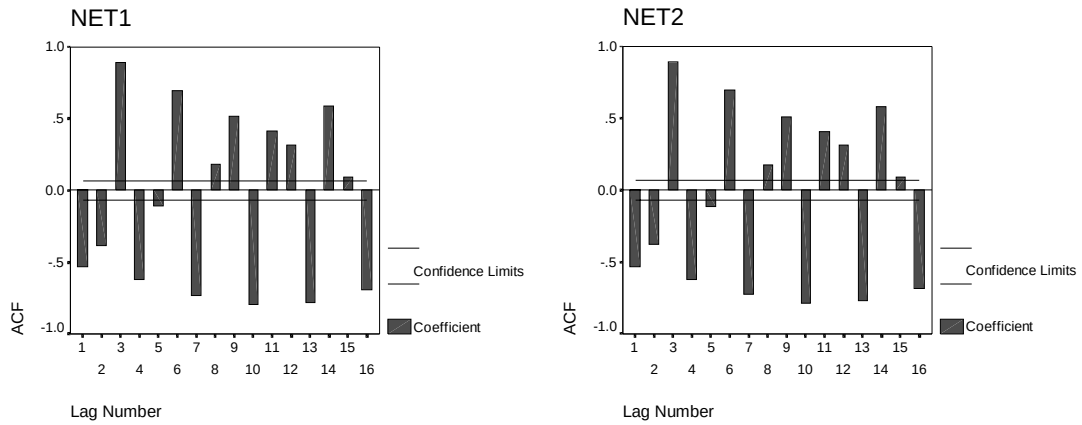

Fig. 6 – Autocorrelation functions

It can be seen that either signal is strongly autocorrelated over several lags. Further, the structure of the autocorrelation function is clearly the same for both signals. Despite the difference in mean level and amplitude of oscillation, both signals seem to share the same (nonlinear) production mechanism.

The structure is better elucidated by the Partial autocorrelation functions (where correlation over intervening lags is factored out, and only residual correlation is depicted) in Fig. 7:

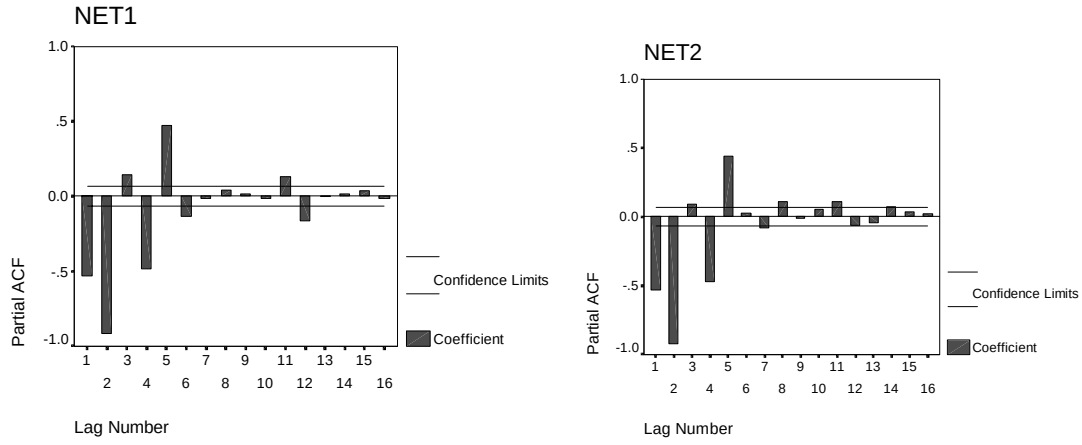

Fig. 7 – Partial autocorrelation functions

Again, the structure appears the same, beyond modest disagreements (like the negative partial autocorrelation at lag 12, Significant for Net1, NonSignificant for Net2).

Fig. 8 shows the cross-correlation function between the two signals:

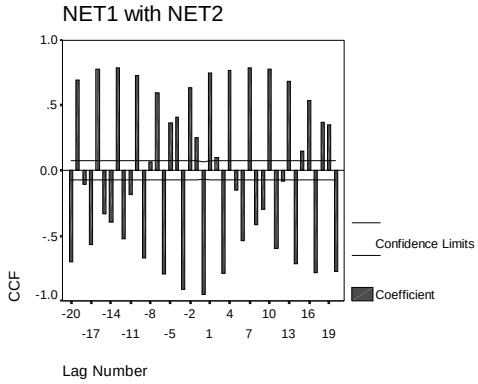

Fig. 8 – Cross-correlation between signals

While extremely suggestive of a structured, strong relationship between the two signals, it is to be noticed that since each signal is very strongly auto-correlated, the observed cross-correlation may be spuriously induced by the (time-lagged) repeating structure of each one of the two signals themselves.

In order to test for a possible added effect of Net1 on the autoregression structure of Net2, we build an ARIMA model with 6 autoregressive terms, 6 moving average terms and the Net1 effect (no differencing). The results are shown in Table 2.

Except for the MA term of order 6, all terms are highly significant, including in particular Net1.

We might conclude that the two series are so strongly correlated that, even after correcting for a substantial amount of self-correlation, the values of one series impact the prediction of the other in a highly significant way.

B	SEB	T-RATIO	APPROX.	PROB.
AR1	-2.4884391	.05597015	-44.460114	.00000000
AR2	-3.7591071	.11608704	-32.381799	.00000000
AR3	-4.0741015	.16066252	-25.358132	.00000000
AR4	-3.4740205	.15510190	-22.398310	.00000000
AR5	-2.1126457	.10453732	-20.209488	.00000000
AR6	-.7064310	.05006308	-14.110818	.00000000
MA1	-1.7906334	.06348049	-28.207619	.00000000
MA2	-2.0089609	.10866128	-18.488287	.00000000
MA3	-1.9888847	.12692663	-15.669562	.00000000
MA4	-1.4824901	.12418843	-11.937425	.00000000
MA5	-.4772882	.09211534	-5.181419	.00000028
MA6	.0295138	.04922116	.599616	.54893512
NET1	-2.4889917	.04522700	-55.033315	.00000000
CONSTANT	.0073550	.00037771	19.472568	.00000000

Table 2

3.2 Considerations

Maximum care has been adopted in shielding the basins and the electrical devices.
Our first care was to ascertain the absence of possible cross talks between channels. To this purpose we performed bench tests both on the acquisition card and on the MEAs.

The test on the acquisition card has been performed by injecting signals on more input channels and verifying possible cross talks on the remaining channels: the channel-to-channel cross talk is < -110 dB (from DC to 100 Hz; up to 10 kΩ source resistance). We also generated spikes to check possible propagation to other channels. All the test completely excluded possible cross talks.

With the same method we have also tested the insulation of the MEA electrodes: the electrode-to- electrode cross talk is < -80 dB (from DC to 1000 Hz; up to 10 kΩ source resistance).

On the other hand the MEAs have a glass support that ensures perfect insulation, and the distance between wires in the MEAs are widely dimensioned to avoid of the mutual capacitance.

We also ascertained that no photons reached the second basin after removing the optical prism , by shielding the basin with a metallic cover. Moreover, it is known that the laser beam produces coherent light that could not give rise to refraction through the plastic and glass supports.

The connection cable between electrodes and the acquisition/stimulation circuit is made by a flat cable with 40 wires shielded against EMI emissions with a suitable copper jacket.
The electronic circuit is included in a plastic box whose walls have been treated with special varnishes that efficiently shield possible EMI noise.
All the cables used for the connection between culture basins, stimulation circuit and acquisition card have been carefully and separately shielded. We also minimized the power supply ripple using a condenser with low ESR, in order to avoid a possible ripple in the generated signals.

The length of the wires between basins and shielded cable is around three centimeters and wires are 4 cm apart. Anyway, voltages and currents are so low that they could not generate interference neither with direct contact: in order to generate interference, they should differ by several order of magnitude.

We also carefully avoided environmental interferences (e.g. cellular phones, power lines, etc.). The data acquisition card is optically isolated from its host PC by up to 500 VDC and it is an external device, connected to the PC through the USB port, that can be located up to 5 meters from the PC. This configuration allows to shorten the connections neurons/acquisition card and to reduce at the same time the risk of possible electrical noise generated by the computer electronic circuits. The PC is located 1.5m apart from the acquisition card, the USB/card cable is shielded and filtered.
Moreover, the stimulation circuit disconnects the voltage generator when the acquisition card gets ready to receive the signals coming form the culture basins.

On the other hand, interferences in the system are easily recognizable, as they affect all the input channels simultaneously, uniformly and in phase. In the same way, possible spikes should be visible simultaneously on all the channels. On the contrary, the acquired signals show different behaviour and amplitudes.
It must be stressed that the signal correlations appear only in some special experimental conditions, that are non subsequent in time.
Finally, in order to avoid the production of a spike when the laser is turned on, the supply cables of the laser have been taken away from the MEAs , and the second basin was shielded. In any case, the registered phenomenon has not the form of a simultaneous spike between signals.

It has also been observed that using a control basin, filled only with culture liquid, even though the liquid is conductive no electrical activity has been shown in the basin if not after direct stimulation (and in this case signals shown completely different behaviour).

However, the experimental results are extreme and a great deal of caution should be exercised before offering a non classical explanation.
Several other experiments , also involving super-position of light stimulation, are under way to get a clearer picture and possible hints to understand the deep physical reasons of this non-local correlations.

3.3 Our quantum model

In the last decade increasing interest has been turned to the search of a biological/physical correlates of mind [18,19,20]. The most authoritative scientist in this field is Sir Roger Penrose [21], who maintains that the biological processes responsible for the "mind" phenomenon are to be searched in the quantum nature of some sub-neural processes.

Many other models have been proposed on this matter, but scarce are the experimental evidences necessary to corroborate the quantum hypothesis.
Of course, the evidence of quantum processes in the neural structure does not show that the mind-body problem could be appropriately explained by the quantum hypothesis, nevertheless it would yield some verification of the biological plausibility of such assumption.

We will draw here a very general model which could both sustain our experimental findings and yield a formal basis for the more complex hypotheses formulated by the other scientists.

Our theoretical assumption is that at some level the information processing inside the brain could be described by means of the Hilbert spaces mathematics [22, 23, 24].
More precisely, we will associate to a portion of brain matter a lattice of qubits, i.e. vectors of a complex 2-dimensional Hilbert space.

The choice of this dimension is motivated both by plainness and by compatibility with the Penrose-Hameroff model, where the tubuline molecules, basic biological elements of their quantum model, are represented in this way.

Then the information inside the network is represented by a sequence of qubits $S = \{q_0, q_1, \ldots, q_n\}$, where contiguous qubits reflect the physical neighborhood of associated neural elements. Thus the global state of the system will be represented by a $|s\rangle$ vector belonging to a 2^n-dimensional Hilbert space.

The other assumption in our model is that these qubits locally interact following a unitary transformation $\hat{U}$.

Locally this means that the global state of the system passes from the state $|s\rangle$ to the state $|s'\rangle = \hat{U}|s\rangle$, where $\hat{U}$ can be expressed as $\hat{U} = \hat{\mathrm{I}} \otimes \hat{U}_{i.i+1} \otimes \hat{\mathrm{I}}$, where $\hat{U}_{i,i+1}$ represents the local unitary transformation of the qubits $\{q_i, q_{i+1}\}$ and $\hat{\mathrm{I}}$ is the identity transformation on the remaining qubits.
Now we have to specify the choice of the local transformations $\hat{U}_{i,i+1}$.

Thus we assume that all these transformations are identical each others and correspond to the CNOT operator($\hat{C}$), represented in its canonical basis by the matrix

$$\hat{C} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{pmatrix}.$$

The choice of this operator is due to the fact that any unitary transformation on a space of *n* qubits can be approximated by a sequence of $\hat{C}$ operators acting of pairs of qubits and phase rotations acting of single qubits [9]. Moreover, the $\hat{C}$ operator is the simplest operator able to generate the so-called *entangled* states.
In fact if we apply the $\hat{C}$ operator to the factorizable (*non-entangled)* state $\frac{1}{\sqrt{2}}(|0\rangle+|1\rangle)\otimes|0\rangle$ we obtain the entangled state $\frac{1}{\sqrt{2}}(|00\rangle+|11\rangle)$.

A property of this operator is that its inverted operator coincides with the operator itself, i.e. $\hat{C}^2 = \hat{\mathrm{I}}$.
This implies that in order to undo the entanglement created between a pair of qubits, only the local transformation itself can invert the process.

Thus if we imagine the global system evolution, we will see a continuous generation and destruction of entanglements inside the system.

Let's now suppose that the system $S = \{q_0, q_1, \ldots, q_n\}$ is physically divided into two subsystems, $S^A = \{a_0, a_1, \ldots, a_l\}$ and $S^B = \{b_0, b_1, \ldots, b_m\}$, not interacting each others.
In the hypothesis that a pair of qubits $\{a_i, b_j\}$ is in an entangled state $\frac{1}{\sqrt{2}}(|00\rangle+|11\rangle)$,

such entanglement will not be undone because the possibility of a local interaction has been eliminated by the physical separation of the two subsystems.
Moreover a following global interaction $\hat{U}$, generated by the concurrence of the local actions $\hat{C}^A$ (acting on the pair $\{a_i, a_{i+1}\}$ of the subsystem S^A) and $\hat{C}^B$ (acting on the pair $\{b_j, b_{j+1}\}$ of the subsystem S^B), will include in the whole entangled state the spatially separated qubits $\{a_{i+1}, b_{j+1}\}$ that we assume in a previous non-entangled state $|0\rangle|0\rangle$.
Formally we have

$$\hat{C}^A \otimes \hat{C}^B \left(\frac{1}{\sqrt{2}}(|00\rangle+|11\rangle)|0\rangle|0\rangle \right) = \frac{1}{\sqrt{2}}(|0000\rangle+|1111\rangle)$$

The physical meaning of this process is that the model depicts a sort of spontaneous generation of entanglement between separated sections of matter: therefore after an initial stage where the system interacts by direct contact, even in the following stage, where the system has been separated into two non-communicating sections , a sort of correlation will persist between the sections.

Qubits are intrinsically probabilistic objects, in the sense that we associate an aleatory event to their measure. Formally, if we assume the state of the qubit q as $\alpha|0\rangle+\beta|1\rangle$,
after its measure we will get 0 with probability $|\alpha|^2$ and 1 with probability $|\beta|^2$.
By operating a phase rotation $\hat{\Phi}$ on q we will vary the probability amplitudes $|\alpha|^2$ and $|\beta|^2$.

The entangled states differ from the non-entangled ones because in the first case the statistical correlation between the results of the measures of the qubits participating in the entangled state vary depending on the possible rotation phases

$\hat{\Phi}$ applied to the single qubits, whereas in the case of non-entangled states the correlation is zero, independently from any possible $\hat{\Phi}$.

Another important issue is that our model can propose a solution to the frequent objection put to the Penrose-Hameroff and other quantum models of mind is that no enough explanation is given about the way used by the brain to work as a quantum computer at room temperature. In fact the theory forecasts that in order to maintain coherence in a quantum system in the pure state $\frac{1}{\sqrt{2}}(|s_1\rangle+|s_2\rangle)$ for non negligible time, without causing collapse to the mixed state $\frac{1}{2}(|s_1\rangle\langle s_1|+|s_2\rangle\langle s_2|)$, very low temperatures (near to the absolute zero) are necessary [25].

But in our case the possibility that the entangled state $\frac{1}{\sqrt{2}}(|00\rangle+|11\rangle)$ collapses or already arises as a mixed state $\frac{1}{2}(|00\rangle\langle 00|+|11\rangle\langle 11|)$ does not invalidate the property of correlation and its emergence as above mentioned. In fact the statistics of the measures on the two qubits is identical in both cases, and the property of correlation shielding due to the phase rotation $\hat{\Phi}$ remains the same even in the case of mixed state $\frac{1}{2}(|00\rangle\langle 00|+|11\rangle\langle 11|)$.

4. CONCLUSIONS

The above model foresees that, after an initial stage where the system interacts by direct contact, also in the following stage where the system has been separated into two sections, a sort of correlation persists between sections.
This is what , at a macroscopic level, we verify in our experiment: it seems that neurons utilize the quantum information to synchronize.

Of course the biological responsible for the quantum behavior are to be identified (neurons, microtubules or other structures), and both the connection between theoretical correlation and electrical correlation , and the connection between laser stimulation and phase rotation $\hat{\Phi}$ are still under investigation.

A viable hypothesis could be that the quantum state influence in some way the probability of obtaining one or more action potentials. It follows that quantum correlated states could work as a synchrony signal for the electrical activity, and these synchrony signals could stay latent until a correct unitary transformation activate them increasing their correlation to the maximum value.

This hypothesis becomes proposable if we think of the enormous number of correlations that could potentially emerge since the laser emission keeps coherent on macroscopic portions of matter.

Another issue to be investigated is a possible classical explanation of the described effect. In particular, we are studying the application of the Kuramoto -Yokoyama model [26]. We think that a promising approach could be the development of a model where the quantum processes represent a sort of microscopic primer of a macroscopic phenomenon such as the synchronization of the electrical signals.

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