Quantum Superposition in the Retina: Evidences and Proposals

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ABSTRACT

The retina is a light-sensitive layer structured as an array of millions of individual receptors that act as nano-antennas for photons. Apparently, the retina is one of the best known quantum detectors due to the rod cells that are able to respond to a single photon. It appears that the retina is an excellent photon detector and it can be hypothesized that quantum processing of information occurs within the retina and subsequent processing of information at the level of neural membranes decrease the overall quantum efficiency. In this article we review some evidences of quantum processing in retina and propose some experiments and ideas to detect quantum superposition in the retina. Actually, if the retina may involve quantum process, it is reasonable that the conventional tools of quantum spectroscopy could bring an unambiguous proof of this claim. Indeed, aim of this work is to show some methods to induce and verify the existence of quantum superposition in biological systems, more specifically the rodopsin molecules in the rod cells.

Key Words: retina, quantum superposition, quantum efficiency, photosensitivity, quantum biology, quantum spectroscopy, Rabi oscillation, spectral hole burning

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Introduction

The retina is a light-sensitive layer at the back of the eye that covers approximately 65 percent of the eye’s interior surface. The retina contains two types of photoreceptors, cones and rods. The photoreceptors are responsible for the transduction of light into electrical signals, which are then delivered to the brain cortex, where we consciously perceive the visual images.

Rods are much more numerous and sensitive than cones. There are about 120 million rod cells in the human retina and they are about 100 times more sensitive to the light than cones. However, the eye’s color sensitivity is provided by cones which are mostly concentrated in macula (Kandel et al., 2000). Perception of color may result when color detectors are activated, e.g., phosphenes (brilliant lights) could be produced when a mild electrical or magnetic current passes through the head. Phosphene perception appears after extensive recurrent processing and is therefore not purely attributable to primary visual processing (Taylor et al., 2010). The rods are responsible for dark-adapted or scotopic vision and reportedly can be triggered by individual photons under optimal conditions. It is known that cGMP (cytoplasm cyclic guanosine monophosphate) in rhodopsin molecules is responsible for scotopic vision (Kandel et al., 2000; Lu et al. 1999).

Vision process begins first after the arriving of photons at the retina. Not all the photons arriving at the retina contribute to trigger the neural signals. The cause of reduced...
efficiency in the perception of light has long been studied by a lot of authors since 1940 s. In fact, the first experiments were conducted in 1942 (Hecht et al., 1942). Rushton estimated that 10% of light incident at the cornea (or equivalently 20% of light incident at the retina) stimulates rhodopsin (Rushton et al., 1956). Barlow estimated the overall quantum efficiency of the human eye and found that the highest efficiency is nearly 5%, which is found in near-threshold intensities of light on a small area at 15° from the nasal axis for the dark-adapted eye (Barlow, 1962). This led to the conclusion that rod photoreceptors can detect a very small number of photons, typically less than 10, during an integration time of about 300 msec. It is now well known that in suitable conditions the rods are sensitive to single photons (Meister and Berry, 1999). This prediction has been confirmed by several experiments (Baylor et al., 1970; Rieke and Baylor, 1998). At the moment, the consensus is that this small number, or absolute threshold, is about 5 to 7 photons (Hecht et al., 1942; Bialek, 2007). The actual number of retinal events varies according to a Poisson distribution and the probability that two photons fall on the same site of retina is vanishingly small.

Quantum Coherence in the Retina
Recently (Manasseh et al., 2012) it has been shown that quantum efficiency estimated from behavior is very low compared with the absorptive quantum efficiency estimated from the properties of the rods at the retina. Experiment was carried out by using a controlled source of light while recording EEG and reaction times. The results have shown that on average around 70 photons are required for untrained subjects to trigger perception 50% of the times even though rod photoreceptors can react to single photons. Much more photons are required to elicit conscious perception than to elicit responses in rod photoreceptors, therefore post-retinal processing significantly contributes to increase detection noise and threshold, decreasing the efficiency of the retina brain detector systems.

There are some other evidences and proposals to show quantum superposition in the retina. One of the other evidence is provided by visual illusions resulting from the lateral inhibition mechanism which allows effective detection of edges (regions where the light intensity changes abruptly) (Georgiev, 2011).

Indeed the existent visual illusion due to the lateral inhibition mechanism means that not only the photon signal is amplified before it enters the brain cortex, but also that the visual information is processed (modified and irreversibly changed) before it enters the cortex.

If quantum coherence would be maintained in the retina, it should be possible to measure with the conventional tools of quantum spectroscopy. Hilaire and Bierman proposed an experimental protocol based upon a technique from quantum optics called “photon echo” to search for the photon echo in the retina (Hilaire and Bierman, 2002). In photon echo technique a short laser pulse is sent to the system being followed by another pulse from the same source. If quantum coherence is occurring in the system, a delayed photon (echo) is detected after the detection of a photon, and the quantum coherent state should be preserved through the neural processing by optical waveguides, the microtubules, following many authors (Wolf and Hameroff, 2001; Khoshbin–Khoshnazar, 2007; Pizzi et al., 2010). This experiment is very difficult, and to our knowledge it has not been realized, yet. Three other proposals which could be shed light on the problem are as follow.

Rabi Oscillation
Rabi oscillations (Knight and Milonni, 1980) in the retinal rod cells (Strini and Pizzi, 2009) can be considered to this task. Given any atomic system where it is possible to consider just two levels, e.g., the fundamental level and a single excited level, it is immediate to induce a quantum superposition between these two levels. In fact, it is possible to irradiate the system with a coherent light beam with a frequency equal to the energy difference between two levels (divided by the Planck’s constant). If we start, e.g., from a system at the fundamental level, this is periodically excited and de-excited at the Rabi frequency. It is well-known that in an equivalent classical system such oscillations cannot be present. On the contrary, the presence of such oscillations is considered as the signature of a genuine quantum effect. The feasibility of the experiment is ensured by the new MicroElectrode Array (MEA) technology (MEA, 2013), that allows record the trans-retinal voltage change of the single photoreceptors. A toad’s retina is placed onto MEA with ganglion
cell site down. The choice of a toad’s retina is due to its well-known response to the single photon. In addition, note that when the information must be conveyed from the retina, this function is only performed by the ganglion cells (Masland, 2001). One type of ganglionic cell is the ON-center ganglion cell, which will respond by increasing its firing rate after a small amount of light hits retina within its receptive field (Westheimer, 2007). The light stimulus is projected onto the photoreceptors in the MEA. The stimulation is supplied by a pulsed solid state laser, with around 500nm, corresponding to the maximum sensitivity of the rod cells. The light stimulus must be adequately attenuated, activated for a suitably short time and focused through an optical system in such a way as to hit the portion of MEA containing the cells with an intensity chosen to ensure the activation of a minimum number of photoreceptors.

Apparently, Rabi oscillations of single molecules are observed with a nearly similar technique (Gerhardt et al., 2009).

**Double-Slit Single-Photon Interference**

The research (Wang and Pizzi, 2012) aimed at investigating the possibility of a Young’s double-slit single-photon experiment in the absence of measuring device, namely using the human eye in place of the photomultiplier of other counting devices.

The proposal is devoted to implement a program which at varying of the minimum perception of light pulses and pauses by the human eye, evaluates how many interruptions of a continuous stream of photons are in principle perceivable by a human eye, in case photons arrive at the two slits in form of corpuscles. The instrumentation consists of a tube that contains a hermetically sealed optical bench consisting of: a single slit collimator, double-slit assembly, detectors slit, a shutter (an ocular), photomultiplier tube, preamplifier-discriminator, programmable counter, and a LED light source. Note that LED is not perfect source, as photons are correlated with each other. But this situation only occurs under the condition that the time interval is much shorter than the coherence time (Kocayk et al., 1996) which is less than 10−8s for real thermal light source. But the operation time of this proposed experiment is longer than the coherence time of a real thermal light source (coherence time is how long a well-maintained phase of the light exists at a given point in space). In addition, events shorter than its integration time could not be sensed and therefore Bose-Einstein distribution could not emerge in this experiment.

After an appropriate time in the dark, needed to activate the scotopic vision, the experimenter is placed at the end of optical bench. The power supply of the LED circuit is activated so that the experimenter from the ocular can see the two slits illuminated. At this point, light intensity of the LED is decreased until the minimum perceivable. The pulsing circuit is activated initially keeping pause and pulse long enough to make the two slits easily perceivable. Gradually the length of pulse and pause are decreased, until a configuration light intensity/pulse duration/pause duration is reached that is minimum possible for the experimenter to perceive the two slits illuminated. Based upon the probability distribution of the specific flow of photons, a non-zero probability exists that the photons pass by only one of the two slits in sufficient number to cause an interruption of light perception in the other slit. The observation has been continued for 450s, well above period provided by the statistical procedure for the appearance of light interruption, and showed no light interruptions. If the experimental parameters evaluation be are considered correct, the results would indicate that in the absence of measurement devices and in the presence of the only conscious perception the quantum superposition is not interrupted, which might suggest to consider the conscious perception (the eye) as a quantum object. Actually the human eye as a detector for quantum phenomena, such as entanglement, in the absence of any other measuring device, has been proposed by other authors as well (Burnner et al., 1996 and Do Martin, 2011).

**Spectral Hole Burning (SHB)**

If the retinal receptors may involve a quantum process, the conventional tools of quantum spectroscopy could bring an unambiguous proof of quantum coherence in the retina. To our knowledge such experiments have never been carried out, yet. The rest of this article describes a proposal for such an experiment, based on SHB technique (Rebane 2012; Slid and Haller, 1998). First of all, we should introduce the concept of zero phonon line (ZPL) which play
very important role in this proposal. Let us consider the absorption of light by one single molecule. The absorption spectrum gives the probability of transition from the ground state to the excited state as a function of frequency, where the frequency equals the energy difference between the states, divided by Planck’s constant. This is true if the molecule is in a free gas phase. However, in the solid state, the transition probability would be a function of the density and of the frequency of the vibrational states of the solid. Crystal lattice vibrations which propagate like waves are called phonons. Because the phonon state population varies largely with the temperature of the crystal, the whole absorption spectrum depends strongly on the temperature. However, at low temperatures, the number of phonons is reduced. Then, there exists a real probability of electronic transitions where the phonons do not participate at all. Such transitions are called zero phonon transitions. Their important property is that they have a very well defined frequency. The corresponding spectral feature shows up as a narrow zero phonon line (ZPL). The narrowest and most intense zero phonon line is observed at absolute zero temperature. The width of the ZPL is then given by the inverse value of the excited state’s lifetime. In some special cases the zero phonon line can be detected at liquid nitrogen temperature (T=77°K). However, more typical is that the sample has to be first cooled to 10-20°K (or less than the liquid helium temperature). For the absorption of light by many molecules, the ground and excited state energy vary randomly from molecule to molecule, and this causes the transition frequency to change randomly, as well. The probability of finding the transition frequency in a frequency interval, most of the molecules can be transferred from the educt to the photo-product state. So, the corresponding inhomogeneous bands do not overlap. If the illumination is terminated, then the initial absorption profile is not restored unless the sample is heated up. Since at low temperatures the inhomogeneous absorption band of the initial state consists of narrow zero phonon line, it is possible to produce such information only in a group of molecules which are selected by their ZPL frequency. Selective bleaching of the inhomogeneously broadened absorption band consisting of narrow homogeneous absorption lines is called spectral hole burning. In short, SHB relies on three basic factors: 1. Existence of narrow homogeneous ZPL, 2. Existence of inhomogeneous broadening, 3. Existence of some kind of molecular mechanism which alters the homogeneous absorption spectrum upon absorption of light.

Few papers suggest that SHB could be applied for studying some biological systems (Zollfk et al., 1992). We propose SHB could be utilized to highlight quantum superposition in the retina. The illumination is supplied by a laser beam to ON-center ganglions cells and the retina should be kept in cryogenic temperature to detect ZPL. Fortunately, the experiment would not be subjected to the thermal interactions that destroy quantum processes within individual neurons (Tegmark, 2000). Note that SHB technique is not only measurement of absorption spectrum. We should have a spectrally narrow laser to “burn a hole” into the absorption spectrum. Thus to get the ZPL we need to measure absorption spectrum at cryogenic temperatures twice, before and after “burning”. The differences between spectra then provide information about ZPL. The proposed experiment, certainly, is not easy: but it would yield an excellent possibility to observe a true quantum effect in the retina. This is surely doable in isolated Bufo bufo retina, but unfortunately it can hardly be figured out to do this in vivo, due to cryogenic temperatures. The possible expansions of the experiment are almost endless, e.g. if no effect is seen, this could mean that there is not such kind of electronic mechanism in the retina that could change the homogeneous absorption spectrum, or the narrow laser was not enough focused to burn a hole in the absorption spectrum. The problem may be reduced by using nano-focusing technique (Hell, 2007).
Final Remarks

The proposed experiments are not easy to perform, but they should be considered as a way to yield the possibility to observe a quantum effect which would be the signature of a true quantum superposition in the retina. In any case, these experiments may put interesting limits to many current hypotheses on the quantum coherence in the retina, in any photosensitive systems (Engle, 2011) and maybe in biological systems in general. They may be useful in the development of quantum computers as well. In addition, in accompany with some other researches on cone (Skaper, 2012) and rod (Haeri et al., 2013) cells may shed light and support progresses on the retina degeneration diseases. However, each proposed experiment should also describe plausible biophysical mechanisms that would explain how the quantum effects examined could affect neural signaling, which is left for future communications.

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References


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