Quantum Mechanics and the Brain

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Abstract

In this paper we discuss possible quantum effects in the brain. We start with a historical review of what some prominent physicists have said about it. We then discuss some proposals that quantum superpositions may be used by the brain. Although decoherence effects in the brain are believed to be too strong to allow quantum computations, we describe how quantum processes support the capability of some eyes to detect small number of photons. Finally, we outline how modern physics techniques may be used to perform experiments that, if successful, would show conditioning to single photons.

Introduction

Do quantum mechanical processes occur in the brain? Both affirmative and negative responses to this question have been given, often with passion and strong conviction. Our answer is positive. There is a second question that is more narrowly focused. Do brain processes do any quantum computing, a question discussed with particular intensity as work on quantum computing has rapidly developed in the last several decades? Our answer to this question is negative, given what scientific evidence there is. Penrose especially has raised a third question, the most dramatic of the three we state. Here it is. Does the brain perform cognitive operations that go beyond those performable by a universal Turing machine, a limit not exceeded by quantum computing? Our answer, again based on current evidence, is also negative to this third question.

There are four main sections which explain in the space available our answers to the three questions just posed. The first section provides some historical background on the views of the godfathers of quantum mechanics about the disruptive character of human or other observers interacting with quantum systems. Many of their answers are still relevant today. The second section focuses on quantum computations and beyond. Here we discuss Penrose's dramatic proposal. The third section turns toward the brain by looking at the eyes of different species as photodetectors. Their resemblance to the photodetectors of quantum optics is stressed. The fourth and final main section contains our proposal for single-photon biological experiments, especially the possibility of insect conditioning to single photons.

Historical Background

Almost since the beginning of quantum mechanics, prominent physicists have had things to say about the interaction of quantum phenomena with the brain. The early focus was, and still often continues to be, on the measuring process. Niels Bohr (1929) was one of the first to point out the apparently dual nature of a macroscopic observer measuring and thereby disturbing in some sense, by the very physical nature of the measurement process, the quantum system being observed. Already in 1931 Bohr's views were formulated more explicitly and carefully by the prominent Russian physicist V. A. Fock (1931/1978):

> A micro-object is revealed in its interaction with and instrument. For instance, the path of a charged particle becomes visible in the irreversible snowballing process that takes place in a cloud chamber or in the emulsion of a photographic plate (the particle loses its energy in ionizing the vapour or the chemicals of the emulsion; hence, its momentum becomes uncertain). The results of the interaction of an atomic object with a measuring instrument (which is described classically) are the main experimental elements the systematization of which, based on the assumptions about the properties of the object, makes up the aim of the theory: from a study of such interactions we can deduce the properties of the atomic object, and the predictions of the theory are formulated as the expected results of these interactions. . . .
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> By making the results of the interaction of a micro-object and a measuring instrument the basis of the new manner of description we introduced an important concept, the concept of *relativity with respect to the means of observation*, which generalizes the well-known concept of relativity with respect to the frame of reference. Such a manner of description does not at all mean that we are ascribing a lesser degree of reality to the micro-object than to the measuring instrument or that we are reducing the properties of the micro-object to the properties of the instrument. On the contrary, a description on the basis of the concept of relativity with respect to

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> the means of observation gives a much deeper, more refined, and more objective picture of the micro-object than was possible on the basis of the idealization of classical physics. …
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> If we take the act of interaction between an atomic object and a measuring instrument as the source of our judgements about the object's properties and if in studying phenomena we allow for the concept of relativity with respect to means of observation, we are introducing a substantially new element into the description of the atomic object and its state and behaviour, that is, the idea of probability and thereby the idea of potential possibility. The need to consider the concept of probability as a substantial element of description rather than a sign of incompleteness of our knowledge follows from the fact that for given external conditions the result of the object's interaction with the instrument is not, generally speaking, predetermined uniquely but only has a certain probability of occurring. With a fixed initial state of the object and with given external conditions a series of such interactions results in a statistics that corresponds to a certain probability distribution. This probability distribution reflects the potential possibilities that exist in the given conditions.
>
> (Fock 1978, pp. 17–19)

Another explicit and well-known formulation of this problem of measurement was given just a year later by von Neumann (1932/1983) in his groundbreaking book on the mathematical foundations of quantum mechanics. We quote in full a long passage that explicitly brings in the brain:

> First, it is inherently entirely correct that the measurement or the related process of the subjective perception is a new entity relative to the physical environment and is not reducible to the latter. Indeed, subjective perception leads us into the intellectual inner life of the individual, which is extra-observational by its very nature (since it must be taken for granted by any conceivable observation or experiment). (Cf. the discussion above.) Nevertheless, it is a fundamental requirement of the scientific viewpoint - - the so-called principle of the psycho-physical parallelism - - that it must be possible so to describe the extra-physical process of the subjective perception as if it were in reality in the physical world …
>
> In a simple example, these concepts might be applied about as follows: We wish to measure temperature. If we want, we can pursue this process numerically until we have the temperature of the environment of the mercury container of the thermometer, and then say: this temperature is measured by the thermometer. But we can carry the calculation further, and from the properties of the mercury, which can be explained in kinetic and molecular terms, we can calculate its heating, expansion, and the resultant length of the mercury column, and then say: this length is seen by the observer. Going still further, and taking the light source into consideration, we could find out the reflection of the light quanta on the opaque mercury column, and the path of the remaining light quanta into the eye of the observer, their refraction in the eye lens, and the formation of an image on the retina, and then we would say: this image is registered by the retina of the the observer. And were our physiological knowledge more precise than it is today, we could go still further, tracing the chemical reactions which produce the impression of this image on the retina, in the optic nerve tract and in the brain, and then in the end say: these chemical changes of his brain cells are perceived by the observer. But in any case, no matter how far we calculate - - to the mercury vessel, to the scale of the thermometer, to the retina, or into the brain, at some time we must say: and this is perceived by the observer. That is, we must always divide the world into two parts, the one being the observed system, the other the observer. …
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> Indeed experience only makes statements of this type: an observer has made a certain (subjective) observation; and never any like this: a physical quantity has a certain value.
>
> (von Neumann 1983, pp. 418–420)

Erwin Schrödinger even made the bold claim that the "observing mind" could not be identified with any physical system. His important discoveries relevant to quantum mechanics were made in the 1920s, but we quote from lectures he gave in Dublin in 1950:

> I must mention one point, in order not to be accused of injustice towards the quantum physicists of our days. I said their statement that in perception and observation subject and object are inextricably interwoven is hardly new. But they could make a case that something about it *is* new. I think it is true that in previous centuries, when discussing this question, one mostly had in mind two things, viz. (a) a direct physical *impression caused* by the object in the subject, and (b) the *state* of the subject that receives the impression. As against this, in the present order of ideas the direct physical, causal, influence between the two is regarded as *mutual*. It is said that there is also an unavoidable and uncontrollable impression from the side of the *subject* onto the *object*. This aspect *is* new, and, I should say, more adequate anyhow. For physical action always is *inter*-action, it always *is* mutual. What remains doubtful to me is only just this: whether it is adequate to term one of the two physically interacting systems the 'subject'. *For the observing mind is not a physical system, it cannot interact with any physical system.* And it might be better to reserve the term 'subject' for the observing mind.
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> (Schroedinger 1996, pp. 156–157)

The outright dualism suggested in the closing sentence is still alive and well among many scientists and philosophers. On the other hand, Penrose, whom we discuss more below, is not sympathetic to such a "dualistic mind" view:

> In my own opinion, it is not very helpful, from the scientific point of view, to think of a dualistic 'mind' that is (logically) *external* to the body, somehow influencing the choices that seem to arise in the action of **R** [state

> vector reduction]. If the 'will' could somehow influence Nature's choice of alternative that occurs with **R**, then why is an experimenter not able, by the action of 'will power', to influence the result of a quantum experiment? If this were possible, then violations of the quantum probabilities would surely be rife! For myself, I cannot believe that such a picture can be close to the truth. To have an external 'mind-stuff' that is not itself subject to physical laws is taking us outside anything that could be reasonably called a scientific explanation.
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> (Penrose 1994, p. 350)

As will be evident, we definitely agree with Penrose on this question of dualism.

Quantum Computation and Beyond

It has been suggested by several scientists that one possible explanation of the extraordinary computational power of the human brain is its use of quantum computing. This topic cannot be reviewed in any detail in the limited space available. A good informal but careful review of the reasons for skepticism about this claim has been given recently by Koch and Hepp (2006). Some detailed negative arguments based on the rapid decoherence process of entangled quantum particles in most environments are to be found in Tegmark (2000). So we shall not explore this issue further here, but approach the relation between quantum phenomena and animal brains from the standpoint of photon detection and conditioning and associative learning.

More radical and, in some ways, more interesting is Penrose's claim (1989; 1994) that "Appropriate physical action of the brain evokes awareness, but this physical action cannot even be properly simulated computationally" (1994, p. 12). He does not, of course, claim this thesis can be at present scientifically established, but it is his current hypothesis of what is most likely the case. So, to be clear, Penrose's view is that the power of the brain goes beyond what can be done by quantum computing, if, in the future, we are successful in building them. (Essentially everyone who has written about quantum computing in technical detail agrees that quantum computers will not have the capability of computing functions that are not computable by a universal Turing machine; the situation is, rather, that such computers, if they can be built, will be able to compute the answers to many complex problems much faster than non-quantum computers.)

From a psychological standpoint Penrose's arguments hinge on the claim that human brains (minds, if you want) are capable of understanding in a way that computers, including quantum ones, are not. His most extended analysis in his 1994 book, which is more detailed on these matters than the 1989 one, centers on the understanding of Gödel's famous negative results that assert the necessary incompleteness of any formal system of arithmetic, namely, whatever the axioms, there will be true statements of arithmetic that cannot be proved. We, as humans,–at least a number of experts–, can understand this result. No computer can. In the 1994 book, Penrose has a rich medley of reponses to the many critics of his earlier argument to this effect in his 1989 book. A lot of what he has to say is certainly worth reading, but in our judgment he is not as convincing as he would like to be, because of the difficulty he recognizes of giving a rich and scientifically satisfactory characterization of what it means to understand something. A second and closely related point is that he ties understanding and awareness to consciousness, and we are more skeptical of making consciousness the centerpiece of the analysis. We believe in consciousness, think it is important, and conjecture, moreover, it will come to be well understood in future neuroscience.

Contrary to Penrose's emphasis on conscious understanding, our view is that the deep and important part of cognition that will be difficult to master scientifically is the unconscious part, which we think does all the hard work of cognitive discovery of new relations, especially of those that are naturally neither recursive nor recursively enumerable, but that can often easily be understood, and even consciously checked recursively, once discovered. For an elaboration of this argument, especially on the point that in many ways unawareness is more fundamental to our mental life than awareness, mainly because we are mostly unaware of mental processes, but aware of their results, see Suppes (2003). Two prime examples are: (*i*) memory retrieval, and (*ii*) speaking rapidly and without premeditation endless grammatical sentences in some natural language. We join those who are doubtful that any quantum computations are involved in these processes, and even less, noncomputational ones a la Penrose, but we also agree with those who hold that the deeply parallel computational processes the brain uses are far from what any current digital computers can yet manage.

Eyes as Photodetectors

Early in the 20th century, behavioral experiments with low-intensity light sources suggested that rods in the eye were sensitive to single photons (Rieke & Baylor 1998). In those early experiments, the stimulus was so weak as to contain about 100 photons, a number far less than the number of photoreceptors on the retina (rods alone in the human eye amount to 120 million). Studies with human subjects conducted by Hecht, Shlaer, and Pirenne (1941; 1942) concluded that, from the 100 photons needed to yield a behavioral response, only 5 to 7 of them were actually absorbed by the retina. The angle used for the light was 10 seconds, of the order of 10^{-5} steradians. Given that the field of vision for the human eye is of the order of 10 steradians, and that the number of rods is of the order of 10^8, this results in an order of 10^2 rods involved. Hecht, Shlaer, and Pirenne 1942 estimated, using more detailed distributions of rods on the retina, that about 500 rods are involved in this process. Because 5 to 7 photons were reaching about 500 rods, they argued that rods were sensitive to single photons. More importantly, the threshold statistics for eliciting a response from a subject satisfied a Poisson distribution characteristic of photons from a thermal light source, thus suggesting that single photons were being detected by the eye.

Further work studying eyes as photodetectors has been undertaken for several different species. For instance, Lilywhite (1977) collected statistics on the locust (*Locusta mi-*

gratoria). Baylor, Lamb, and Yau 1979 examined the response of toads' rods to single photons.

To study the locust eyes' sensitivity to single photons, Lilywhite (1977) exposed them to very dim flashes of light, in a way similar to that of (Hecht, Shlaer, & Pirenne 1942). The electric activities of the eye were monitored by an oscilloscope measuring the photoreceptor membrane potential using a glass microelectrode inserted in it. If no light was sent, the signal in the oscilloscope was flat, but every time a light pulse hit the eye, spikes showed on the electric signal (neurophysiologists often call these spikes *bumps*, to distinguish them from action potentials). The hypothesis was that each spike corresponded to a single photon. To test this hypothesis, Lillywhite (1977) studied their statistical distribution. Since his source of pulses was the heated element of a lightbulb, individual photons should have satisfied a Poisson distribution (Mandel & Wolf 1995). If the spikes shown in the oscilloscope were produced by single photons, then they should also satisfy a Poisson distribution. If, on the other hand, they required more than one photon arriving simultaneously at the eye, a different distribution of spike count would follow. After analyzing statistically the distribution of spikes, Lillywhite concluded that they indeed satisfied a Poisson distribution, thus inferring that the locust eye is sensitive to single photons. Lillywhite was able to estimate the efficiency (i.e., the ratio between the number of spikes and of incident photons) of the locust eye as being 0.59 ± 0.19, with an almost zero dark-count rate.

Several other authors have studied the sensitivity of insect eyes to single photons. Howard et al. (1984) compared the dynamics of photoresponse in 8 species of insects, observing different response times but confirming the single-photon sensitivity claimed by Lillywhite. Single-photon sensitivity was also observed by (Howard, Dubs, & Payne 1984) with similar methods to those used by Lillywhite. But we know of no detailed experiment where true single photons were sent in a controlled way to an insect's eye and correlated to spikes in its electrical activities.

Insect Conditioning and Associative Learning

Pavlov's dogs, conditioned to salivate on hearing a bell (the conditioned stimulus CS) a short time before the appearance of food (the unconditioned stimulus US), are the classical example of conditioning. (Pavlov 1927, but first reported in 1903). Recently Watanabe and Mizunami (2006) have shown that the salivary neurons of the cockroach can be similarly conditioned to respond to odors CS) applied to the antenna of the cockroach prior to receiving sucrose solution (US). This is reported as being the first conditioning of salivation in a non-mammalian species.

Because of the remarkable properties of insect eyes, we are concentrating on insect conditioning and associative learning. To make connections with quantum mechanics, we also focus on conditiong to quantum phenomena. The most natural source is visual conditioning to light of such weak intensity that the photons being absorbed can be counted. But a natural question is this. Why use such insects as cockroaches, crickets or locusts, rather than the much more studied Drosophila or honey bee (*Apis mellifera*), whose eye structures are also suitable? There are two reasons. The first is that in Drosophila and bees it is hard to study the physiological processing of their neurons and neural circuits in comparison to cockroaches and crickets (Lent & Kwong, 2004). The second reason is that cockroaches and similar insects are naturally at home in very dimly lit environments, and their eyes are adapted to detecting a small number of photons in otherwise completely dark containers.

We have not focused in a systematic way on what kinds of evidence count in showing that conditioning or associative learning has occurred, partly because it is often obvious. But there is an important general distinction that we track in our subsequent proposal for new experiments. This is the distinction between behavioral and neural conditioning. The antenna movement of a cockroach is a good example of an observable behavioral response. The reponse of salivary neurons mentioned above is a clear example of neural conditioning. In several species of insects, but in this case, especially crickets, in experiments on visual learning, the neural response of octopaminergic neurons to reward and dopaminergic neurons to punishment have been studied (Unoki, Matsumoto, & Mizunami 2006). The extensive study of dopamine neurons in response to reward in monkeys suggest that similar results should be achievable in other species (see especially Shcultz et al. 1993; Schultz 1998). The reference just cited for crickets is an excellent beginning. For a review of recent studies in insects showing that the biogenic amines like dopamine or octopamine affect not only motivation but play a direct reinforcing role, see Riemensperger, Voller, Stock, Buchner & Fiala 2005; Giurfa 2006.

Proposed Single-Photon Experiments

In the following sections, we discuss some experiments that we believe are feasible with today's technology. We will mainly be interested in experiments involving only one photon at a time. We start with a section on how quantum states with only one photon can be created in the laboratory. We focus on experiments with the visual system of insects, because we believe they are better evolved to deal more efficiently with single-photons than the human or other mammalians visual systems. For instance, some insects have a very low dark-count rate (i.e., false signals indicating the presence of a photon when in complete darkness). In contrast, the human eye has high dark-count rates. The estimated efficiency of the locust eye is about 0.6 (Lillywhite 1977), much higher then the human eye, where only about 5% of the incident photons reach the retina (Hecht, Shlaer, & Pirenne 1941; 1942).

Physics of preparing single-photon stimuli

The first time physicists realized that the laws of nature required energy to be quantized was when Planck studied the thermal light emitted by a blackbody (Planck 1901). To describe the spectrum of blackbody radiation, Planck had to assume that light could only have energies that were integer multiples of h, a fundamental constant that nowadays carries his name. Later on, in 1905, Einstein explained the photoelectric effect by assuming that light was made of particles, each with energy proportional to their frequency and to Planck's constant. So, Planck's thermal light source was explained by Einstein as being composed of light particles, called photons, each with well-defined energy $E = h\omega/2\pi$.

Thermal light sources are the most common light sources available. One important characteristic of a thermal light source is that, if we focus on a single frequency (by using a monochromatic filter), the number of photons is not fixed. For example, if we have two light flashes of the same duration and same intensity coming from a thermal source, the numbers of photons in the flashes are not always the same, but they follow a Poisson distribution. Interestingly enough, light flashes with a well defined number of photons, called Fock states, are hard to produce in a laboratory, and were not available until fairly recently. However, producing light sources with a controlled number of photons, for example, one photon at a time, is a straightforward task with today's technology. Since we are interested in such single-photon sources, we briefly discuss how they can be created.

There are many different techniques available to generate single photons, such as quantum dots (Santori *et al.* 2002; 2004), molecule fluorescence (Brunel *et al.* 1999), semiconductors (Hu, Yang, & Yang 2005), and parametric down conversion (Hong & Mandel 1985; Mandel & Wolf 1995; Diamanti, Waks, & Yamamoto 2004). It may be argued that the most commonly used technique is parametric down conversion (Mandel & Wolf 1995). This occurs when a photon hits a nonlinear crystal and is transformed into two correlated photons, usually named *signal* and *idle* photons (see Figure 1). Since energy and momentum must be conserved, if the incident photon has frequency ω_0 and wave vector $\mathbf{k}_0$, then the energy and momentum of the signal (s) and idle (i) photons must satisfy two equations, where the second one for momentum is a vector one.

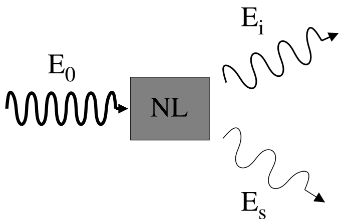

Figure 1: Example of a parametric down conversion. A photon with energy E_0 hits a nonlinear crystal (NL) and is transformed into two new photons, the idler and signal photons, with energies E_i and E_s.

$$\omega_0 = \omega_s + \omega_i,$$

and

$$\mathbf{k}_0 = \mathbf{k}_s + \mathbf{k}_i.$$

Thus, if we use a monochromatic light source and we restrict the angle of the idler photon, we can control the frequency of the signal photon. Because the rate of down conversion is low, and depends on the choice of signal photon, a strong pulsed laser beam is used to generate a reasonable single photon count.

Using parametric down conversion we can design a simple experimental setup where only one photon at a time is sent to the insect eye. Such a device is shown in Figure 2. A pulsed laser sends a very short pulse to the nonlinear crystal. Most of the laser light goes through the crystal, but a small amount of it is downconverted. For the purpose of generating single photons in channel s, the laser intensity is tuned such that the probability for generating a pair of photons is in the range of 0.1 to 0.3, as higher probabilities increase the chance of two pairs being generated simultaneously (Migdall, Branning, & Castelletto 2002). If a pair of photons is generated by parametric down conversion, and one of then goes through one of the slits, the other photon will necessarily go through the other slit, given that slits are chosen to be on the paths that correspond to those given by the conservation of energy and momentum equations. Furthermore, because there are no light sources in the direction i or s, photons exist in those channels only when a parametric down conversion occurred. Because photons are generated in pairs, if a photon is detected in D_i, there is, with very high probability, a photon in channel s. Summarizing, with the setup shown in Figure 2, a laser pulse is sent periodically, with period Δt, and at each time window if there is a photon at D_i we can infer, with very high probability, the existence of a photon at s.

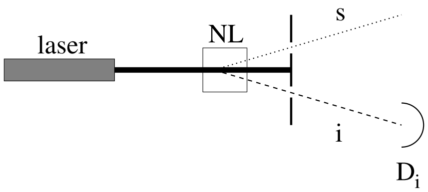

Figure 2: Schematic representation of an apparatus used to send single photons to channel s. A laser generates two correlated photons in a nonlinear crystal LN. Only photons that fit within the angle determined by the slits can reach detector D_i. The dashed line represents the idler photon i, and the dotted line the simultaneously generated signal photon s.

One of the main problems with the above simple setup is related to the efficiency of D_i. Since D_i does not detect all photons arriving in it, sometimes a photon will be in s without a signal in D_i. To prevent miscountings due to this inefficiency, we can insert in s an optical switch, which is open during a short time window when D_i shows the presence of a photon (usually this windows needs to stay open for less than 100 psec (Hong & Mandel 1986)). This switch would guarantee that only when we measure a photon in D_i would a photon go through channel s.

Eye as single-photon detector

Once we have a single-photon source, we can truly test whether an insect eye is sensitive to single photons. With some apparatus, we can know for sure when a photon was sent to channel s, by using a electro-optical switch that opens only when a photon is detected at D_i, as described above. Single-photon sources are useful to determine the physical characteristics of a detector. For example, Rarity, Ridley, & Tapster (1987) describe a process using parametric down conversion to determine the absolute efficiency of photodetectors. Their idea is that in parametric down conversion two photons are generated simultaneously in directions that are correlated. There are no other photons in these directions, except the ones generated by parametric down conversion. Let us, for the moment, ignore dark count rates, and let us assume that the only issue to be measured is efficiency of detectors D_i and D_s placed in the idler and signal channels. Let us use detector D_i as a trigger, such that we only register events in which a photon was detected by D_i. Let n_{is} be the number of simultaneous (within the time window of a few nanoseconds) events with a photon detected both in D_i and D_s, and $n_{i\bar{s}}$ the number of simultaneous events with a photon in D_i but no photon in D_s. Then the efficiency E of the detector D_s is given by

$$E = \frac{n_{is}}{n_{is} + n_{i\bar{s}}}.$$

Rarity, Ridley, & Tapster (1987) used more detailed statistics of the sub-Poisson characteristics of parametric down conversion to determine the efficiency of the detector, but the above expression gives an intuitive idea of how the procedure works. The inclusion of dark-count rates is also straightforward (de Barros & Suppes 2000).

A characterization of the eye as a single-photon detector with sources that are truly presenting one photon at a time is, therefore, possible with the above scheme. This would be a direct way to establish that the eye responds to single photons, as we would not rely on the statistical distribution of spikes. Furthermore, this procedure would allow us to measure the absolute efficiency of the insect eye.

Sensitivity to polarized single photons. Classically, light can be though of as an electromagnetic wave propagating in space. This wave is composed of oscillating electric and magnetic vector fields that are (in the absence of charges) perpendicular to each other and to the wave's direction of propagation (Jackson 1999). When the electric (or magnetic) vector field is oriented spatially in a well-defined way, we say that the wave is polarized. For example, if the electric field vector is always oriented in a fixed direction, we say that the electromagnetic wave is linearly polarized. If the electric field rotates clockwise, we say the wave is circularly polarized with positive helicity. If we think of a classical field as a collection of photons, a linearly polarized wave is itself made up of linearly polarized photons. By this we mean a photon that, when reaching a linear polarizer with orientation that coincides with its own, passes through.

It is well known that animal eyes can distinguish polarized photons (Horvath & Varju 2004). Some insects use patterns of polarized light to orient themselves with respect to the sky (Wehner 1989; Homberg *et al.* 2004). The locust (*Schitocerca gregaria*) takes advantage of the fact that light reflected by water at a certain angle is linearly polarized to avoid flying over the sea (Shashar, Sabbah, & Aharoni 2005).

Given the sensitivity of insect eyes to light polarization, we could use the single-photon source of Figure 2 to generate polarized single-photon states. This could be accomplished by inserting a polarizer in channel i. Because photons in i and s are correlated, it follows that if, say, we chose a circular polarizer with positive helicity in i, the photon in s would have circular polarization with negative helicity. Similar relations exist for linear polarizations. Thus, we could think of single-photon experiments that could study the response of the eye with respect to polarized states. But we do not expect the eye to be able to distinguish the polarization of individual photons, as this is forbidden by quantum cloning theorems (Wootters & Zurek 1982). However, we conjecture that some insects can learn such polarization from a small sample of photons.

Single-photon conditioning

Any insect whose eyes are good detectors of single photons is a good candidate for testing the possibility of conditioning to the occurrence of single photons. As is clear from the literature, the ability to observe evidence of conditioning in neurons of the insect brain will vary considerably from one species to another. On the other hand, the behavioral evidence will be easier to get, even if it too will vary across species.

Given the history of successful conditioning of crickets, cockroaches, etc., we see no problems in principle of performing these experiments. But it is not certain they will work, and so it seems desirable that they be undertaken. Note that the results already available support the conclusion that conditioning to a small number of photons (< 10) can reliably be repeated. This small number of photons already puts us in the quantum domain. Moreover, given the same small number (< 10) as the estimate of the number of photons effective in some human experiments (Hecht et al, 1942), it is conceivable that humans can be conditioned in a quantum regime of light, so that single-photon conditioning experiments are worth trying on them as well, even if the results are more problematic than for insects.

Let us assume, for purpose of commentary, that such single-photon insect-conditioning experiments are successful. What do they imply about the relation between quantum mechanics and the brain? They would show very clearly sensitivity in animals that can be so conditioned to the smallest quanta, i.e., photons, of standard quantum mechanics or quantum electrodynamics. The animals are learning to recognize photons as signals of something to approach, for a reward, or to avoid, to escape punishment. (The use of the verb *recognize* is not meant to imply any commitment to conscious recognition.) That animals have evolved to be sensitive to signals of such low energy is surprising, but easy enough to see as valuable in the life of a cricket or cockroach, spent mainly in the dark. The evolutionary part that seems most remarkable is the evolution of the eye as a detector of photons nearly equal to the best modern charge-coupled or homodyne devices. This technical feat that probably took many millions of years was not even recognized as such until the twentieth century with the discovery of quantum mechanics.

Final remarks

The message that we have meant to deliver is that there is a perhaps surprising evolutionary history of biological adaptation of many different animal species to quantum phenomena, indeed at levels not measured by physicists until late in the twentieth century. In his recent Frisch Lectures, Warrant (2004) gives a detailed survey of the wide range of insects, fish, and worms that have evolved to survive in very dimly lit environments, all natural candidates for adaptation to signals consisting of a few photons.

As an important example we focused on insects, and proposed at one extreme of quantum optics, animal conditioning to single photons. Positive experimental results would provide clear evidence of the relevance of quantum phenomena to brain processes.

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