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Can Mind Affect Matter Via Active Information?

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Abstract

Mainstream cognitive neuroscience typically ignores the role of quantum physical effects in the neural processes underlying cognition and consciousness. However, many unsolved problems remain, suggesting the need to consider new approaches. We propose that quantum theory, especially through an ontological interpretation due to Bohm and Hiley, provides a fruitful framework for addressing the neural correlates of cognition and consciousness. In particular, the ontological interpretation suggests that a novel type of "active information", connected with a novel type of "quantum potential energy", plays a key role in quantum physical processes. After introducing the ontological interpretation we illustrate its value for cognitive neuroscience by discussing it in the light of a proposal by Beck and Eccles about how quantum tunneling could play a role in controlling the frequency of synaptic exocytosis. In this proposal, quantum tunneling would enable the "self" to control its brain without violating the energy conservation law. We argue that the ontological interpretation provides a sharper picture of what actually could be taking place in quantum tunneling in general and in synaptic exocytosis in particular. Based on the notions of active information and quantum potential energy, we propose a coherent way of understanding how mental processes (understood as involving non-classical physical processes) can act on traditional, classically describable neural processes without violating the energy conservation law.

1. Introduction

Cognitive neuroscience has made remarkable advances in recent years in understanding the neural basis of cognition and consciousness. But as is well known, unsolved problems remain. There is, for example, the problem of phenomenal binding. We know a great deal about how the brain receives information and analyzes it, but it is much harder to explain how such distributed information is synthesized into the coherent multi-modal "virtual reality" that is part of the content of our conscious experience. More deeply, there is the "hard problem" of consciousness: why are there conscious experiences associated with neural processes at all? Then there is the problem of mental causation: Are mental processes physical and, if not (as many philosophers still argue), how can they possibly affect physical processes (which they seem to do) without violating the causal closure of the physical domain? Further, there is the problem of how to understand the neural basis of meaning and intentionality. Also, is there a physiological basis of creativity and intelligence (for example, can these be understood in computational terms)?

Intensive research is currently taking place on many of these questions. However, much of this research does not give attention to certain fundamental, underlying assumptions about the nature of physical processes in general, which are also tacitly present in cognitive neuroscience. One such assumption is that the brain is a system that, from the point of view of physics, can be understood entirely in terms of the conceptual framework of classical physics. Of course, it seems obvious that many observable neural processes can indeed be understood in the framework of classical physics. But does this justify the popular speculation among neuroscientists that *all* neural processes relevant to cognition and consciousness can be thus understood? We already pointed out that cognitive neuroscience is faced with some fundamental unsolved problems. When faced with such problems, one good strategy is to examine the various assumptions that one has made, and to see whether some of the problems arise as a result of holding on to such assumptions.

Our suggestion is that some of the problems of cognitive neuroscience are connected with the tacit speculation about the classical physical nature of all relevant neural processes. Therefore we think that it is worthwhile to challenge the assumption that all neural processes relevant to cognition and consciousness can be understood in terms of the concepts of classical physics. We do this by considering the possible role of quantum physical concepts in this context. When doing this we do not want to claim that cognition and consciousness can be completely understood in terms of quantum concepts. Rather, we think it is more likely that quantum physics has its limits and that a new theory needs to be developed to give a satisfactory account of the physical and physiological aspects of cognition and consciousness. But at the present stage it may be important to consider quantum physical ideas, partly in order to reveal the way in which hidden commitments to classical physics may tacitly and unnecessarily constrain neuroscience, and partly to get a physically based idea of the direction that a more satisfactory theory of cognition and consciousness might take.

In this paper we, thus, want to explore the potential relevance of particular aspects of quantum physics to some of the questions that cognitive neuroscience faces. The key idea is that, when quantum physics is looked at from a particular point of view, it seems that an entirely new type of information plays an active role in physical processes. An important possibility is that this information is not only present in the traditional domain treated by quantum theory, but it could also have implications on the macroscopic scale. The notion of information is clearly central in cognitive neuroscience. A fundamental change is, thus, possible in cognitive neuroscience if it turns out that this new "active information" is involved in neural processes, including those underlying cognition and consciousness. In this paper we will explain what this new information is, consider how it could play a role in some neural processes, and finally discuss some of the possible implications.

2. Quantum Physics and its Interpretation

Traditional quantum theory correctly predicts the results of a wide range of measurements. But as is well known it gives rise to a number of philosophical problems and paradoxes. For this reason, many scientists find it unattractive to consider the relevance of quantum physics in the context of cognitive neuroscience.

However, there is an alternative way of looking at quantum physics that is in several respects clearer than traditional quantum theory. This "ontological interpretation" was proposed by David Bohm in 1952 and has been subsequently developed further (see Bohm and Hiley 1993). Although the ontological interpretation provides in many ways a clear and understandable view of the quantum domain, it by no means suggests a return to classical physics. On the contrary, it involves a number of radically new features, in particular the suggestion that a new kind of active information plays a role in physical processes. These features have been discussed in some detail in previous publications by Bohm and Hiley (1987, 1993), Bohm (1989, 1990), Hiley (1994, 1995, 2001), Pylkkänen (1992) and by Hiley and Pylkkänen (1997, 2001).

In this paper we want to explore the question of whether there is some way in which active information could play a role in neural processes. In particular, we will consider the notion of active information in relation to the approach proposed by Beck and Eccles (1992) and further developed by Beck (1996, 2001); see also Lindahl and Århem (1994, 1996).

3. A Brief Review of the Ontological Interpretation of Quantum Theory

The simplest way to approach the ontological interpretation is to write the complex wave function ψ for a particle of mass m in terms of two real functions R and S:

$$\psi(r,t) = R(r,t)\exp\left[i\,S(r,t)/\hbar\right] \ , \tag{1}$$

where R is the wave amplitude, S is the action, and $\hbar$ is Planck's action divided by 2π. When this is put into Schrödinger's equation, the resulting equation can be split into its real and imaginary parts. The real part takes the form:

$$\frac{\partial S}{\partial t} + \frac{(\nabla S)^2}{2m} + V + Q = 0 \ . \tag{2}$$

This equation and particularly the last term Q $\left(= -\frac{\hbar^2}{2m}\frac{\nabla^2 R}{R}\right)$ have some interesting consequences. To bring these out, let us note the close similarity to the classical mechanical particle equation

$$\left(\frac{\partial S}{\partial t}\right) + \frac{(\nabla S)^2}{2m} + V = 0 \ . \tag{3}$$

Notice that only the term Q from Eq. (2) is missing. Equation (3) is the classical Hamilton-Jacobi equation, which describes a particle moving in a classical potential V, and S is the classical action. We can put this equation into a more familiar form by noting that the energy E and momentum p of the particle are given by

$$E = -\frac{\partial S}{\partial t} \qquad \text{and} \qquad p = \nabla S \ . \tag{4}$$

Inserting these into Eq. (3), we obtain

$$E = \frac{p^2}{2m} + V \ , \tag{5}$$

which is just an expression for the conservation of energy in the classical context: the total energy is the sum of kinetic energy and potential energy.

Assuming that E and p according to Eq. (4) also hold for Eq. (2), we find a similar energy equation, but now with an additional energy term Q, which is only present for particles with quantum properties. Since this additional term distinguishes between classical and quantum behavior, we call Q the "quantum potential energy". Equation (2) will be called the quantum Hamilton-Jacobi equation.

The imaginary part of Schrödinger's equation can be written in the form:

$$\frac{\partial \rho}{\partial t} + \nabla .\left(\rho\frac{\nabla S}{m}\right) = 0 \ , \tag{6}$$

where ρ is the probability density of finding the particle at position r. This equation can, thus, be interpreted as the conservation of probability, which ensures that, if we start with the quantum probability distribution, we will end up with the same probability distribution as in standard quantum mechanics.

The quantum potential energy does not behave like an additional energy of classical type. It has no external source, but is some form of internal energy, split off from the kinetic energy (see Brown and Hiley 2000). Furthermore, if we look at traditional quantum mechanical problems and examine the quantum potential energy in mathematical detail, we find that it contains information about the experimental environment in which the particle finds itself, hence its possible role as an information potential.

Since the classical Hamilton-Jacobi equation allows us to calculate an ensemble of trajectories, we assume that the quantum Hamilton-Jacobi equation also allows us to calculate an ensemble of trajectories, modified by the presence of the quantum potential energy. In other words, we can think of the quantum potential as feeding energy into each individual particle as it goes through the experimental apparatus. We assume that each particle will follow one definite trajectory from beginning to end. Nevertheless the ensemble of particles will exhibit wave-like behavior (*e.g.* an interference pattern builds up gradually when the particles hit a screen one by one). That is, in an interferometer the particle will end up as a spot on the screen, thus corresponding closely to what we actually observe in the laboratory. In this regard there is no need for any collapse of the wave function to account for the fact that we observe a spot on a screen or other detecting devices. This spot is produced by the particle which is assumed to arrive there at the end of its trajectory.

One immediate reaction to the notion of a particle following a trajectory in quantum mechanics is that surely this must violate the uncertainty principle. However, uncertainties can be thought of in two distinct ways. The conventional view is to say that the particle itself cannot be localized at a point with a definite momentum. The other view is simply to say that we cannot measure the position and the momentum of the particle at the same time. Indeed, this is a much more accurate description of the actual situation, because it can be shown in every case that it is not possible to build a piece of apparatus that enables one to measure both the position and the momentum at exactly the same instant. The traditional view in quantum physics has been to assume that this inability to measure means that the particle does not have a well-defined position and a well-defined momentum simultaneously. However, the empirical data in no way rules out the possibility that the particle actually has a well-defined position and momentum simultaneously. It merely shows that we cannot measure them simultaneously. Because the empirical evidence does not rule out either possibility, one is free to make the hypothesis one feels to be reasonable on grounds other than empirical ones.[1]

One reason why we think it is worthwhile to explore the hypothesis that, say, an electron is moving along a trajectory under the influence of the quantum potential is that in this approach many of the well-known paradoxes and ambiguities of quantum theory can be resolved (Bohm and Hiley 1993). The second reason is that it opens up an entirely new way of looking at the role of energy and information in physics in general, which in turn can have far-reaching implications in other domains such as biology and psychology.

Let us now move on to give a particular example that we will use later again. One of the traditional puzzles in quantum mechanics is how particles can penetrate a potential barrier when their kinetic energy is less than the barrier height (so-called quantum tunneling). In the standard approach we are left with the account that sometimes the particle goes through while at other times it does not. All we can know are the probabilities of this happening in an ensemble of particles. It is assumed that whatever happens to the individual particle is genuinely indeterministic. In the Bohm theory, however, whether a particle goes through a barrier or not is determined by the position of the particle in the initial wave function. We illustrate this by numerically calculating the trajectories from the quantum Hamilton-Jacobi equation (2), and the result is shown in Figure 1.

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[1] For a fuller account of how this hypothesis should be understood see Bohm and Hiley (1993). We would like to emphasize that in our view all theories are primarily ways of looking, which may be correct in a given domain but are likely to be incorrect in some more general domain. Accordingly, we are not claiming or assuming that the model of an electron moving along trajectories is a complete and final description of *the* fundamental level of reality (for arguments questioning the existence of such a single fundamental level of reality see *e.g.* Bohm 1957/1984 and Schaffer 2003). Instead, we assume that this model may indeed be correct – and provide us with a great deal of insight – in its own domain, but will turn out to be incorrect in a broader domain. For example, it is possible that at the level of Planck time (10^{-43} sec) movement is discrete and the notion of a particle moving continuously along trajectories becomes inapplicable. This notion, thus, ought to be replaced at this level, for example by the notion of a series of converging and diverging quantum mechanical waves, which give rise to particle-like manifestations in a discrete fashion (see Bohm and Hiley 1993, pp. 367–368). This involves taking as fundamental a new basic order in physical processes, the "implicate order". Actually, the implicate order prevails already at the level of the ontological interpretation, for example in the way the wave function enfolds information about the whole environment at each region of space, and also enables non-local correlations between the particles in suitable conditions. However, we assume that the implicate order is even more prevalent at Planck scales where the "explicate order" of continuously moving particles has to be given up. Moreover, we think that the implicate order provides a general framework for discussing the relation of mind and matter in a coherent way. See Bohm and Hiley (1993), Chap. 15, and Bohm (1980).

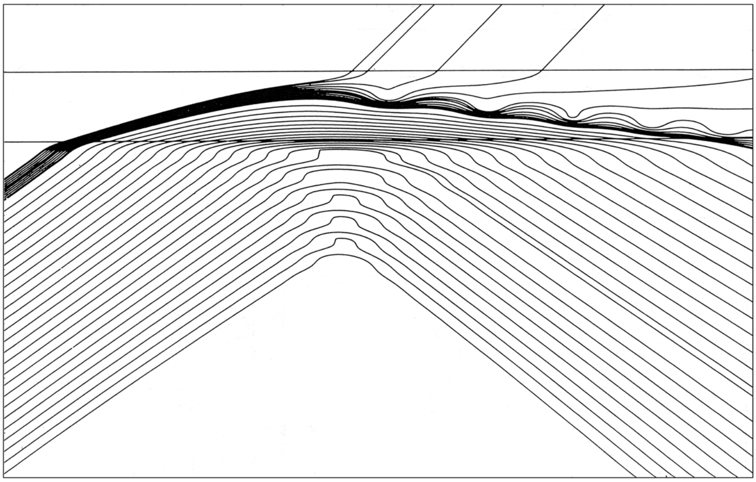

Figure 1: Possible individual particle trajectories for an ensemble of particles described by a Gaussian wave packet incident on a potential barrier indicated by the two horizontal lines in the upper part of the plot. Time evolves from left to right, and the distance from the barrier is plotted vertically. The mean kinetic energy of the incident particles is half the barrier energy: $\langle E_{\text{kin}} \rangle = V/2$. Particles at the front of the packet penetrate the barrier while those in the rear are reflected. Notice that particles are reflected well before they reach the barrier. This happens because of the presence of the quantum potential (see Fig. 2). Notice also that there is a group of particles that become temporarily trapped in the barrier before being transmitted or reflected out of the barrier. (Reprinted from Dewdney and Hiley 1982.)

For this illustration we have assumed that the initial wave function describing the particle is a Gaussian packet with a mean kinetic energy that is half the barrier height. If we look at the trajectories in Fig. 1, we see that those trajectories toward the front of the wave function penetrate the barrier and those to the rear are reflected even before they reach the barrier. There is also a group of trajectories that remains inside the barrier for a significant period of time. All of this is consistent with the standard approach using only wave functions, where we are left with a reflected wave packet, a transmitted wave packet and a wave packet inside the barrier which slowly diminishes with time. The Bohm theory adds to this picture insofar as it specifies which particles will penetrate the barrier and which will not.

It might seem strange to find that reflected particles do not even reach the barrier. We can account for this if we look at the quantum potential shown in Fig. 2, which is calculated directly from the standard solution of Schrödinger's equation. The shape of the quantum potential forms a series of time-dependent barriers in front of the classical potential barrier. These time-dependent barriers prevent the particle from going further. When we look at the quantum potential and the classical potential in the region of the barrier, we see that the effective height of the barrier is reduced. In addition, the particles in the front of the packet have their kinetic energy increased, so that they can actually penetrate the barrier without violating the law of energy conservation. In other words: although the total energy is strictly conserved, there is a redistribution of energy between the kinetic energy, the quantum potential energy and the classical potential energy. The interchange of energy between these various qualities of energy allows the particles to penetrate the barrier without violating the conservation of energy.

This example shows how the Bohm theory works and illustrates what happens in situations that are often considered to be puzzling. The Bohm account clarifies such puzzles because the equations include a novel form of energy.

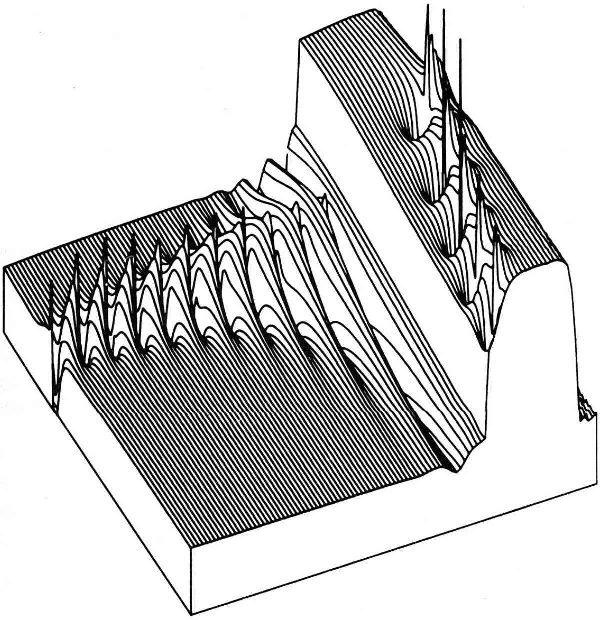

Figure 2: Quantum potential for the situation shown in Figure 1. The distance of the particle from the barrier decreases from left to right, and time increases toward the front of the diagram. Notice the rise of the potential in front of the barrier which is responsible for the reflection of particles before they reach the barrier. (Reprinted from Dewdney and Hiley 1982.)

4. Possible Connections with Neuroscience

Let us now consider how this new way of looking at quantum theory might help us to understand what is going on in a well-known neural process which is commonly thought to involve an individual quantum process: the detection of a single photon by a rod in the retina of the eye. The photon is absorbed by the 11-cis retinal molecule. This induces a conformal change in the retina, allowing it to relax to its more stable all-trans configuration. This process in turn triggers a chain of events which first leads to a signal in the optic nerve, and eventually to a conscious experience of light.

In order to compare the Bohm approach with other approaches that have been used to discuss the brain, consider a typical quantum experiment in which a single particle is first fired at the particle analogue of a half-silvered mirror. (For a particular particle we mean by a "half-silvered mirror" any device that allows the particle to pass half of the time.) Suppose we have two observers situated at some distance from this mirror so that one receives the particle if it is transmitted and the other receives it if it is reflected. Standard quantum mechanics insists that we describe the whole system by a wave function. The initial wave function for the particle before it enters the mirror, and the initial wave functions for two observers A and B can be written in the form

$$\Psi_{\text{initial}} = \psi_{\text{particle}}\ \phi_1(A)\ \phi_1(B)\ , \tag{7}$$

where ϕ_1 describes the observer before it sees the particle.

After the particle has had time to reach either one of the observers, Schrödinger's equation tells us that the final wave function must be an entangled wave function which can be written as

$$\Psi_{\text{final}} = \psi_{\text{particle}}\ \phi_2(A)\ \phi_1(B)\ +\ \psi_{\text{particle}}\ \phi_1(A)\ \phi_2(B)\ , \tag{8}$$

where ϕ_2 describes the observer after it saw the particle.

If one looks at this wave function in the usual interpretation involving only wave functions, we see that the states of the individual observers are not well-defined. The first term in this wave function tells us that observer A sees the particle while observer B does not. The second term tells us that *at the same time* observer B sees the particle while A does not. We emphasize here that this is not an either/or description. *Both terms in the final wave function are present at the same time.* However, what actually happens is that either A sees the particle or B sees the particle, and there is never a linear superposition. To account for this, the standard approach simply says that at some stage the wave function collapses to one of the terms, but no reason whatsoever is given as to why this collapse should take place.

Penrose and Hameroff have also pondered these kinds of questions in their discussion of physical aspects of mind (see for example Hameroff and Penrose 1996). Penrose suggested that, if we bring in general relativity, we can have an objective reduction of the wave function. Penrose and Hameroff then use this idea and propose that such a spontaneous, orchestrated, objective collapse of the wave function is the physical correlate of a non-computable insight. We do not want to comment on the details of this suggestion here, but merely wish to point out that in the situation we have considered above there must be a simultaneous non-local collapse induced by gravity at both observers. This ensures that both observers, who may in principle be far apart from each other, will obtain a consistent result saying that the particle is experienced by only one of them. This may well be a possible mechanism, but it seems to be an extreme version of some sort of non-locality. Of course, we know that non-locality occurs in quantum mechanics and, in particular, that it occurs also in Bohm theory. However, the Bohm theory does not need such a non-local explanation in this particular experiment. One thus wonders whether the gravitational collapse introduced by Hameroff and Penrose is necessary to produce the collapse of the wave function.

It may be possible to avoid this problem by rejecting the idea of collapse and instead – if one finds it acceptable – adopting some kind of Everett interpretation (as in some approaches that invoke environmental decoherence). In the Bohm theory, however, there is no such problem to begin with. The particle either goes through the half-silvered mirror, or it is reflected. If it goes through, observer A sees it, while if it is reflected, observer B sees it. Although the Bohm theory has a linear superposition of states, the information contained in the quantum potential is only active where the particle is. The information in the other channel is inactive and, therefore, has no effect. Thus, if quantum theory has a role to play in brain function, then the Bohm theory seems to be worth exploring already for this fact alone. There are further features, however, that make the Bohm approach appealing, which we will explain as we proceed.

5. Active Information

We have mentioned that it is convenient to think about the quantum potential in terms of active information. Before explaining how the notion of active information links with the role information plays in brain activity it is necessary to explain in more detail how the notion of active information can be used to explain quantum effects. To do this it is most convenient to consider a particle Mach-Zehnder interferometer as shown in Figure 3.

Here a beam of particles is incident on the first half-silvered mirror M_1, where it is split in two. Half of the particles follow the upper path while the other half follow the lower path. The beam will recombine at the second half-silvered mirror M_2. If both paths have exactly the same length, constructive interference occurs, and it is not difficult to show that all the particles reach B and no particles reach A. The reason for this is due to the phase changes that take place at the mirrors. Thus, the final wave function at B will be non-zero due to constructive interference, while the wave function at A will be zero due to destructive interference. If we consider particles entering the interferometer one at a time, the situation in which one of the puzzles of quantum theory is starkly revealed, then every particle will reach B and none will reach A. This means that only the detector at B will fire as each particle arrives.

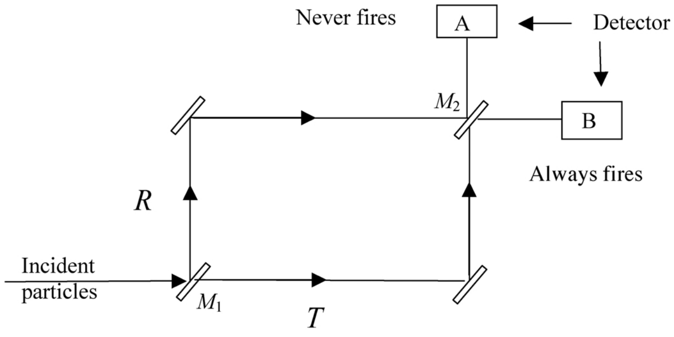

Figure 3: Set-up of a Mach-Zehnder interferometer

Clearly, we have arrived at this conclusion by making use of the linear superposition of the two beams. This seems to present no difficulty for the standard interpretation as long as we have a stream of particles. But suppose we reduce the intensity of the beam so that only a single particle enters. The standard interpretation will give a straightforward answer, because the probability of arriving at B is one and probability of arriving at A is zero. In this situation, it is tempting to say that surely the particle follows one and only one path. Indeed, in the Bohm approach the particle does actually follow one path but in a certain sense it also behaves as if it had followed both paths when it gets to the detectors. So we can ask how the particle following one path knows that the other path is actually open.

This is where active information comes in. While the particle travels along one path, it is subjected to the quantum potential calculated from the wave function associated with that path. In this case we say that the quantum potential carries active information. The wave function associated with the second path also provides a quantum potential, but the information in that quantum potential is merely passive, because there is no particle in the second path for it to act on. When the particle passes through the second half-silvered mirror the two wave functions overlap again and both components contribute to the quantum potential acting on the particle. Thus, the passive information becomes active again, that is, linear superposition takes place, giving rise to a new quantum potential. The particle then responds to this information, traveling to B and not to A.

Now let us go on to consider the situation where we make a late choice to block one of the paths. This is Wheeler's delayed choice experiment. Here the standard interpretation should present no difficulties. The wave function on the closed path becomes zero and therefore does not contribute any further. The wave function on the open path meets the second half-silvered mirror, part of it is transmitted and part of it reflected, so that each detector fires 50% of the time.

A similar situation appears in the Bohm interpretation, but now we can discuss alternatives. If the particle follows the upper path, while the lower path is closed, the information coming from the wave function of the lower part is zero, so that the particle is either transmitted or reflected with equal probability when it strikes the second half-slivered mirror. If the particle follows the blocked path, nothing happens. So the explanation in both cases is straightforward.

Unfortunately, Wheeler and others have somewhat confused the situation by discussing this experiment in terms of the notion of wave-particle duality (connected to Bohr's principle of complementarity). Wheeler (1978) suggests that, when both paths are open, we see the effect of the wave properties of systems, but when one path is closed, we see particle behavior. To clarify Wheeler's problem, suppose that the experimenter delays his choice of whether to leave both paths open or block one of them until the particle has passed the half-silvered mirror M_1 but not yet reached M_2. This would, according to Wheeler, frustrate the particle in its "choice" of whether to behave like a wave or a particle. This is the problem that Wheeler considers a paradox. The fact that the particle is not frustrated must imply that the "past must be affected by what we choose to do in the future". However, no such statement is necessary in the Bohm approach because both the wave and the particle aspect are taken into account all the time.

After this discussion of Wheeler's delayed choice experiment, it is now time to consider the notion of active information in more detail. First of all, it is suggested that information is objective in the sense that *information for the particle* is regarded. This contrasts with the common idea of information, which is seen as information for human beings. Here we consider a role for information in the absence of subjects. This notion of objective active information opens up new connections between information and meaning, some of which have been discussed by Hiley (2002).

The proposal is that active information at the quantum level organizes the dynamical evolution of the system itself. To make this notion more concrete we can consider the root of the word information, which literally means to put form into a process. As we remarked earlier, the quantum potential appears to be some kind of internal energy which carries information about the environment. Therefore we consider the idea that the whole process, particle plus active environment (which in terms of a measurement requires the specification of experimental conditions), is being formed partly from within. This suggests that the process is more organic than mechanical. In this respect the system does not require an external force to solely determine its future behavior, thus clearly enriching the notion of causality. It looks as if the classical potential can be regarded as a "push-pull" potential while the quantum potential involves something subtler such as information.

After a detailed examination of this potential in many different experimental situations, Bohm and Hiley (1993) suggested that it acts by producing a change in the form of the process. In a somewhat Aristotelian fashion, a "formative cause" is present in addition to "material" and "efficient" causes. Indeed, we can specify this idea by looking at the form of the quantum potential $Q = -\frac{\hbar^2}{2m}\frac{\nabla^2 R}{R}$, where R is the amplitude of the quantum wave. This rather strange potential introduces a "force" which must be contrasted with the force introduced by a classical wave. The classical wave produces a force that is directly proportional to the square of the amplitude. The greater the amplitude, the bigger the force it produces, a fact that anyone who swims in rough sea can experience at first hand. But in the case of the quantum wave the amplitude also appears in the denominator. Therefore, increasing the magnitude of the amplitude does not necessarily increase the quantum potential energy. A small amplitude can produce a large quantum effect. The key to the quantum potential energy lies in the second spatial derivative, indicating that the shape or form of the wave is more important than its magnitude.

For this reason, a small change in the form of the wave function can produce large effects in the development of the system. The quantum potential produces a law of force that does not necessarily fall off with distance. Therefore, the quantum potential can produce large effects between systems that are separated by large distances. This feature removes one of the difficulties in understanding the non-locality that arises between particles in entangled states, such as those in the EPR-paradox (see Bohm and Hiley 1993, Chap. 7, for more details).

In the cases considered so far the quantum potential is determined by the Schrödinger equation. But this equation is not deduced from any primitive notions in quantum mechanics. Rather, it was discovered by mathematical arguments that were far from unambiguous, as Schrödinger himself admitted (see Schrödinger 1926 and also de Gosson 2001). Therefore we propose that active information may determine the unfolding of more general processes, which are not necessarily governed by the Schrödinger equation, but can involve other, deeper factors. We want to keep this possibility in mind when discussing the role of active information in neural systems.

6. Now to the Brain

Most cognitive neuroscientists assume that, from the point of view of physics, the brain can be treated completely in terms of classical concepts. This is certainly one of the reasons why neuroscientists have so far disregarded the possible relevance of the notion of active information, as it appears in the Bohm approach, for neuroscience. However, there are some exceptions to this viewpoint. Eccles (1986) proposed that quantum processes may be important in understanding the more subtle activities of the brain. Following a suggestion by Margenau (1984), Eccles postulated a "mind-field" that could somehow alter quantum transition probabilities. How this could happen exactly was left unanswered. We think that the notion of active information could make such proposals much stronger. Therefore, let us look at Eccles' proposal in light of the Bohm approach. To do this we start by first summarizing Eccles' proposal, which was developed further in cooperation with Beck (Beck and Eccles 1992, Beck 1996, 2001).

Eccles advocated a dualist approach to the mind-matter problem. More precisely, he suggested that mind ought to be understood as a non-material field carrying little or no energy, which nevertheless can trigger neural processes, for example in the motor cortex. A typical materialist objection to such an idea has been that any such effect of a non-material mind on the activity of the material brain would necessarily violate the conservation of energy. Such a violation is thought to be very implausible and, as a consequence, Eccles' suggestions were considered as contradicting established natural science. The problem for Eccles was, thus, to show that a non-material mental field can affect neural firing without violating the energy conservation law.

In this regard, he drew on a proposal by Margenau (1984), according to which the

> ... mind may be regarded as a field in the accepted physical sense of the term. But it is a nonmaterial field, its closest analogy is perhaps a probability field. It cannot be compared with the simpler

> nonmaterial fields that require the presence of matter (hydrodynamic flow or acoustic)... Nor does it necessarily have a definite position in space. And as far as present evidence goes it is not an energy in any physical sense.

Eccles suggested that this non-material field could change the probability of synaptic vesicular emission, provided that one appeals to quantum principles. He went on to propose that particular quantum effects can be used to control the frequency of exocytosis without violating the conservation of energy.

In order to explore possible sites for such quantum effects to be operative, Beck and Eccles (1992) concentrated on the function of spine synapses. Here the regulatory function that results from exocytosis occurs only with probabilities much smaller than one for each incoming nerve impulse. They therefore regarded this exocytosis as a candidate for quantum processes to influence neural activity. The appearance of the low transition probabilities in synaptic exocytosis implies that there exists an activation barrier against the opening of an ion channel in the presynaptic vesicular grid. Such barrier transitions can occur either purely stochastically by thermal fluctuations or by stimulation of a trigger process. Beck and Eccles proposed a two-state quantum trigger which activates the gating process by means of quasi-particle tunneling. The calculations given by Beck and Eccles suggest that this is an appropriate place for quantum tunneling to occur, so that the probabilities of exocytosis could be changed by a "mind-field".

Let us now consider this in light of the Bohm approach. For the sake of the argument, let us assume that the "mind-field" can be seen as containing active information which contributes to the quantum potential.[2] As

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[2] We do not discuss the ontological nature of the "mind-field" in more detail here. Our focus in this paper is on whether a non-classical physical process could play an interesting role in the neural processes correlated with mental processes. One possibility is to see the "mind-field" as an emergent property in biological systems of a particular organization and complexity (in an analogous way as superconductivity can be seen as an emergent property in particular physical systems). However, different doctrines in the philosophy of mind might interpret the idea of a "mind-field" in their own way (in case they would accept such an idea). For example, a property dualist could see it as a mental property; a functionalist would focus on the functional role it plays; an eliminative materialist could see it as a new scientific (physicalist) concept of mind, replacing traditional folk-psychological categories; etc. (see *e.g.* Churchland 1988). Another interesting issue (which is also not discussed here) is the relation between the idea of a "mind-field" which contains active information and the various proposals for field theories of consciousness currently explored in consciousness studies (see *e.g.* McFadden 2002, see also the recent review by Lipkind 2005).
A little more clarification of our viewpoint, however, might be useful here. In our research, we assume that mind and matter are two *aspects of* or *ways of looking at* an underlying reality (a viewpoint that has roots in Aristotle and Spinoza and, more recently, Russell, and is variously labeled as "aspect monism" or "neutral monism" in

described above, this action of the quantum potential effectively reduces the height of the barrier to increase the probability of exocytosis. Thus we could regard the “mind-field” as initiating a subsequent neural process which finally activates the motor neurons to produce the outward behavior. In this sense, active information is merely the trigger for the usual classical processes that follow the gating of ion channels (more details can be found in Århem 2000, Århem and Lindahl 1997).

So far we have discussed but one specific example of how quantum ideas may help to understand the mind-brain relation. There may be other brain processes where the notion of active information could be more appropriate. One suggestion that we presently investigate is the behavior of dendritic fields, where it has been suggested that important information processing may be going on (Pribram 2004). Here statistical processes involving active information may be important, as discussed in a preliminary way by Hiley (2004). In this paper we want to return to consider the general relevance of quantum theory to the mind-matter problem, leaving specific details for later publication.

To begin this general discussion let us distinguish three basically different points of view in this respect. First there is the view that only the laws of classical physics are relevant for processes going on in the brain. This means that neural processes are entirely determined by those laws alone, and there is no room for any non-classical “mind-field” to have an influence upon neural processes. The second view arises if we suppose that quantum processes, as understood in standard quantum mechanics, trigger some neural processes in the brain. This implies that there is a mixture of determinism and uncontrollable indeterminism entering through the collapse of the wave function. The third view is that there are quantum processes triggering some neural processes in the brain, but that these quantum processes can in turn be affected by some higher-level processes, such as the putative “mind-field” (which we think of as a

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philosophy). We follow Bohm in proposing that such a reality can, for convenience, be analyzed in terms of *levels* that differ with respect to their subtlety. Each level then has both a physical and a mental aspect, and this makes a “two-way traffic” between levels possible. Bohm suggested, radically, that even the quantum level can be thought to have, via active information, a *primitive mind-like quality*, although it obviously has no consciousness. We think this is a very important contribution that Bohm made to mind-matter research. It opens an option to provide a mathematical description of putative “proto-mental” features (i.e., active information) at the quantum level.

What we have called the “mind-field” could then be seen as a fairly subtle level of reality. Like all levels, this level has both a physical aspect and a mental aspect. We assume that for the “mind-field” the physical aspect is very subtle, for example more subtle than the quantum field. But the important point is that the “mind-field” is still assumed to have a physical aspect, it can thus influence other such levels (e.g the known neural levels) and be influenced by them. In this way we claim to avoid dualism or idealism without falling into reductive materialism. The whole point of double-aspect approaches is to avoid these extremes.

higher level of organization with, like all levels, both a mental aspect and a physical aspect[3]). This means that quantum processes are not, as usual, assumed to be merely indeterministic but can, at least in circumstances where higher levels have a non-negligible effect, be used to determine the outcome of physical processes.

It seems to us that the third alternative is most interesting in the present context. The first view raises the well-known conflict between determinism and free will which already Kant tried to resolve, and which still presents a major problem area in the current philosophy of mind (see *e.g.* Davidson 2001, Kane 1996). The second view merely postulates a fundamentally indeterministic element in neural processes, but the strange combination of determinism and indeterminism that it implies does not, in our view, capture what is involved in human activity including the role of the mind.

The third view opens up the possibility that the mind, regarded as a process taking place at a higher level of organization with both a mental and a physical aspect, goes beyond processes studied in traditional neuroscience but can nevertheless play an active role in the physical world through its effect, for example, upon exocytosis. “Mind” acts on “matter”, but this is not a question of a mechanical interaction of two separate substances. Rather, mind is now understood as a new level containing active information, which affects the quantum potential, which in turn affects the physical processes in the brain. This view implies that the laws of quantum theory are only approximate, and that in particular situations a higher level such as the “mind-field” can produce results different from the statistical predictions of standard quantum theory. We propose that this view has the potential to be developed into a theory of mind and matter which does much better justice to the subtle aspects of the mind than the traditional fairly crude neural models of mental processes.

For Eccles, the motivation of exploring the quantum approach to the brain was to find a way for the “self” to control its brain. This means that Eccles was not merely interested in the usual indeterministic way of looking at quantum theory, but he assumed a version of the third view described above. One of the problems of Eccles’ approach is, however, that it appeals to the standard interpretation of quantum theory. In this interpretation it is difficult to discuss, in a meaningful way, the idea

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[3] We follow Bohm in assuming that, at each level, information is the *link* or *bridge* between the mental and the physical sides. In this way we try to answer the traditional objection against double-aspect theories of neutral monism, namely that the nature of the reality, of which mind and matter are thought to be aspects, is left mysterious. Note especially that our view does not suffer from the traditional arguments against (substance) dualism, which are often directed against Eccles’ view. For more details see *e.g.* Bohm (1990), Bohm and Hiley (1993), pp. 381–390, Pylkkänen (1992), Hiley and Pylkkänen (1997, 2001).

that the self controls its brain, because individual quantum processes are supposed to be indeterministic and therefore not determined by anything, including the "self". It is, thus, necessary to go beyond standard quantum theory to make an approach such as Eccles' coherent. Indeed, most of the current attempts to appeal to quantum physics when discussing the nature of the mind or the mind-matter relation involve some modification of standard quantum theory. For example, Penrose and Hameroff's theory of orchestrated objective reduction in microtubules proposes that usual quantum theory has to be modified by the idea of a gravitational collapse of the wave function. Their idea is that the non-computational nature of such a spontaneous gravitational collapse underlies the non-computational aspects of human intelligence.

In a similar vein we propose that an understanding of the way in which the mind affects neural processes does not merely require the postulation of quantum effects triggering neural processes in the brain, but the additional idea that something else, active information, contained in the "mind-field" can in turn affect the quantum potential. This goes beyond the predictions of standard quantum theory and implies that we do not propose that mind can be reduced to the quantum level. Instead the idea is that mind can be seen as a relatively autonomous, higher level of active information, which has both a physical and a mental aspect (see footnote 3). Our consideration of Bohmian quantum physics and its extension suggests a natural way to think about how mind can have a genuine effect upon neural processes. This indicates a novel class of physical processes involving mind and matter, which we will address in subsequent research (see also Bohm 1980, Chap. 7, Bohm and Hiley 1993, Chap. 15, and Pylkkänen 2004.)

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