Is the Brain Analogous to a Quantum Measuring Apparatus?

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Abstract

Researchers have suggested since the early days of quantum theory that there are strong analogies between quantum phenomena and mental phenomena and these have developed into a vibrant new field of quantum cognition during recent decades. After revisiting some early analogies by Niels Bohr and David Bohm, this paper focuses upon Bohm and Hiley's ontological interpretation of quantum theory which suggests further analogies between quantum phenomena and biological and psychological phenomena, including the proposal that the human brain operates in some ways like a quantum measuring apparatus. After discussing these analogies I will also consider, from a quantum perspective, Hintikka's suggestion that Kant's notion of things in themselves can be better understood by making an analogy between our knowledge-seeking activities and an elaborate measuring apparatus.

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> *But the greatest thing by far is to have a command of metaphor. This alone cannot be imparted by another; it is the mark of genius, for to make good metaphors implies an eye for resemblances.* - Aristotle, *Poetics* XXII.

> *Although, in the present case, we can be concerned only with more or less fitting analogies, yet we can hardly escape the conviction that in the facts which are revealed to us by the quantum theory and lie outside the domain of our ordinary forms of perception we have acquired a means of elucidating general philosophical problems.* - Bohr, N. *Atomic Physics and the Description of Nature.*

1 Introduction

The idea that quantum phenomena are in some ways analogous to mental phenomena has been around almost from the very beginning of quantum mechanics. Already in his 1929 article "The Quantum of Action and the Description of Nature" (see Bohr 1934), as well as in his 1933 article "Light and Life" Niels Bohr drew attention to the similarity between measurement in atomic mechanics and introspection in psychology:

> ...the necessity of considering the interaction between the measuring instruments and the object under investigation in atomic mechanics corresponds closely to the peculiar difficulties, met with in psychological analyses, which arise from the fact that the mental content is invariably altered when the attention is concentrated on any single feature of it. (Bohr 1933:458)

Bohr's proposals inspired the physicist David Bohm to write an entire section "Analogies to quantum processes" in his acclaimed 1951 text-book *Quantum Theory.* For example, Bohm expanded upon Bohr's above analogy as follows:

> If a person tries to observe what he is thinking about at the very moment that he is reflecting on a particular subject, it is generally agreed that he introduces unpredictable and uncontrollable changes in the way his thoughts proceed thereafter. [...] If we

> compare (1) the instantaneous state of a thought with the position of a particle and (2) the general direction of change of that thought with the particle's momentum, we have a strong analogy. [...] the actions involved in making any single aspect of the thought process definite appear to introduce unpredictable and uncontrollable changes in other equally significant aspects. (Bohm 1951:169; see also Pylkkänen 2014).

This analogy has to do with the limitations in our attempts to give a full description of a phenomenon. In classical physics we got used to the idea that phenomena exist independently of the means by which the are observed. But in both atomic physics and in the psychological domain things seem to be otherwise. We are typically able to measure a particular feature of the object under interest. But the very interaction that is required to take place between the object and the measuring instruments for such a measurement to be possible means that other features of interest become indeterminate, and cannot perhaps be even said to exist in a well-defined sense in that situation.

One common reason to propose such analogies is that they can help us to understand otherwise puzzling phenomena. For example, quantum theory is often thought to be difficult, if not impossible to understand (remember Feynman: "I think I can safely say that nobody understands quantum mechanics" (1965: 129)). But if quantum processes are analogous to thought processes, then our very familiarity or acquaintance with our own thought processes via introspection might help us to understand quantum processes, as Bohm proposed already in 1951 (see Pylkkänen 2014: 77-79). Conversely, certain principles and mathematical tools of quantum theory (such as quantum probability, entanglement, non-commutativity, non-Boolean logic and complementarity) might provide a good way of modelling many significant and puzzling cognitive phenomena (such as decision processes, ambiguous perception, meaning in natural languages, probability judgments, order effects and memory), as indeed has been proposed by many researchers (see Wang et al. 2013). So if there is a similarity or analogy between quantum phenomena and mental phenomena, this can be beneficial in two directions, both when trying to understand quantum phenomena and when trying to understand mental phenomena.

People who saw analogies between quantum processes and mental phenomena realised early on that such analogies might not only be a mere coincidence, but that there might be a deeper underlying reason or explanation for why they exist. As we will see below, already Niels Bohr thought that quantum processes could play a non-trivial role in the operation of sensory organs and neuronal signalling. Similarly, Bohm speculated that if it would turn out, as Bohr had suggested, that the physical aspect of thought is such that quantum-theoretical limitations play an essential role in determining its nature, we could in a natural way explain a great many features of our thinking.

As is well known, in 1952 Bohm proposed a new interpretation of quantum theory which in some ways goes beyond Bohr's thinking. While Bohm's theory does not allow us to measure the position and momentum of a particle simultaneously, it does provide a hypothesis about what quantum objects are and how they move even when they are not being measured, a hypothesis contrary to what Bohr thought to be possible and meaningful. In a later development of Bohm's 1952 approach called the "ontological interpretation of quantum theory", Bohm and Hiley (1987, 1993) came up with new interesting analogies between quantum phenomena and biological and psychological phenomena. For example, they proposed that there is an analogy between the way information contained in the so called quantum potential guides a quantum particle, and the way information at other levels of organisation guides physical processes (e.g. information in the DNA molecule guides protein construction (Goel 2008) and information in our subjective experience (e.g. when reading a map) can guide our physical actions).

In some ways going back to Bohr's early suggestions, they also proposed that the human brain operates in some ways like a quantum measuring apparatus, in the way it manifests and reveals aspects of the subtle quantum world in the classical sub-world we find in our every-day experience. This suggestion implies a radically new view of mental phenomena, in which it is assumed that these latter literally involve quantum phenomena. In this paper I will discuss some of the new possibilities for understanding the mind and conscious experience opened up by Bohm and Hiley's ontological interpretation and the analogies they propose to illustrate its relevance. I will conclude the paper by discussing Hintikka?s (1989) suggestion that Kant?s notion of things in themselves can be better understood by making an analogy between our knowledge-seeking activities and an elaborate measuring apparatus. I will show that it makes an important difference to Hintikka?s analogy whether we are considering a quantum or a classical measurement apparatus.

2 The quantum world and its classical sub-world

From the perspective of physics there seems to be a fundamental difference between the phenomena we encounter in our every-day experience (where classical physics is approximately correct) and the phenomena we encounter at the microscopic domain (where quantum mechanics is needed). Bohm and Hiley's (1987, 1993) ontological interpretation of quantum theory attempts to provide a consistent account of how these two different domains of phenomena are coherently related in a single overall picture. This picture suggests that there fundamentally exists a single world which they call an "overall quantum world". In this world there are particles and fields, but in addition to the forces that we find in classical physics, these particles and fields are influenced by the action of a so called quantum potential (for the fields, a super-quantum potential). So an elementary particle such as an electron is assumed to be a particle which is always accompanied by a field which latter gives rise to a new kind of potential, the quantum potential. One radically new feature is that rather than pushing and pulling the particle mechanically, the quantum potential literally in-forms the energy and movement of the particle. This is why Bohm and Hiley characterised it as an *information potential* (see also Hiley 2004). The action of the quantum potential accounts for all the non-relativistic quantum phenomena that we have encountered (e.g. particle interference, tunnelling etc).

As we already mentioned, the quantum potential has new features (such as active information but also non-locality and objective irreducible wholeness) which are radically different in comparison with those of classical potentials (see also Aharonov et al. 2018 for an account of how similar holistic features arise in the usual interpretation of quantum theory). It is because of these kind of features of the quantum potential that Bohm and Hiley characterise the overall quantum world as being "subtle" in its fundamental character. However in some conditions the quantum potential has a negligible effect, in which case the particles and fields behave according to classical physics, and a manifest classical sub-world which we meet in our every-day experience emerges within the overall subtle quantum world.

3 Bohm's discovery of a quantum ontology

To understand in more detail why Bohm and Hiley propose that the quantum world is subtle, it is useful to briefly consider the background and mathematical nature of Bohm's theory.

The usual interpretation of quantum theory assumed that one can not think of a quantum object, such as an electron, as a particle which has simultaneously a well-defined position and momentum, and which is moving along a trajectory. Independently rediscovering and completing an approach originally proposed by Louis de Broglie in 1927, Bohm (1952 a and b) "did the impossible" (Bell 1987) - he showed how by starting from Schrödinger's equation one could produce a consistent hypothesis about how, say, electrons are particles which have a well-defined position and momentum, and are moving along trajectories. As is well known, the Bohm interpretation postulates that a particle (say an electron) is not a particle OR a field (as in the conventional interpretation of quantum theory), but it is always a particle AND a field. The field guides the particle through a new potential, the quantum potential, and in this way one can give an intelligible explanation of many puzzling quantum phenomena, such as the two-slit experiment, tunnelling, the measurement problem etc. (see Bohm and Hiley 1987, 1993).

To see how the Bohm theory arises from Schrödinger's equation let us briefly consider its mathematical form. To get to the Bohm theory one writes the wave function in polar form,

$\psi(\mathbf{r},t) = R(\mathbf{r},t)\exp[iS(\mathbf{r},t)/\hbar]$.

Here R and S are two physically real fields that describe the time evolution of the particle (R is the amplitude or intensity and S the phase of the wave function). The next step is to substitute this expression into the Schrödinger equation and then separating the real and imaginary parts of the resulting equation, the real part gives

$$\frac{\partial S}{\partial t} + \frac{1}{2m}\nabla S^2 + V + Q = 0. \tag{1}$$

This equation is an expression for the conservation of energy and looks very much like a formulation of classical mechanics, the Hamilton-Jacobi equation, except that there appears an extra term Q which looks like some form of potential energy, which is why Bohm called it the quantum potential. It takes the form

$$Q = -\frac{\hbar^2}{2m}\frac{\nabla^2 R}{R} \tag{2}$$

It is natural to interpret Q as an additional potential acting on the particle, alongside the classical potential V. This implies that even in the quantum domain we can still regard every particle as having a well-defined position and momentum giving rise to a trajectory even though we are unable to measure position and momentum simultaneously. In order to produce the quantum behaviour the 'particle' must be accompanied by the R, S coupled field, $\psi(\mathbf{r}, t)$, which satisfies the Schrödinger equation. Thus Bohm's quantum ontology for non-relativistic particle quantum mechanics is not just a particle ontology, it is a particle AND field ontology; it is the field which gives rise to the quantum potential. Quantum trajectories can be (and have been) calculated for many different situations, including the classic two-slit interference experiment (see Bohm and Hiley 1993, and Oriols and Mompart 2019 for more details).

Because of the uncertainty principle we cannot observe the trajectory of a single quantum object directly as long as we remain in the domain in which quantum mechanics is valid. So the idea that a single quantum object moves along a trajectory ought to be seen as a hypothesis which has not been empirically verified. However, by making use of measurements of weak values it is possible to measure average trajectories (see Flack and Hiley 2018).

Importantly, Bohm's interpretation also provides a way of thinking about when we should use quantum mechanics, and when classical mechanics is sufficient to provide a good approximate description. The quantum potential is negligibly small in conditions where Newtonian mechanics works for all practical purposes (see Bohm and Hiley 1993, ch8). In this way we can understand how a manifest classical sub-world can arise within the over-all quantum world.

We already mentioned above that according to Bohm and Hiley the quantum potential is not pushing and pulling the particle mechanically, but is influencing the particle in a more subtle way by literally in-forming its energy. This can be seen by examining the mathematical form of the quantum potential.

$$Q = -\frac{\hbar^2}{2m}\frac{\nabla^2 R}{R} \tag{3}$$

Because the amplitude or intensity of the field R is both in the numerator and the denominator of the equation, multiplying R by an arbitrary constant will not affect the size of the quantum potential. Q only depends on the *form* (second spatial derivative) of the quantum field, R not on how big R is. This means that even a field which has a very small intensity can have a significant effect. Thus even very distant features of the environment (e.g. slits) can have a significant effect on the particle. Hiley has recently emphasized that the kind of formative causation we see with the quantum potential is reminiscent of Kant's discussion of phoronomy (see Stan 2021) and is similar to the more familiar Coriolis force (Hiley and Pylkkänen 2022).

Bohm and Hiley introduced a number of analogies to help us to understand what is going on with the quantum particle. Think about a ship on autopilot, guided by radar waves. The radar waves are not pushing and pulling the ship, but rather the form of the radar waves is taken up by the ship and used to in-form the larger energy of the ship. This is a good analogy, but we should not take it too literally. For one thing, the quantum potential can mediate non-local correlations, while radar waves operate at the classical level, and their influence is not non-local but limited by the speed of light. Also, the quantum state for a many-body system can be seen as a common pool of information which is organising the behaviour of an entire set of particles in a way which does not depend on any pre-assigned function. This is a radically quantum mechanical holistic feature, which is characteristic of the unity we find with living organisms rather than with mechanically operating devises.

4 Consciousness and the quantum vs. classical world

Orthodox cognitive neuroscience typically assumes that the neural correlates of consciousness are processes which take place in the classical domain. In other words, it is assumed that there is no need to refer to subtle quantum effects when trying to understand how these processes function and why there is conscious experience associated with them. This may seem like a harmless and reasonable assumption, but in actual fact it is currently speculative and serves to make the famous hard problem of consciousness (Chalmers 1995) perhaps harder than it need be. The hard problem of consciousness is the problem of explaining how and why physical processes give rise to consciousness (Chalmers 1995). If we assume that the physical correlates of consciousness are mechanical, then the question arises how could such objective, mechanical processes possibly give rise to the subjective and holistic (and in some ways non-mechanical) experience we encounter in consciousness? The ontological interpretation of quantum theory provides another way of approaching the question about the physical correlates of consciousness. As we pointed out above, it proposes that the more fundamental ground of existence is the subtle quantum world, exemplified by the properties of the quantum potential. Why should we assume that a holistic, subtle and subjective phenomenon such as conscious experience should be entirely reducible or explained in terms of the mechanical classical domain, which after all is an abstraction from the overall quantum world?

I suggest that consciousness requires a certain kind of interplay of the classical sub-world and the subtle part of the overall quantum world. One possibility is that conscious experience typically requires that aspects of the manifest classical world are being presented to the subtle part of the quantum world (to what we might call "the quantum mind" or "the quantum (part of the) self" (cf. Zohar and Marshall 1990; Wendt 2015).

It is worth underlining that in this quantum approach to consciousness I am by no means denying the role of the classical domain of reality (i.e. the domain where non-trivial quantum effects are negligible and for which classical (mechanistic) physics provides a good approximate description for all practical purposes). On the contrary, it seems obvious that a great deal of the processes connected to cognition and consciousness take place in (and require) the classical domain. Indeed, Bohm and Hiley (1993: 178) write that "meaningful sense perception and communication has to go through the classical level in which the effects of [the] wave function can be consistently left out of account". The question is whether processes that only take place at the classical level can be conscious. My proposal is that this is not possible. This is, of course, an intuition that has a long history and underlies Leibniz's analogy of the mill (see Lodge 2014), and (I suggest) Chalmers's hard problem of consciousness. So if the classical level is not enough for consciousness, what more is needed? How could quantum phenomena help, for example?

5 The principle of soma-significance

Let us consider a simple example, namely reading a newspaper. The newspaper is an object in the classical domain, and the printed ink is likewise a classical phenomenon. The printed ink can be thought of as information that carries a significance that can be understood by a suitable system, for example a person who knows the language in which the text is written. Even a suitably programmed computer can respond to the information, even if it is likely that, unlike the human being, it does not understand the meaning of the information (Searle 1980). Light waves carry the information contained in the printed ink to the eye of the observer, from where it is carried toward higher and more subtle levels of brain function where its meaning is apprehended. Bohm (2003) called this kind of process where a somatic process carries information, which is carried toward more subtle somatic levels a "soma-significant" process. He generalised this into a principle of soma-significance which is a thesis that each configuration of matter and energy ("soma") carries a meaning ("significance") at least potentially if not actually.

In our example, it is natural to say that consciousness comes in only at the more subtle soma-significant levels. In other words, it seems obvious that a typical soma-significant process (such as reading a newspaper) starts unconsciously in the classical domain, and consciousness only appears at some stage when the significance is carried toward sufficiently subtle physical levels. Once the meaning is interpreted by the brain, this may give rise to what Bohm called a "signa-somatic" response, depending on the meaning of the information (e.g., if the meaning is "danger", this typically gives rise to a powerful signa-somatic response, where e.g. adrenaline flows). But what is it that makes this initially non-conscious soma-significant process become conscious at some stage of the process as it moves toward the higher levels? This is the hard problem of consciousness in the scheme of soma-significance. What we have said thus far is that consciousness comes in at the more subtle levels of soma-significance.

To summarise: the above implies that there are manifest levels (such paper and printed ink) and more subtle levels (such as pattern of neural energy). In perception significance is typically carried toward more subtle levels (soma-significant process); once its meaning is apprehended the meaning is typically active and organises the lower levels (signa-somatic process). There is thus a two-way traffic between manifest and subtle levels. (See also Bohm 1989, 1990; Bohm and Pylkkänen 1991; Pylkkänen 2017; for recent critical discussions of the notion of active information, see Loorits 2021, Peuhu 2021 and Pttiniemi 2021).

6 Is the brain analogous to a quantum measuring apparatus?

But what do we mean by subtle? Quantum mechanics can give some insight here. The Bohmian model of the electron can be seen as a prototype model of a coupling between a subtle aspect (the quantum field described by the wave function) and a more manifest aspect (the corpuscle or particle aspect of the electron). The subtle aspect enfolds information about the environment of the particle, and then signa-somatically organises the movement of the particle. I am not saying that the electron is conscious, but we could say that conscious experience arises in a soma-significant process where a manifest physical process (describable by classical physics) connects to the subtle quantum domain.

Indeed, Bohm and Hiley (1993: 179) suggest that as "...the process of perception unfolds into the the brain, it may as it were connect to the subtle quantum domain which latter may in turn reconnect to the classical domain, as outgoing action is determined through amplification of quantum effects." They are not here commenting explicitly on how non-conscious information becomes conscious information, but they are implying that perception is a process which originates in the classically describable domain (e.g. it involves printed ink, light waves and macroscopic neural processes), but also typically involves "connecting" to what they call the subtle quantum domain. And they further suggest that our outgoing physical action can be influenced by the subtle quantum domain. Thus, the hypothesis is that at least some cognitive and conscious processes essentially involve the subtle quantum domain in a non-trivial way. If the apprehension of meaning and the operation of intelligence and the choice of an action in a situation takes place in (or involves) the quantum domain, it clearly cannot be ignored when trying to account for perception, cognition, volition and action.

As a general starting point, let us propose that as long as a process takes place in the classically describable domain, no conscious experience arises. In other words, we are saying that conscious experience only arises at some point when the process connects to the subtle quantum domain. So we are assuming that for a soma-significant process to result into a conscious experience of meaning, it is required that somewhere in the brain there are sites where a classically describable process can connect to the quantum domain. This is not to say that connecting to the quantum domain in this way is sufficient for consciousness, but we are assuming that it is necessary.

A signa-somatic process which involves a conscious experience of meaning, in turn, requires that the subtle quantum domain can influence the classically describable domain (e.g. bodily movements) through amplification of quantum effects. This requires that some parts of the brain could be so sensitive that they could respond to and amplify quantum effects. Bohm and Hiley (1993: 179) point out that if this were the case, then "..the brain would be a system that could, like a measuring apparatus, manifest and reveal aspects of the quantum world in the overall processes." This is a very interesting analogy. We know for a fact that a quantum measuring apparatus is able to measure properties of a quantum object and reveal these in the classical domain. Could it be that the brain is also capable of doing this?

The idea that there can be amplification of quantum effects in biological systems is not controversial. For there exists a well-known neural process which is commonly thought to involve amplification of the effects of 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 retinal, 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 (see Kandel et al. 1991: 405). Bohm and Hiley point out that because the retina is an extension of the brain, there could be other parts of the brain in which a similar sensitivity may exist, e.g. in certain kind of synapses (1993: 179; cf. Eccles 1986; Salari et al. 2017). Niels Bohr speculated already in 1933 that similar sensitivity to quantum effects, involving amplification, could take place in other sense organs:

> ...since the absorption ... perhaps of only a single quantum on ... a retinal partition is sufficient to produce a sight impression, the sensitiveness of the eye may ... be said to have reached the limit imposed by the atomic character of light effects. [...] this ideal refinement of the eye ... suggests that other organs also ... will exhibit similar adaptation to their purpose, and that also in these cases the feature of individuality symbolised by the quantum of action, together with some amplifying mechanism, is of decisive importance. (Bohr 1933: 457)

In a later 1951 talk "Medical research and natural philosophy" he further proposed that such amplification processes play a role in nerve signals:

> ...the fineness of our senses, like visual perception, has been found to go down to the atomic level, and we must assume that amplification processes analogous to those applied in the registration of atomic phenomena play a decisive role in the mechanisms of nervous messages. (Bohr 1998: 152)

The role of subtle (non-trivial) quantum phenomena in neural processes is still an open and controversial issue, but in my view recent advances in quantum biology do suggest that Bohr's speculations were on the right track (see Jedlicka 2017; Collini et al. 2010; Adams and Petruccione 2020).

So in summary, I am proposing that for conscious experience to arise and to have causal effects in the physical world we need a two-way connection between the manifest classical domain and the subtle quantum domain. Perhaps conscious experience requires that a classical process (e.g. a neural process carrying visual information in the brain) connects to the subtle quantum domain (to the level of the quantum potential associated with the brain) where the meaning of the information is consciously apprehended. In a reverse process the subtle quantum domain can via the action of the quantum potential connect to the classical domain and control physical behaviour via affecting particles and/or fields in e.g. synapses or microtubules (see Atmanspacher 2020). This would require, of course, that quantum effects are amplified so that they can have macroscopic effects, similarly to the way the retina amplifies effects of single photons. As we saw, Bohm and Hiley suggest that the brain may be analogous to a quantum measuring apparatus in the sense that it can reveal and manifest aspects of the quantum world in the classical domain. It is implicit in their suggestions that there are deeper, more subtle levels of information processing in the brain than that carried out by action potentials, and there is recent experimental evidence that points to that direction (see Singh et al. 2021a,b).

7 How does conscious experience arise?

It is interesting to consider Bohm and Hiley's proposals in relation to the physicist Jack Sarfatti's suggestion that so called back-action plays a key role in how conscious experience arises in the context of the ontological interpretation. When describing this interpretation above I have emphasised the way the R, S coupled field, $\psi(\mathbf{r}, t)$, which satisfies the Schrödinger equation influences the particle through the quantum potential. But if the field influences the particle, might not the particle influence or "act back" upon the field? After all, the law of action and reaction is one of the basic principles of physics. Indeed, Bohm himself considers the possibility of a kind of back-action (a dependence of the ψ -field on the actual location of the particle in very short distances and very short times) in his interpretation already in his 1952 "hidden variables" papers (1952: 171; 179) and Bohm and Hiley discuss it briefly in *The Undivided Universe* (1993: 345-6). They emphasise that the way the quantum field affects the particle must not be seen as an external force, but rather as much more subtle influence, which we have described as in-forming. If there is a back-action from the particle to the field, could it also be a more subtle kind of influence? Sarfatti's fascinating suggestion is that conscious qualia arise in some circumstances, where matter acts back on the quantum field: "Our basic ansatz to solve the hard problem is that 'active quantum information' ... physical waves are intrinsically mental. Qualia are excitations in them directly imprinted by the back-reaction of the classical material beables..." (Sarfatti and Shimansky 2018).

This condensed proposal has two parts. On the one hand there is the assumption that active quantum information physical waves are intrinsically mental. The back-action then makes such intrinsically mental waves conscious. Thus this proposal thus tells us both what it is in the world that is intrinsically mental and what it is that makes such intrinsically mental states conscious in some situations.[1] In another context Sarfatti speaks about "conscious 'qualia' as the impressions on the macro-quantum coherent pilot waves by their classical electromagnetic signal sensory inputs."[2] Macro-quantum coherence here refers to Fröhlich's (1968) suggestion that there should be vibrational effects within active cells, as a result of a biological quantum coherence phenomenon. These effects are supposed to arise from the existence of a large energy of metabolic drive and should not need a low temperature (Penrose 1994: 352).[3]

Sarfatti's proposal fits into the scheme of soma-significance in the sense that he provides one suggestion about how consciousness arises. Such suggestions are hard to come by in consciousness studies. The currently prominent proposals (e.g. integrated information theory (Tononi et al. 2016), higher-order theories (Rosenthal 1997; Gennaro 2012), global workspace theories (Baars 2017) etc.) each have their appeal but also difficulties. Sarfatti puts the origin of consciousness to a fundamental level of nature, somewhat similar to David Chalmers's double-aspect theory of information and related pan(proto)psychist schemes (Chalmers 1995, 1996, 2015, 2020a,b; Skribna 2017; see also Pylkkänen 2020; Hiley and Pylkkänen, 2001, 2005, 2022).

[1]More precisely, Sarfatti and Shimansky refer to the waves as "Bohm-Aharonov advanced destiny and retarded history physical waves". Sarfatti's "post-quantum mechanics" (PQM) makes use of Roderick Sutherland's Lagrangian formalism which describes Bohm's formalism within Yakir Aharonov's locally retrocausal weak measurement framework. While Sarfatti's PQM opens up some radical possibilities, I will not consider all of them here, but focus on the idea that mental states are macro-coherent quantum fields and conscious qualia are the effects of back-action upon these fields.

[2]Jack Sarfatti, e-mail to the author, Fri, 8 Jan 2021.

[3]There has been some controversy about whether Fröhlich states could play a role in the correlates of cognition and consciousness. Reimers et al. (2009) suggest that coherent Fröhlich condensates involve extremely large energies, are extremely fragile and are inaccessible in a biological environment. They take this to imply that the Penrose-Hameroff orchestrated objective-reduction model (Hameroff and Penrose 2014) and related theories for cognitive function that embody coherent Fröhlich condensation as an essential element are untenable. Yet Lundholm et al. (2015) claim that they have for the first time observed a quantum coherent-like state in a biological protein (lysozyme) and Zhang et al. (2019) claim to have developed a full quantum statistical theory using nonequilibrium equations of motion for the Fröhlich condensate. See also Hameroff (2021).

8 Philosophical implications of the analogies between quantum and mental phenomena

Suppose, for the sake of the argument, that Bohr, Bohm and others are correct is suggesting that quantum phenomena and mental phenomena are analogous. What would be the philosophical implications of this analogy? One of the central questions of philosophy is the relationship between the mind and the world, the subject and the object, the knower and the known. Quantum theory implies radical changes to our picture of the world. If we then say that even mental phenomena are in some ways quantum-like it seems that we have radically changed the philosophical situation. We would then have the quantum-like mind trying to understand itself, the quantum world, and the relation between itself and the quantum world. Of course, the possibility that both reality and mind are quantum-like might increase the likelihood that the mind can understand the world. As we mentioned in the introduction, if quantum and mental phenomena are analogous, our familiarity or acquaintance with the nature of our thought processes could help us to understand quantum phenomena. And conversely, the mathematical tools of quantum theory might also be successfully used to describe and model the mind.

9 Quantum embodiment: experiencing the classical world through our body and the quantum world through our process of thought

In his 1951 text-book *Quantum Theory* David Bohm makes the very interesting suggestion that muscular forces provide a direct experience of the effects of classical theory. He says that the pre-Galilean concepts of force, obtained from immediate experience with muscular forces, were in general correct because there is usually a great deal friction in common experience. But he makes an even more radical proposal when he writes:

> If it should be true that the thought processes depend critically on quantum-mechanical elements in the brain, then we could say that thought processes provide [a] direct experience of the effects

> of quantum theory. ... the behavior of our thought processes may perhaps reflect in an indirect way some of the quantum-mechanical aspects of the matter of which we are composed. (Bohm 1951: 171-2)

To say that our immediate experience with muscular forces provides us a direct experience of the effects of classical theory resonates with research on embodied cognition (see Wilson and Foglia 2017). We have access to the nature of physical reality not just via our cognitive processes but also via our bodily experiences, while being embedded and active in physical environments. We use the body as a tool for obtaining experiences which then form the basis of the concepts we use in physics.

To say that the behaviour of thought processes provides a direct experience of the effects of quantum theory is more subtle. It is not that via attending to our thought processes we are directly experiencing only quantum effects. Like most researchers Bohm acknowledges that a great deal of the processes of thought take place in the classical domain and form a mechanism, but he speculates that "...certain key points controlling this mechanism (which are, in turn, affected by the actions of this mechanism) are so sensitive and delicately balanced that they must be described in an essentially quantum-mechanical way" (1951: 171; note that Bohm is here anticipating the important role of criticality in neural functioning, see Jedlicka 2017: 4). So according to this hypothesis, in our introspection of thought we have a direct experience of a mechanism which is controlled by quantum effects, and in this sense we have an indirect, classically mediated experience of quantum effects. This means that just like physical reality as a whole, our physical body (including our thought processes) has both a quantum part and a classical part. The fact that we are such a system, capable of conscious experience then enables us to have direct experiences of both quantum and classical aspects of physical reality, merely by virtue of being such a system.

10 The hidden aspects of reality: complementarity and the implicate order

But what does it mean for the mind to be quantum-like? To some extent this implies limitations. For example, if a kind of uncertainty principle applies to thought, this points to the limitations of our ability to get information about our mental processes in introspection. More generally this suggests that reality is organised in such a way that in any given situation there exists more than what can be made explicit and measured at a given moment. This is one aspect of Niels Bohr's principle of complementarity. David Bohm developed the notion of implicate order to capture this and other features of quantum theory. He would say that if in a quantum measurement we explicate the position of a particle, the momentum will remain implicit and vice versa. He used the term "intrinsically implicate order" to describe situations in which we cannot make all relevant aspects explicit or manifest at the same time. A quantum object exists in an intrinsically implicate order, at least until physics develops in such a way that we are able to go beyond the uncertainty principle and explicate its position and momentum simultaneously in a quantum measurement. But there is a sense in which our conscious experience, too, exists in an intrinsically implicate order. We can typically be conscious of only one object, scene etc. at a given time, while some other things and aspects inevitably remain implicit and complementary. There is thus a deep analogy between the structure of physical reality and the structure of consciousness, which points to the possibility that physical reality and consciousness are aspects of a deeper underlying ground (Bohm 1980; Pylkkänen 2007).

11 Kantian considerations

It is also interesting to consider quantum analogies in relation to Kant's transcendental philosophy (or his "Copernican revolution"). When we are saying that both the world and the mind are quantum-like, from which perspective are we saying this? Is it the quantum-like mind which realises, as a result of scientific research, that the world is quantum-like? Or is it the quantum-like mind which in a sense "makes" the world quantum-like (in a Kantian fashion)? For Kant, our mind is Newtonian in the sense that some key features of Newtonian physics happen to be a key part of the *a priori* structure of the human mind (for example the forms of perception (time and space) and the category of causality). If the mind has a quantum-like aspect, does this also affect how we necessarily meet the world? And in this meeting, must the world stretch toward (or accommodate to) our quantum mind, in a Kantian fashion?

Jaakko Hintikka (1989: 246) takes Kant to be saying that "[t]hings are allegedly unknowable in themselves because we can know them only by means of certain processes which "color", i.e., affect, the resulting knowledge". Hintikka then makes the following observation:

> ...if we knew these processes well enough to understand precisely how it is that they influence their eventual product, i.e., our knowledge, we could as it were subtract these influences from our knowledge, and the rest would tell what things are in themselves, in the sense of in so far as they have not been affected by our knowledge-seeking processes. Hence, in order for things in themselves to be unknowable, our knowledge-seeking processes must likewise be unknowable in certain respects. (1989: 246)

He goes on to suggest that a useful analogy here is "...to compare our knowledge-seeking activities, plus the conceptual system they use, with an elaborate measuring or registering apparatus." (1989: 246-7):

> Its feelers touch the real objects, but we don't "see" them; we can reach them only by means of the apparatus. Our knowledge of reality is what we can tell of it on the basis of the registrations of the "machine" at our end. These are not due completely to the objects at the receiving end of the apparatus, but are influenced by the mode of operation of the instrument itself. Some registrations may even be caused completely by the structure of the apparatus. (1989: 247)

He then notes that while we might think that there is no way of eliminating the influence of our measuring technique, we can do so at least to some extent by learning more about the principles of operation of the measuring apparatus.

> By so doing we can extract more information from its readings, by being able to tell which tremors of its needles merely reflect the resonances of our own machine and which ones can be traced all the way to the objects touched by the feelers of the apparatus on its hidden side. For instance, we might be able to disregard

> altogether some merely apparent registrations. By so doing, we could as it were subtract the influence of our own tools from our prima facie knowledge of things. Now it is precisely this influence that allegedly makes it impossible for us to know things as they are in themselves. Hence our insights into our own knowledge-seeking processes [...] will enable us to gain knowledge of things in themselves [...] more faithfully than it did before. (1989: 247)

Hintikka concludes from his reflections on this analogy that rather than saying that things in themselves are *unknowable* (unreachable in the same sense as the contents of a locked room), we ought to say that they are *inexhaustible* (unreachable in the same sense as infinity). While he thinks that we may eliminate many contributions of our own knowledge-seeking activities ("the influence of the measuring technique") he also thinks that there is no reason to believe that we can eliminate all of them:

> ...the uneliminability is not due to any intransgressible boundary, but means only inexhaustibility. It is a fallacy to think that we are separated from things as they really are by a fixed impenetrable iron curtain. (1989: 249-50)

Hintikka again uses his analogy to show that Kant was mistaken in assuming that the boundaries of possible experience are the inescapable limits of our knowledge in general:

> ...in order to know that there is an absolute limit to what the instrument can do is to possess knowledge of the very kind which presumably will enable us to transgress that limit. To change the metaphor, in order to draw a boundary of what we can know, we must know what there is on the other side of the boundary. If we cannot do the latter, we cannot do the former, either. (1989: 250)

The way Hintikka compares our knowledge-seeking activities (and conceptual system) with a measuring apparatus is very interesting in relation to our discussion of quantum mechanics. Hintikka is clearly presupposing a classical ("Newtonian") measuring apparatus in his analogy, because he sees no limit to the extent that we can subtract the influence of the measuring apparatus from our knowledge of things. According to the usual interpretation of quantum theory the situation is, of course, the opposite. The uncertainty principle is usually taken to imply absolute limit to the extent in which we can eliminate the influence of the measuring apparatus. Niels Bohr wrote already in 1933:

> In order fully to understand this fundamental limitation of the mechanical analysis of atomic phenomena, one must realise clearly, further, that in a physical measurement it is never possible to take the interaction between object and measuring instruments directly into account. For the instruments cannot be included in the investigation while they are serving as means of observation.

To take the interaction into account, we would need to study how the "feelers" (to use Hintikka's expression) of the quantum measurement apparatus interact with the quantum object. Typically such interaction requires at least one quantum of action, which is according to Bohr is uncontrollable, unpredictable and indivisible. In any case, to study this interaction we would need another measuring apparatus which would change the boundary conditions of the situation, and in this way influence the feelers in such a way that they would no longer be able to serve their function. Thus, as long as we are not able to go beyond the quantum domain, we cannot study the interaction between the object and the measuring instruments without profoundly influencing it. Thus, unlike what is the case in Hintikka's analogy, there is a sense in which current quantum mechanics implies that the "door is closed" in a complementary way when it comes to observation: if we observe position accurately, the momentum in that situation is completely unknown, behind a closed door as it were. There is not even a keyhole from which we could attempt to get some information.

Elsewhere Bohr notes how quantum theory calls into question the classical ideal of observing both the spatio-temporal and causal properties of an object in a single observation:

> ...any attempt at an ordering in space-time leads to a break in the causal chain, since such an attempt is bound up with an essential exchange of momentum and energy between the individuals and

> the measuring rods and clocks used for observation; and just this exchange cannot be taken into account if the measuring instruments are to fulfil their purpose. (Bohr 1934: 98)

So if we are saying that our knowledge-seeking activities are analogous to a quantum measuring apparatus, we reach a conclusion different from Hintikka, if we rely on the usual interpretation of quantum theory. There is a sense in which both Kant and the usual interpretation of quantum theory emphasise absolute limits for our possibility to gain knowledge about "things in themselves" and "quantum objects in themselves", respectively. On the other hand Bohm saw the uncertainty principle as a reflection or property of the quantum domain, which could be transcended if we managed to discover a sub-quantum level of reality. A hypothetical Bohmian sub-quantum measurement apparatus is closer to the kind of apparatus Hintikka has in mind. If quantum mechanics develops along the lines Bohm speculates, it may be possible in the future to obtain more and more knowledge about quantum things in themselves, even though some aspects of these things may always remain hidden because of their inexhaustibility. And analogously, as our knowledge of our human knowledge seeking activities (including their possible quantum mechanical aspects) increases, we may obtain more and more knowledge about things in themselves, even though they too are inexhaustible. Even Kant might agree with this if Hintikka is correct in noting that "..in the happier formulations of his own idea of things in themselves Kant did in fact treat them as an unreachable asymptotic limit rather than a fixed boundary" (1989: 250).

12 Concluding remarks: analogies between quantum theory and mind

In this paper we have explored whether the relation between quantum and classical domains of physical reality is in some ways analogous between the relation of mental and physical properties. In the ontological interpretation of quantum theory a quantum object such as an electron is a particle which is accompanied by a new type of field which contains active information. For anyone who has been thinking about the traditional mind-body problem (e.g. how can the information in our mental states guide our physical actions), it should be fascinating to realise that even at the level of elementary particles we have a situation where an informational property is guiding a material object. In the ontological interpretation we find in an elementary form something similar to what we find in a much more developed form with human beings. One could stop here and say that we are dealing with a mere analogy. However, it is tempting to go further and ask whether the analogy is pointing to a deeper and more literal connection between quantum theory and the mind-matter relation. After all, our brains are composed of the very particles and fields to which quantum mechanics applies. Philosophers of mind have typically ignored considering theories of fundamental physics such as relativity and quantum theory. The justification for this has been that relativity deals with very high speeds (special relativity) and very large masses (general relativity), while quantum theory applies to atomic phenomena. It is assumed that the relationship between mind and body, when it comes to the physical aspects has to be understood at the every-day macroscopic level. Of course, it is acknowledged that we need to take into account neurophysiological processes, but the relevant ones are assumed to operate at the classical level.

Quantum analogies are tempting us to think otherwise. The similarities between quantum and mental phenomena could be a mere coincidence, but those of us bitten by the quantum bug are not happy to leave it at that. Neurophysiological processes involve the operation of ion channels and the movement of molecules, and biological cells have a rich microstructure, including microtubules which have received much attention in recent years. How can we be so sure that no non-trivial quantum effects (such as superposition, objective wholeness, active information, entanglement, quantum coherence or orchestrated quantum collapse) play a role in the neural correlates of cognition and conscious experience?

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