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From Quantum Nonlocality to Mind-Brain Interaction

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Abstract

Orthodox Copenhagen quantum theory renounces the quest to understand the reality in which we are imbedded, and settles for practical rules that describe connections between our observations. However, an examination of certain nonlocal features of quantum theory suggests that the perceived need for this renunciation was due to the uncritical importation from classical physics of a crippling metaphysical prejudice, and that rejection of that prejudice opens the way to a dynamical theory of the interaction between mind and brain that has significant explanatory power.

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“Nonlocality gets more real”. This is the provocative title of a recent report in Physics Today (1998). Three experiments are cited. All three confirm to high accuracy the predictions of quantum theory in experiments that suggest the occurrence of an instantaneous action over a large distance. The most spectacular of the three experiments begins with the production of pairs of photons in a lab in downtown Geneva. For some of these pairs, one member is sent by optical fiber to the village of Bellevue, while the other is sent to the town of Bernex. The two towns lie more than 10 kilometers apart. Experiments on the arriving photons are performed in both villages at essentially the same time. What is found is this: The observed connections between the outcomes of these experiments defy explanation in terms of ordinary ideas about the nature of the physical world *on the scale of directly observable objects.* This conclusion is announced in opening sentence of the report (Tittle *et al.* 1998) that describes the experiment: “Quantum theory is nonlocal”.

This observed effect is not just an academic matter. A possible application of interest to the Swiss is this: The effect can be used in principle to transfer banking records over large distances in a secure way (Tittle *et al.* 1999). But of far greater importance to physicists is its relevance to two fundamental questions: What is the nature of physical reality? What is the form of basic physical theory?

The answers to these questions depend crucially on the nature of physical causation. Isaac Newton erected his theory of gravity on the idea of instant action at a distance. According to Newton’s theory, if a person were to suddenly kick a stone, and send it flying off in some direction, every particle in the entire universe would *immediately* begin to feel the effect of that kick. Thus, in Newton’s theory, every part of the universe is instantly linked, causally, to every other part. To even think about such an instantaneous action one needs the idea of the instant of time “now”, and a sequence of such instants each extending over the entire universe.

This idea that what a person does in one place could instantly affect physical reality in a faraway place is a mind-boggling notion, and it was banished from classical physics by Einstein's theory of relativity. But the idea resurfaced at the quantum level in the debate between Einstein and Bohr. Einstein objected to the "mysterious action at a distance", which quantum theory seemed to entail, but Bohr defended "the necessity of a final renunciation of the classical ideal of causality and a radical revision of our attitude towards the problem of physical reality"(Bohr 1935).

The essence of this radical revision was explained by Dirac at the 1927 Solvay conference (Dirac 1928). He insisted on the restriction of the application of quantum theory to our knowledge of a system, rather than to the system itself. Thus physical theory became converted from a theory about 'physically reality', as it had formerly been understood, into a theory about human knowledge.

This view is encapsulated in Heisenberg's famous statement (Heisenberg 1958):

"The conception of the objective reality of the elementary particles has thus evaporated not into the cloud of some obscure new reality concept, but into the transparent clarity of a mathematics that represents no longer the behaviour of the particle but rather our knowledge of this behaviour."

This conception of quantum theory, espoused by Bohr, Dirac, and Heisenberg, is called the Copenhagen interpretation. It is essentially subjective and epistemological, because the basic reality of the theory is 'our knowledge'.

It is certainly true that science rests ultimately on what we know. That fact is the basis of the Coperhagen point of view. However, the tremendous successes of the classical physical theory inaugurated by Galileo, Descartes, and Newton during the seventeenth century, had raised the hope and expectation that human beings could extract from careful observation, and the imaginative creation of testable hypotheses, a valid idea of the general nature, and rules of behaviour, of the reality in which our human knowledge is imbedded. Giving up on that hope is indeed a radical shift. On the other hand, classical physical theory left part of reality out, namely our conscious experiences. Thus it had no way to account either for the existence of our conscious experiences or for how knowledge can reside in those experiences. Hence bringing human experience into our understanding of reality seems to be a step in the right direction: it might allow science to explain, eventually, how we know what we know. But Copenhagen quantum theory is only a half-way house: it does bring in human experience, but at the stiff price of excluding the rest of reality.

Yet how could the renowned scientists who created Copenhagen quantum theory ever believe, and sway most other physicists into believing, that a complete science could leave out the physical world? It is certainly undeniable that we can never know for sure that a proposed theory of the world around us is really true. But that is not a sufficient reason to renounce, as a matter of principle, the attempt to form at least a coherent idea of what the world *could* be like. Clearly some extraordinarily powerful consideration was in play.

That powerful consideration was a basic idea about the nature of physical causation that had been injected into physics by Einstein's theory of relativity. That idea was not working!

The problem is this. Quantum theory often entails that an act of acquiring knowledge in one place instantly changes the theoretical representation of some faraway system. Physicists were—and are—reluctant to believe that performing a nearby act can instantly change a faraway physical reality. However, they recognize that "our knowledge" of a faraway system can instantly change when we learn something about a nearby system. In particular, if certain properties of two systems are known to be strongly correlated, then finding out something about one system can tell us someing about the other. For example, if we know that two particles start from some known point at the same time, and then move away from that point at the same speeds, but in opposite directions, then finding one of these particles at a certain point allows us to 'know' where the other particle lies at that same instant: it must lie at the same distance from the starting point as the observed particle, but in the opposite direction. In this simple case we do not think that the act of observing the position of one particle *causes* the other particle to *be* where it is. We realize that is only our knowledge of the faraway system that has changed. This analogy allows us resolve, by fiat, any mystery about an instantaneous faraway effect of a nearby act: if something faraway can instantly be altered by a nearby act then it *must be* our knowledge. But then the analog in quantum theory of the physical reality of classical physical theory *must be* our knowledge.

This way of dodging the action-at-a-distance problem was challenged by Einstein, Podolsky, and Rosen (1935) in a famous paper entitled: "Can quantum-mechanical description of physical reality be considered complete?" The issue was whether a theory that is specified to be merely a set of rules about connections between human experiences can be considered to be a complete description of physical reality. Einstein and his colleagues gave a reasonable definition of "physical reality", and then argued, directly from some basic precepts of quantum theory itself, that the answer to this question is 'No'. But Bohr (1935) composed a subtle reply.

Given the enormity of what must exist in the universe, and the relative smallness human knowledge, it is astonishing that, in the minds of most physicists, Bohr prevailed over Einstein in this debate: the majority of quantum physicists acquiesced to Bohr's claim that quantum theory, regarded as a theory about human knowledge, is a complete description of physical reality. This majority opinion stems, I believe, more from the lack of a promising alternative candidate than from any decisive logical argument.

Einstein (1951), commenting on the orthodox Copenhagen position, said: "What I dislike about this kind of argument is the basic positivistic attitude, which from my view is untenable, and seems to me to come to the same thing as Berkeley's principle, *esse est percipi*, "to be is to be perceived". Several other scientists also reject the majority opinion. For example, Murray Gell-Mann (1979) asserts: "Niels Bohr brainwashed a whole generation into believing that the problem was solved fifty years ago". Gell-mann believes that in order to integrate quantum theory coherently into cosmology, and to understand the evolutionary process that has produced creatures that can have knowledge, one needs to have a coherent theory of the evolving quantum mechanical reality in which these creatures are imbedded.

It is in the context of such efforts to construct a more complete theory that the significance of the experiments pertaining to quantum nonlocality lies.

The point is this: If nature really is nonlocal, as these experiments suggest, then the way is open to the development of a rationally coherent theory of nature that integrates the subjective knowings introduced by Copenhagen quantum theory into an objectively existing and evolving physical reality. The basic framework is provided by the version of quantum theory constructed by John von Neumann (1932)

All physical theories are, of course, provisional, and subject to future revision and elaboration. But at a given stage in the development of science the contending theories can be evaluated on many grounds, such as utility, parsimony, predictive power, explanatory power, conceptual simplicity, logical coherence, and aesthetic beauty. The development of von Neumann's theory that I shall describe here fares well on all of these counts.

To understand von Neumann's improvement one must appreciate the problems with its predecessor. Copenhagen quantum theory gives special status to measuring devices. These devices are physical systems: they are made up of atomic constituents. But in spite of this, these devices are excluded from the world of atomic constituents that are described in the mathematical language of quantum theory. The measuring devices, are described, instead, in a different language, namely by "the same means of communication as the one used in classical physics" (Bohr 1958). This approach renders the theory pragmatically useful but physically incoherent. It links the theory to "our knowledge" of the measuring devices in a useful way, but disrupts the dynamical unity of the physical world by treating in different ways different atomic particles that are interacting with each other. This tearing apart of the physical world creates huge conceptual problems, which are ducked in the Copenhagen approach by renouncing man's ability to understand reality.

The Copenhagen version of quantum theory is thus a hybrid of the old familiar classical theory, which physicists were understandably reluctant to abandon completely, and a totally new theory based on radically different concepts. The old ideas, concepts, and language were used to describe our experiences, but the old idea that visible objects were made up of tiny material objects resembling miniature planets, or minute rocks, was dropped. The observed physical world is described rather by a mathematical structure that can best be characterized as representing *information* and *propensities*: the *information* is about certain *events* that have occurred in the past, and the *propensities* are objective tendencies pertaining to future events.

These "events" are the focal point of quantum theory: they are happenings that in the Copenhagen approach are ambiguously associated both with the "measuring devices" and with increments in the knowledge of the observers who are examining these devices. Each increment of knowledge is an event that updates the knowledge of the observers by bringing it in line with the observed outcome of an event occurring at a device. The agreement between the event at the device and the event in the mind of the observer is to be understood in the same way as it is understood in classical physics.

But there's the rub: the connection between human knowledge and the physical world never has been understood in classical physics. The seventeenth century division between mind and matter upon which classical physically theory was erected was such a perfect cleavage that no reconciliation has ever been achieved, in spite of tremendous efforts. Nor is such a reconciliation possible within classical physics. According to that theory, the world of matter is built out of microscopic entities whose behaviours are fixed by interaction with their immediate neighbors. Every physical thing or activity is just some arrangement of these local building blocks and their motions, and all of the necessary properties of all of these physical components are consequences of the postulated ontological and dynamical properties of the tiny parts. But these properties, which are expressible in terms of numbers assigned to space-time points, or small regions, do not entail the existence of the defining qualities of conscious experience, which are experiential in character. Thus the experiential aspect of nature is not entailed by the principles of classical physical theory, but must be postulated as an ad hoc supernumerary that makes no difference in the course of physical events. This does not yield the conceptually unified sort of theory that physicists seek, and provides no dynamical basis for the evolution, through natural selection, of the experiential aspect of nature.

The fact that quantum theory is intrinsically a theory of mind-matter interaction was not lost upon the early founders and workers. Wolfgang Pauli, John von Neumann, and Eugene Wigner were three of the most rigorous thinkers of that time. They all recognized that quantum theory was about the mind-brain connection, and they tried to develop that idea. However, most physicists were more interested in experiments on relatively simple atomic systems, and were understandably reluctant to get sucked into the huge question of the connection between mind and brain. Thus they were willing to sacrifice certain formerly-held ideals of unity and completeness, and take practical success to be the measure of good science.

This retreat both buttressed, and was buttressed by, two of the main philosophical movements of the twentieth century. One of these, materialism-behaviourism, effectively denies the existence of our conscious "inner lives", and the other, postmodern-social-constructionism, views science as a social construct without any objective mind-independent content. The time was not yet ripe, either philosophically or scientifically, for a serious attempt to study the physics of mind-matter connection. Today, however, as we enter the third millenium, there is a huge surge of interest among philosophers, psychologists, and neuroscientists in reconnecting the aspects of nature that were torn asunder by seventeenth century physicists.

John von Neumann was one of the most brilliant mathematicians and logicians of his age, and he followed where the mathematics and logic led.

From the point of view of the mathematics of quantum theory it makes no sense to treat a measuring device as intrisically different from the collection of atomic constituents that make it up. A device is just another part of the physical universe, and it should be treated as such. Moreover, the conscious thoughts of a human observer ought to be causally connected *most directly and immediately* to what is happening in his brain, not to what is happening out at some measuring device.

The mathematical rules of quantum theory specify clearly how the measuring devices are to be included in the quantum mechanically described physical world. Von Neumann first formulated carefully the mathematical rules of quantum theory, and then followed where that mathematics led. It led first to the incorporation of the measuring devices into the quantum mechanically described physical universe, and eventually to the inclusion of *everything* built out of atoms and their constituents. Our bodies and brains thus become, in von Neumann's approach, parts of the quantum mechanically described physical universe. Treating the entire physical universe in this unified way provides a conceptually simple and logically coherent theoretical foundation that heals the rupturing of the physical world introduced by the Copenhagen approach. It postulates, for each observer, that each experiential event is connected in a certain specified way to a corresponding brain event. The dynamical rules that connect mind and brain are very restrictive, and this leads to a mind-brain theory with significant explanatory power.

Von neumann showed in principle how all of the predictions of Copenhagen quantum theory are contained in his version. However, von Neumann quantum theory gives, in principle, much more than Copenhagen quantum theory can. By providing an objective description of the entire history of the universe, rather than merely rules connecting human observations, von Neumann's theory provides a quantum framework for cosmological and biological evolution. And by including both brain and knowledge, and also the dynamical laws that connect them, the theory provides a rationally coherent dynamical framework for understanding the relationship between brain and mind.

There is, however, one major obstacle: von Neumann's theory, as he formulated it, appears to conflict with Einstein's theory of relativity.

Reconciliation with Relativity

Von Neumann formulated his theory in a nonrelativistic approximation: he made no attempt to reconcile it with the empirically validated features of Einstein's theory of relativity.

This reconciliation is easily achieved. One can simply replace the nonrelativistic theory used by von Neumann with modern relativistic quantum theory. This theory is called relativistic quantum field theory. The word "field" appears here because the theory deals with such things as the quantum analogs of the electric and magnetic fields. To deal with the mind-brain interaction one needs to consider the physical processes in human brains. The relevant quantum field theory is called quantum electrodynamics. The relevant energy range is that of atomic and molecular interactions. I shall assume that whatever high-energy theory eventually prevails in quantum physics, it will reduce to quantum electrodynamics in this low-energy regime.

But there remains one apparent problem: von Neumann's nonrelativistic theory is built on the Newtonian concept of the instants of time, 'now', each of which extends over all space. The evolving state of the universe, $S(t)$, is defined to be the state of the entire universe at the instant of time t. Einstein's theory of relativity rejected, at least within classical physical theory, the idea that the Newtonian idea of the instant "now" could have any objective meaning.

Standard formulations of relativistic quantum field theories (Tomonaga 1946 & Schwinger 1951) have effective instants "now", namely the Tomonaga-Schwinger surfaces σ. As Pauli once strongly emphasized to me, these surfaces, while they may give a certain aura of relativistic invariance, do not differ significantly from the constant-time surfaces "now" that appear in the Newtonian physics. All efforts to remove completely from quantum theory the distinctive role of time, in comparison to space, have failed.

To obtain an objective relativistic version of von Neumann's theory one need merely identify the sequence of constant-time surfaces "now" in his theory with a corresponding objectively defined sequence of Tomonaga-Schwinger surfaces σ.

Giving special objective physical status to a particular sequence of spacelike surfaces does not disrupt any testable demands of the theory of relativity: this relativistic version of von Neumann's theory is fully compatible with the theory of relativity at the level of empirically accessible relationships. But the theory does conflict with a *metaphysical idea* spawned by the theory of relativity, namely the idea that there is no dynamically preferred sequence of instantaneous "nows". The theory resurrects, at a deep level, the Newtonian idea of instantaneous action.

The astronomical data (Smoot *et al.* 1992) indicates that there does exist, in the observed universe, a preferred sequence of 'nows': they define the special set of surfaces in which, for the early universe, matter was distributed almost uniformly in mean local velocity, temperature, and density. It is natural to assume that these empirically specified surfaces are the same as the objective preferred surfaces "now" of von Neumann quantum theory.

Nonlocality and Relativity

von Neumann's objective theory immediately accounts for the faster-than-light transfer of information that seems to be entailed by the nonlocality experiments: the outcome that appears first, in the cited experiment, occurs in one or the other of the two Swiss villages. According to the theory, this earlier event has an immediate effect on the evolving state of the universe, and this change has an immediate effect on the *propensities* for the various possible outcomes of the measurement performed slightly later in the other village.

This feature—that there is some sort of objective instantaneous transfer of information—conflicts with the spirit of the theory of relativity. However, this quantum effect is of a subtle kind: it acts neither on matter, nor on locally conserved energy-momentum, nor on anything else that exists in the classical conception of the physical world that the theory of relativity was originally designed to cover. It acts on a mathematical structure that represents, rather, *information and propensities*.

The theory of relativity was originally formulated within classical physical theory. This is a deterministic theory: the entire history of the universe is completely determined by how things started out. Hence all of history can be conceived to be laid out in a four-dimensional spacetime. The idea of "becoming", or of the gradual unfolding of reality, has no natural place in this deterministic conception of the universe.

Quantum theory is a different kind of theory: it is formulated as an indeterministic theory. Determinism is relaxed in two important ways. First, freedom is granted to each experimenter to choose freely which experiment he will perform, i.e., which aspect of nature he will probe; which question he will put to nature. Then Nature is allowed to pick an outcome of the experiment, i.e., to answer to the question. This answer is partially free: it is subject only to certain statistical requirements. These elements of 'freedom of choice', on the part of both the human participant and Nature herself, lead to a picture of a reality that gradually unfolds in response to choices that are not necessarily fixed by the prior physical part of reality alone.

The central roles in quantum theory of these discrete choices—of the choices of which questions will be put to nature, and which answer nature delivers—makes quantum theory a theory of discrete events, rather than a theory of the continuous evolution of locally conserved matter/energy. The basic building blocks of the new conception of nature are not objective tiny bits of matter, but choices of questions and answers.

In view of these deep structural differences there is a question of principle regarding how the stipulation that there can be no faster-than-light transfer of information of any kind should be carried over from the invalid deterministic classical theory to its indeterministic quantum successor.

The theoretical advantages of relaxing this condition are great: it provides an immediate resolution all of the causality puzzles that have blocked attempts to understand physical reality, and that have led to a renunciation of all such efforts. And it hands to us a rational theoretical basis for attacking the underlying problem of the connection between mind and brain.

In view of these potential advantages one must ask whether it is really beneficial for scientists to renounce for all time the aim of trying to understand the world in which we live, in order to maintain a metaphysical prejudice that arose from a theory that is known to be fundamentally incorrect?

I use the term "metaphysical prejudice" because there is no theoretical or empirical evidence that supports the non-existence of the subtle sort of instantaneous action that is involved here. Indeed, both theory and the nonlocality experiments, taken at face value, seem to demand it. The denial of the possibility of such an action is a metaphysical commitment that was useful in the context of classical physical theory. But that earlier theory contains no counterpart of the informational structure upon which the action in question acts.

Renouncing the endeavour to understand nature is a price too heavy to pay to preserve a metaphysical prejudice.

Is Nonlocality Real?

I began this article with the quote from Physics Today: "Nonlocality gets more real." The article described experiments whose outcomes were interpreted as empirical evidence that nature was nonlocal, in some sense. But do nonlocality experiments of this kind provide any real evidence that information is actually transferred over spacelike intervals? An affirmative answer to this question would provide direct positive support for rejecting the metaphysical prejudice in question

The evidence is very strong that the predictions of quantum theory are valid in these experiments involving pairs of measurements performed at essentially the same time in regions lying far apart. But the question is this: Does the fact that the predictions of quantum theory are correct in experiments of this kind actually show that information must be transferred instantaneously, in some (Lorentz) frame of reference?

The usual arguments that connect these experiments to nonlocal action stem from the work of John Bell (1964). What Bell did was this. He noted that the argument of Einstein, Podolsky, and Rosen was based on a certain assumption, namely that "Physical Reality", whatever it was, should have at least one key property: What is physically real in one region cannot depend upon which experiment an experimenter in a faraway region freely chooses to do at essentially the same instant of time. Einstein and his collaborators showed that if this property is valid then the physical reality in a certain region must include, or specify, the values that certain unperformed measurements *would have revealed* if they had been performed. However, these virtual outcomes are not defined within the quantum framework. Thus the Einstein-Podolsky-Rosen argument, if correct, would prove that the quantum framework cannot be a complete description of physical reality.

Bohr countered this argument by rejecting the claimed key property of physical reality: he denied the claim pertaining to no instantaneous action at a distance. His rebuttal is quite subtle, and not wholly convincing.

Bell found a more direct way to counter the argument of Einstein, Podolsky, and Rosen. He accepted both a strong version of what Einstein, Podolsky and Rosen were trying to prove, namely that there was an underlying physical reality (hidden-variables) that determined the results that *all* of the pertinent unperformed measurements *would* have if they were performed. He also assumed, with Einstein, Podolsky and Rosen. that there was no instantaneous action at a distance. Finally, Bell assumed, as did all the disputants, that the *predictions* of quantum theory were correct. He showed that these assumptions led to a mathematical contradiction.

This contradiction showed that *something* was wrong with the argument of Einstein, Podolsky, and Rosen. But it does not fix where the trouble lies. Does the trouble lie with the assumption that there is no instantaneous action at a distance? Or does it lie in the hidden-variable assumption that "outcomes" of unperformed measurements exist?

Orthodox quantum theory gives an unequivocal answer: the hidden-variable assumption that outcomes of unperformed measurements exist is wrong: it directly contradicts quantum philosophy!

This way of understanding Bell's result immediately disposes of any suggestion that the validity of the predictions of quantum theory entails the existence of instantaneous or faster-than-light influences.

Bell, and others who followed his "hidden-variable" approach, (Clauser 1978) later used assumptions that appear weaker than this original one (Bell 1987). However, this later assumption is essentially the same as the earlier one: it turns out to entail (Stapp 1979 & Fine 1982) the possibility of defining numbers that could specify, simultaneously, the values that all the relevant unperformed measurements would reveal if they were to be performed. But, as just mentioned, one of the basic precepts quantum philosophy is that such numbers do not exist.

Eliminating Hidden Variables

The purpose of Bell's argument was different from that of Einstein, Podolsky, and Rosen, and the logical demands are different. The challenge faced by Einstein and his colleagues was to mount an argument built directly on the orthodox quantum principles themselves. For only by proceeding in this way could they get a logical hook on the quantum physicists that they wanted to convince.

This demand posed a serious problem for Einstein and co-workers. Their argument, like Bell's, involved a consideration of the values that unperformed measurements would reveal if they were to be performed. Indeed, it was precisely the Copenhagen claim that such values do not exist that Einstein and company wanted to prove untenable. But they needed to establish the existence of such values without begging the question, i.e., without making an assumption that was equivalent to what the were trying to show.

The strategy of Einstein et. al. was to prove the existence of such values by using only quantum precepts themselves, plus the seemingly secure idea from the theory of relativity that what is physically real 'here and now' cannot be influenced by what a faraway experimenter chooses to do 'now'.

This strategy succeeded: Bohr (1935) was forced into an awkward position of rejecting Einstein's premise that "physical reality" could not be influenced by what a faraway experimenter chooses to do:

"...there is essentally the question of *an influence on the very conditions which define the possible types of predictions regarding future behavior of the system.* Since these conditions constitute an inherent element of any phenomena to which the term 'physically reality' can be properly attached we see that the argument of mentioned authors does not justify their conclusion that quantum-mechanical description is essentially incomplete."

I shall pursue here a strategy similar to that of Einstein and his colleagues, and will be led to a conclusion similar to Bohr's, namely the failure of Einstein's assumption that physical reality cannot be influenced from afar.

The first step is to establish a logical toe-hold by bringing in *some* the notion of "what would happen" under a condition that is not actually realized. This is the essential key step, because all proofs of nonlocality depend basically on using some such "counterfactuality". But any such step stands in danger of conflicting with quantum philosophy. So one must secure this introduction of "counterfactuality" in order to get off the ground.

A very limited, but sufficient, notion of counterfactuality can be brought into the theoretical analysis by combining two ideas that are embraced by Copenhagen philosophy. The first of these is the freedom of experimenters to choose which measurements they will perform. In the words of Bohr (1958):

"The freedom of experimentation, presupposed in classical physics, is of course retained and corresponds to the free choice of experimental arrangements for which the mathematical structure of the quantum mechanical formalism offers the appropriate latitude."

This assumption is important for Bohr's notion of complementarity: some information about all the possible choices is simultaneously present in the quantum state, and Bohr wanted to provide the possibility that any one of the mutually exclusive alternatives might be pertinent. Whichever choice the experimenter eventually makes, the associated set of predictions is assumed to hold.

The second idea is the condition of no backward-in-time causation. According to quantum thinking, experimenters are to be considered free to choose which measurement they will perform. Moreover, if an outcome of a measurement appears to an observer at a time earlier than some time T, then this outcome can be considered to be fixed and settled at that time T, independently of which experiment will be *freely chosen* and performed by another experimenter at a time later than T: the later choice is allowed go either way without disturbing the outcome that has already appeared to observers at an earlier time.

I shall make the weak assumption that this no-backward-in-time-influence condition holds for *at least one* coordinate system (x,y,z,t).

These two conditions are, I believe, completely compatible with quantum thinking, and are a normal part of orthodox quantum thinking. They contradict no quantum precept or combination of quantum predictions. They, by themselves, lead to no contradiction. But they do introduce into the theoretical framework a very limited notion of a result of an unperformed measurement, namely the result of a measurement that is actually performed in one region at an earlier time t coupled with the measurement NOT performed *later* by some faraway experimenter. My assumption is that this earlier outcome, which is actually observed by someone, can be treated as existing independently of which of the two alternative choices will made by the experimenter in the later region, even though only one of the two later options can be realized. This assumption of no influence backward in time constitutes the small element of counterfactuality that provides the needed logical toe-hold.

The Hardy Experimental Setup

My aim is to show that the assumptions described above lead to the need for some sort of instantaneous (or faster-than-light) transfer of information about which choice is made by an experimenter in one region into a second region that is spacelike separated from the first. To do this it is easiest to consider an experiment of the kind first discussed by Lucien Hardy (1993). The setup is basically similar to the ones considered in proofs of Bell's theorem. There are two spacetime regions, L and R, that are "spacelike separated". This condition means that the two regions are situated far apart in space relative to their extensions in time, so that no point in either region can be reached from any point in the other without moving either faster than the speed of light or backward in time. This means also that in some frame of reference, which I take to be the coordinate system (x,y,z,t) mentioned above, the region L lies at times greater than time T, and region R lies earlier than time T.

In each region an experimenter freely chooses between two possible experiments. Each experiment will, if chosen, be performed within that region, and its outcome will appear to observers within that region. Thus neither choice can affect anything located in the other region without there being some influence that acts faster than the speed of light or backward in time.

The argument involves four predictions made by quantum theory under the Hardy conditions. These conditions and predictions are described in Box 1.

Box 1: Predictions of quantum theory for the Hardy experiment.

The two possible experiments in region L are labelled L1 and L2.

The two possible experiments in region R are labelled R1 and R2.

The two possible outcomes of L1 are labelled L1+ and L1-, etc.

The Hardy setup involves a laser down-conversion source that emits a pair of correlated photons. The experimental conditions are such that quantum theory makes the following four predictions:

1. If (L1,R2) is performed and L1- appears in L then R2+ must appear in R.

2. If (L2,R2) is performed and R2+ appears in R then L2+ must appear in L.
3. If (L2,R1) is performed and L2+ appears in L then R1- must appear in R.
4. If (L1,R1) is performed and L1- appears in L then R1+ appears sometimes in R.

The three words "must" mean that the specified outcome is predicted to occur with certainty (i.e., probability unity).

Two Simple Conclusions

It is easy to deduce from our assumptions two simple conclusions.

Recall that region R lies earlier than time T, and that region L lies later than time T.

Suppose the actually selected pair of experiments is (R2, L1), and that the outcome L1- appears in region L. Then prediction 1 of quantum theory entails that R2+ must have already appeared in R prior to time T. The no-backward-in-time-influence condition then entails that this outcome R2+ was fixed and settled prior to time T, independently of which way the later free choice in L will eventually go: the outcome in region R at the earlier time would still be R2+ even if the later free choice had gone the other way, and L2 had been chosen *instead of* L1.

Under this alternative condition (L2,R2,R2+) the experiment L1 would not be performed, and there would be no physical reality corresponding to its outcome. But the actual outcome in R would still be R2+, and we are assuming that the predictions of quantum theory will hold no matter which of the two experiments is eventually performed later in L. Prediction 2 of quantum theory asserts that it must be L2+. This yields the following conclusion:

Assertion A(R2):

If (R2,L1) is performed and outcome L1- appears in region L, then if the choice in L had gone the other way, and L2, instead of L1, had been performed in L then outcome L2+ would have appeared there.

Because we have two predictions that hold with certainty, and the two strong assumptions of 'free choice' and 'no backward causation', it is not surprising that we have been able to derive this conclusion. In an essentially deterministic context we are often able to deduce from the outcome of one measurement what would have happened if we had made, instead, another measurement. Indeed, if knowing the later *actual* outcome allows one to know what some earlier condition must have been, and if this earlier condition entails a unique result of the later *alternative* measurement, then one can conclude from knowledge of the later *actual* outcome what would have happened if, instead, the later *alternative* measurement had been performed. This is about the simplest possible example of counterfactual reasoning.

Consider next the same assertion, but with R2 replaced by R1:

Assertion A(R1):

If (R1,L1) is performed and outcome L1- appears in region L, then if the choice in L had gone the other way, and L2, instead of L1, had been performed in L then outcome L2+ would have appeared there.

This assertion cannot be true. The fourth prediction of quantum theory asserts that under the specified conditions, L1- and R1, the outcome R1+ appears sometimes in R. The no backward-in-time-influence condition ensures that this earlier fact would not be altered if the later choice in region L had been L2. But A(R1) asserts that under this altered condition L2+ would appear in L. The third prediction then entails that R1- must always appear in R. But that contradicts the earlier assertion that R1+ sometimes appears in R.

The fact that A(R2) is true and A(R1) can be stated briefly:

R2 implies LS is true, and

R1 implies LS is false,

where LS is the statement

LS:"If experiment L1 is performed in region L and gives outcome L1- in region L then if, instead, experiment L2 had been performed in region L the outcome in region L would have been L2+."

These two conditions, which follow from 'orthodox' assumptions, impose a severe condition on any putative model of reality. It imposes, first of all, a sharp constraint that ties Nature's choice of outcome under one condition set up in L to Nature's choice of outcome under a different condition set up in L. And it asserts, moreover, that this constraint depends upon what the experimenter decides to do in a region R that is spacelike separated from L.

I believe that it is impossible for any putative model of reality to satisfy these conditions if the information about the free choice made by the experimenter in R is not available in L. Lacking any model that could satisfy this condition without allowing the information about the choice made in R to be present in L one must allow this faster-than-light transfer of information.

This extensive discussion of nonlocality is intended to make thoroughly rational the critical assumption of the objective interpretation von Neumann's formulation of quantum theory that is being developed here, namely the assumption that there is a preferred set of successive instants "now" associated with the evolving objective quantum state of the universe.

The Physical World as Active Information

Von Neumann quantum theory is designed to yield all the predictions of Copenhagen quantum theory. But those predictions are about connections between increments of human knowledge. Hence the von Neumann theory must necessarily encompass those increments of knowledge. Von Neumann's theory is, in fact, essentially a theory of the interaction of these subjective realities with an evolving objective physical universe.

The evolution of this physical universe involves three related processes. The first is the deterministic evolution of the state of the physical universe. It is controlled by the Schroedinger equation of relativistic quantum field theory. This process is a local dynamical process, with all the causal connections arising solely from interactions between neighboring localized microscopic elements. However, this local process holds only during the intervals between quantum events.

Each of these quantum events involves two other processes. The first is a choice of a Yes-No question by the mind-brain system. The second of these two processes is a choice by Nature of an answer, either Yes or No, to this question. This second choice is partially free: it is a random choice, subject to the statistical rules of quantum theory. The first choice is the analog in von Neumann theory of an essential process in Copenhagen quantum theory, namely the free choice made by the experimenter as to which aspect of nature is going to be probed. This choice of which aspect of nature is going to be probed, i.e., of which specific question is going to be put to nature, is an essential element of quantum theory: the quantum statistical rules cannot be applied until, and unless, some specific question is first selected.

In Copenhagen quantum theory this choice is made by an experimenter, and this experimenter lies outside the system governed by the quantum rules. This feature of Copenhagen quantum theory is not altered in the transition to von Neumann quantum theory: choice *by a person* of which question will be put to nature is not controlled by any rules that are known or understood within contempory physics. This choice on the part of the mind-brain system that constitutes the person, is, in this specific sense, a free choice: it is not governed by the physical laws, as they are currently understood.

Only Yes-No questions are permitted: all other possibilities can be reduced to these. Thus each answer, Yes or No, injects one "bit" of information into the quantum universe. These bits of information are stored in the evolving objective quantum state of the universe, which is a compendium of these bits of information. The quantum state state of the universe is therefore an informational structure. But this stored compendium of bits of information has causal power: it specifies the propensities (objective tendencies) that are associated with the two alternative possible answers to the next question put to Nature.

This essential feature of the quantum state, that it has causal efficacy, in the form of propensities for future events, I shall express by saying that the quantum state represents *Active Information.*

Once the physical world is understood in this way, as a stored compendium of locally efficacious bits of information, the instantaneous transfers of information along the preferred surfaces "now" can be understood to be changes, not in personal human knowledge, but in the state of objective active information.

Mind-Brain Interaction

Von Neumann quantum theory—particularly as explicated by Wigner (1987)—is essentially a theory of the interaction between the evolving physical universe and the sequence of events that constitute our streams of consciousness. The theory specifies the general form of the interaction between our subjective conscious knowings and activities in our brains. However, the details need to be filled in, predictions deduced, and comparisons made to empirical data.

A key feature of quantum brain dynamics is the strong action of the environment upon the brain. This action creates a powerful tendency for the brain to transform almost instantly (See Tegmark 2000) into an ensemble of components, each of which is very similar to an *entire* classically-described brain. I assume that this transformation does indeed occur, and exploit it in two important ways. First, this close connection to classical physics makes the dynamics easy to describe: classical language and imagery can be used to describe in familar terms how the brain behaves. Second, this description in familar classical terms makes it easy to identify the important ways in which this behaviour differs from what classical physics would predict.

A key micro-property of the human brain pertains to the migration of calcium ions from micro-channels through which these ions enter the interior of the nerve terminals to the sites where they trigger the release of a vesicle of neuro-transmitter. The quantum mechanical rules entail (Stapp 1993, 2000) that each release of a vesicle of neurotransmitter causes the quantum state of the brain to split into different classically describable components, or branches.

Evolutionary considerations entail that the brain must keep the brain-body functioning in a coordinated way, and more specifically, must plan and put into effect, in each normally encountered situation, a single coherent course of action that meets the needs of that person. Due to the quantum splitting mentioned above, the quantum state of the brain will tend to decompose into components that specify alternative possible courses of action. In short, the purely mechanical evolution in accordance with the Schroedinger equation will normally cause the brain to evolve into a growing ensemble of *alternative possible branches*, each of which is essentially *an entire classically described brain* that specifies a possible appropriate plan or course of action.

This ensemble that constitutes the quantum brain is mathematically similar to an ensemble that occurs in a classical treatment when one takes into account the uncertainties in our knowledge of the intitial conditions of the particles and fields that constitute the classical representation of a brain. This close connection between what quantum theory gives and what classical physics gives is the basic reason why von Neumann quantum theory is able to produce all of the correct predictions of classical physics. To unearth quantum effects one can start from this superficial similarity at the lowest-order approximation that yields the classical results, and then dig deeper.

In the quantum treatment there is a second part of the dynamics: the ordered sequence of mind-brain events. The effect of each such event is to *discard* part of the ensemble that constitutes the quantum brain, and thus reduce that prior ensemble to a subensemble.

Three problems then arise: 1) How is the retained subensemble picked out from the prior ensemble? 2) What is the character of the conscious experience that constitutes the mind part of this mind-brain event? 3) What role does this conscious experience, itself, play in this reduction process?

The answers to these questions are determined, in general terms, by von Neumann's basic dynamical assumption. In the present case this assumption amounts to this: the physical event reduces the initial ensemble that constitutes the brain prior to the event to the subensemble consisting of those branches that are compatible with the associated conscious event. This rule is just the application at the level of the brain of the same rule that Copenhagen quantum theory applies at the level of the device.

This dynamical connection means that, during an interval of conscious thinking, the brain changes by an alternation between two processes. The first is the generation, by a local deterministic mechanical rule, of an expanding profusion of alternative possible branches, with each branch corresponding to an entire classically describable brain embodying some specific possible course of action. The brain is the entire ensemble of these separate quasi-classical branches. The second process involves an event that has both physical and experiential aspects. The physical aspect, or event, chops off all branches that are incompatible with the associated conscious aspect, or event. For example, if the conscious event is the experiencing of some feature of the physical world, then the associated physical event would be the updating of the brain's representation of that aspect of the physical world. This updating of the brain is achieved by *discarding* from the ensemble of quasi-classical brain states all those branches in which the brain's representation of the physical world is incompatible with the information that is consciously experienced.

This connection is similar to a functionalist account of consciouness. But here it is just a consequence of the basic principles of physics, rather than some peculiar extra ad hoc structure that is not logically entailed by the basic physics.

The quantum brain is an ensemble of quasi-classical components. It was just noted that this structure is similar to something that occurs in classical statistical mechanics, namely a "classical statistical ensemble." But a classical statistical ensemble, though structurally similar to a quantum brain, is fundamentally a different kind of thing. It is a representation of a set of truly distinct possibilities, only one of which is real. A classical statistical ensemble is used when a person does not know which of the conceivable possibilities is real, but can assign a 'probability' to each possibility. In contrast, *all* of the elements of the ensemble that constitute a quantum brain are equally real: no choice has yet been made among them, Consequently, and this is the key point, the entire ensemble acts as a whole in the determination of the upcoming mind-brain event.

A conscious thought is associated with the actualization of some macroscopic quasi-stable features of the brain. Thus the reduction event is a macroscopic happening. And this event involves, dynamically, the entire ensemble. In the corresponding classical model each element of the ensemble evolves independently, in accordance with a micro-local law of motion that involves just that one branch alone. Thus there are crucial dynamical differences between the quantum and classical dynamics.

The only element of dynamical freedom in the theory—insofar as we leave out Nature's choices—is the choice made by the quantum processor of *which* question it will ask next, and *when* it will ask it. These are the only inputs from mind to brain dynamics. This severe restriction on the role of mind is what gives the theory its predictive power.

Asking a question about something is closely connected to focussing one's attention on it. Attending to something is the act of directing one's mental power to some task. This task might be to update one's representation of some feature of the surrounding world, or to plan or execute some other sort of mental or physical action.

The key question is then this: Can freedom merely to choose which question is asked, and when it is asked, lead to any statistically significant influence of mind on the behaviour of the brain?

The answer is Yes!

There is an important and well studied effect in quantum theory that depends on the timings of the reduction events arising from the queries put to nature. It is called the Quantum Zeno Effect. It is not diminished by interaction with the environment (Stapp 1999, 2000).

The effect is simple. If the *same* question is put to nature sufficiently rapidly and the initial answer is Yes, then any noise-induced diffusion, or force-induced motion, of the system away from the subensemble where the answer is Yes will be suppressed: the system will tend to be confined to the subensemble where the answer is Yes. The effect is sometimes jokingly called the "watched pot" effect: according to the old adage "A watched pot never boils"; just looking at it keeps it from changing. Similarly, a state can be pulled along gradually by posing a rapid sequence of questions that change sufficiently slowly over time. In short, according to the dynamical laws of quantum mechanics, the freedom to choose which questions are put to nature, and when they are asked, allows mind to exert a strong influence on the behaviour of the brain.

But what freedom is given to the human mind?

According to this theory, the freedom given to Nature herself is quite limited: Nature simply gives a Yes or No answer to a question posed by a subsystem. It seems reasonable to restrict in a similar way the choice given to a human mind. The simplest way to do this is to allow brain to select from among all experientially distinquishable possible courses of action specified by the quasi-classical components that comprise it, the one with the greatest statistical weight. The mathematical structure of quantum theory is naturally suited to this task. The choice given to mind can then be to say Yes or No: to consent to, or veto, this possible course of action. The question will be simply: Will the 'optimal' course of action produced by brain process be pursued or not. The positive answer will cause the branches of the brain that are incompatible with this positive answer to be discarded; the negative answer will cause the branches of the brain that are incompatible with that negative answer to be discarded.

The timings of the questions must also be specified. I assume that the rate at which the questions are asked can be increased by conscious effort. Then the quantum Zeno effect will allow mind to keep attention focussed on a task, and oppose both the random wanderings generated by uncertainties and noise, and also any directed tendency that is generated by the mechanical forces that enter into the Schroedinger equation, and that would tend to shift the state of the brain out of the subspace corresponding to the answer 'Yes'.

5. Explanatory Power

Does this theory explain anything?

This theory was already in place (Stapp 1999) when a colleague brought to my attention some passages from "Psychology: The Briefer Course", written by William James (1892). In the final section of the chapter on Attention James writes:

"I have spoken as if our attention were wholly determined by neural conditions. I believe that the array of *things* we can attend to is so determined. No object can *catch* our attention except by the neural machinery. But the *amount* of the attention which an object receives after it has caught our attention is another question. It often takes effort to keep mind upon it. We feel that we can make more or less of the effort as we choose. If this feeling be not deceptive, if our effort be a spiritual force, and an indeterminate one, then of course it contributes coequally with the cerebral conditions to the result. Though it introduce no new idea, it will deepen and prolong the stay in consciousness of innumerable ideas which else would fade more quickly away. The delay thus gained might not be more than a second in duration— but that second may be critical; for in the rising and falling considerations in the mind, where two associated systems of them are nearly in equilibrium it is often a matter of but a second more or less of attention at the outset, whether one system shall gain force to occupy the field and develop itself and exclude the other, or be excluded itself by the other. When developed it may make us act, and that act may seal our doom. When we come to the chapter on the Will we shall see that the whole drama of the voluntary life hinges on the attention, slightly more or slightly less, which rival motor ideas may receive. ..."

In the chapter on Will, in the section entitled "Volitional effort is effort of attention" James writes:

"Thus we find that *we reach the heart of our inquiry into volition when we ask by what process is it that the thought of any given action comes to* *prevail stably in the mind.*"

and later

"*The essential achievement of the will, in short, when it is most 'voluntary,' is to attend to a difficult object and hold it fast before the mind. ... Effort of attention is thus the essential phenomenon of will.*"

Still later, James says:

"Consent to the idea's undivided presence, this is effort's sole achievement." ..."Everywhere, then, the function of effort is the same: to keep affirming and adopting the thought which, if left to itself, would slip away."

This description of the effect of mind on the course of mind-brain process is remarkably in line with the what arose from a purely theoretical consideration of the quantum physics of this process. The connections discerned by psychologists are explained of the basis of the same dynamical principles that explain the underlying atomic phenomena. Thus the whole range of science, from atomic physics to mind-brain dynamics, is brought together in a single rationally coherent theory of an evolving cosmos that consists of a physical reality, made of objective knowledge or information, interacting via the quantum laws with our streams of conscious thoughts.

Much experimental work on attention and effort has occurred since the time of William James. That work has been hampered by the nonexistence of any putative physical theory that purports to explain how our conscious experiences influence activities in our brains. The behaviourist approach, which dominated psychological during the first half of the twentieth century, and which essentially abolished, in this field, not only the use of introspective data but also the very concept of consciousness, was surely motivated in part by the apparent implication of classical physics that consciousness was either just a feature of a mechanical brain, or had no effect at all on the brain or body. In either of these two cases human consciousness could be eliminated from a scientific account human behaviour.

The failure of the behaviourist programs led to the rehabilitation of "attention" during the early fifties, and many hundreds of experiments have been performed during the past fifty years for the purpose of investigating empirically those aspects of human behaviour that we ordinarily link to our consciousness.

Harold Pashler's book "The Psychology of Attention" (Pashler 1998) describes a great deal of this empirical work, and also the intertwined theoretical efforts to understand the nature of an information-processing system that could account for the intricate details of the objective data. Two key concepts are the notions of a processing "Capacity" and of "Attention". The latter is associated with an internally directed *selection* between different possible allocations of the available processing "Capacity". A third concept is "Effort", which is linked to incentives, and to reports by subjects of "trying harder".

Pashler organizes his discussion by separating perceptual processing from postperceptual processing. The former covers processing that, first of all, identifies such basic physical properties of stimuli as location, color, loudness, and pitch, and, secondly, identifies stimuli in terms of categories of meaning. The postperceptual process covers the tasks of producing motor actions and cognitive action beyond mere categorical identification. Pashler emphasizes (p. 33) that "the empirical findings of attention studies specifically argue for a distinction between perceptual limitations and more central limitations involved in thought and the planning of action." The existence of these two different processes, with different characteristics, is a principal theme of Pashler's book (Pashler 1998 p. 33, 263, 293, 317, 404).

In the quantum theory of mind-brain being described here there are two separate processes. First, there is the unconscious mechanical brain process governed by the Schroedinger equation. It involves processing units that are represented by complex patterns of neural activity (or, more generally, of brain activity) and subunits within these units that allow "association": each unit tends to be activated by the activation of several of its subunits. The mechanical brain evolves by the dynamical interplay of these associative units. Each quasi-classical element of the ensemble that constitutes the brain creates, on the basis of clues, or cues, coming from various sources, a plan for a possible coherent course of action. Quantum uncertainties entail that a host of different possibilities will emerge. (Stapp 1993, 2000). This mechanical phase of the processing already involves some selectivity, because the various input clues contribute either more or less to the emergent brain process according to the degree to which these inputs activate, via associations, the patterns that survive and turn into the plan of action.

This conception of brain dynamics seems to accommodate all of the perceptual aspects of the data described by Pashler. But it is the high-level processing, which is more closely linked to our conscious thinking, that is of prime interest here. The data pertaining to that second process is the focus of part II of Pashler's book.

Conscious process has, according to the physics-based theory described here, several distinctive characteristics. It consists of a sequence of discrete events each of which consents, on the basis of a high-level evaluation that accesses the whole brain, to an integrated course of action presented by brain. The rapidity of these events can be increased with effort. Effort-induced speed-up of the rate of occurrence of these events can, by means of the quantum Zeno effect, keep attention focussed on a task. Between 100 and 300 msec of consent seem to be needed to fix a plan of action, and initiate it. Effort can, by increasing the number of events per second, increase the input into brain activity of the high-level evaluation and control that characterizes this process. Each conscious event picks out from the multitude of quasi-classical possibilities created by brain process the subensemble that is compatible with this conscious event. This correspondence, between a conscious event and the associated physical event—via a reduction of the prior physical ensemble to the subensemble compatible with the experience of the observer—is the core interpretive postulate of quantum theory. Applied at the level of the device it is the basis of Copenhagen quantum theory. Thus von Neumann-Wigner quantum theory applies at the level of the brain the same reduction principle that is used by quantum physicists to account both for the approximate validity of the laws of classical physics, and also for the deviations from those laws that produce quantum phenomena.

Examination of Pashler's book shows that this physics-based theory accommodates naturally for all of the complex structural features of the empirical data that he describes. He emphasizes (p. 33) a specific finding: strong empirical evidence for what he calls a central processing bottleneck associated with the attentive selection of a motor action. This kind of bottleneck is what the physics-based theory predicts: the bottleneck is the single sequence of mind-brain quantum events that von Neumann-Wigner quantum theory is built upon.

Pashler (p. 279) describes four empirical signatures for this kind of bottleneck, and describes the experimental confirmation of each of them. Much of part II of Pashler's book is a massing of evidence that supports the existence of a central process of this general kind.

This bottleneck is not automatic within classical physics. A classical model could easily produce simultaneously two responses in different modalities, say vocal and manual, to two different stimuli arriving via two different modalities, say auditory and tactile: the two processes could proceed via dynamically independent routes. Pashler (p. 308) notes that the bottleneck is undiminished in split-brain patients performing two tasks that, at the level of input and output, seem to be confined to different hemispheres.

Pashler states (p. 293) "The conclusion that there is a central bottleneck in the selection of action should not be confused with the ... debate (about perceptual-level process) described in chapter 1. The finding that people seem unable to select two responses at the same time does not dispute the fact that they also have limitations in perceptual processing...". I have already mentioned the independent selectivity injected into brain dynamics by the purely mechanical part of the quantum mind-brain process.

The queuing effect for the mind-controlled motor responses does not exclude interference between brain processes that are similar to each other, and hence that use common brain mechanisms. Pashler (p. 297) notes this distinction, and says "the principles governing queuing seem indifferent to neural overlap of any sort studied so far." He also cites evidence that suggests that the hypthetical timer of brain activity associated with the cerebellum "is basically independent of the central response-selection bottleneck."(p. 298)

The important point here is that there is in principle, in the quantum model, an essential dynamical difference between the unconscious processing carried out by the Schroedinger evolution, which generates via a local process an expanding collection of classically conceivable possible courses of action, and the process associated with the sequence of conscious events that constitutes a stream of consciousness. The former are not limited by the queuing effect, because all of the possibilities develop in parallel, whereas the latter do form elements of a single queue. The experiments cited by Pashler all seem to support this clear prediction of the quantum approach.

An interesting experiment mentioned by Pashler involves the simultaneous tasks of doing an IQ test and giving a foot response to a rapidly presented sequences of tones of either 2000 or 250 Hz. The subject's mental age, as measured by the IQ test, was reduced from adult to 8 years. (p. 299) This result supports the prediction of quantum theory that the bottleneck pertains to both 'intelligent' behaviour, which requires conscious processing, and selection of motor response, to the extent that the latter is consciously experienced as either an intended or recognized updating of the person's body and/or environment.

The quantum approach constitutes, in practice, a different way of looking at the data: it separates the conscious process of selecting and recognizing the intended or actual reality from the unconscious process of generating possible courses of action, and puts aside, temporarily, but in a rationally coherent quantum-based way, the question of exactly how the choices associated with the conscious decisions are made. The point is that quantum theory suggests that this latter process of making a discrete choice is governed by a dynamics that is more complex than the mechanical process of grinding out possibilities, and that one therefore ought not be locked into a narrow mechanical perspective that makes the dynamics that underlies the two processes the same, and the same as the idealized dynamical process that classical physical theory was based upon.

Another interesting experiment showed that, when performing at maximum speed, with fixed accuracy, subjects produced responses at the same rate whether performing one task or two simultaneously: the limited capacity to produce responses can be divided between two simultaneously performed tasks. (p. 301)

Pashler also notes (p. 348) that "Recent results strengthen the case for central interference even further, concluding that memory retrieval is subject to the same discrete processing bottleneck that prevents simultaneous response selection in two speeded choice tasks."

In the section on "Mental Effort" Pashler reports that "incentives to perform especially well lead subjects to improve both speed and accuracy", and that the motivation had "greater effects on the more cognitively complex activity". This is what would be expected if incentives lead to effort that produces increased rapidity of the events, each of which injects into the physical process, via quantum selection and reduction, bits of control information that reflect high-level evaluation.

In a classical model one would expect that a speed-up of the high-level process would be accompanied by an increase in the consumption of metabolic energy, as measured by blood flow and glucose uptake. But Pashler suggests, cautiously, that this is not what the data indicate. In any case, the quantum reduction processes do not themselves consume metabolic energy, so there is, in the quantum model, no direct need for a speed up in conscious processing itself to be accompanied by an increased energy consumption in the parts of the brain directly associated with this processing.

Studies of sleep-deprived subjects suggest that in these cases "effort works to counteract low arousal". If arousal is essentially the rate of occurrence of conscious events then this result is what the quantum model would predict.

Pashler notes that "Performing two tasks at the same time, for example, almost invariably... produces poorer performance in a task and increases ratings in effortfulness." And "Increasing the rate at which events occur in experimenter-paced tasks often increases effort ratings without affecting performance". "Increasing incentives often raises workload ratings and performance at the same time." All of these empirical connections are in line with the general principle that effort increases the rate of conscious events, each of which inputs a high-level evaluation and a selection of, or focussing on, a course of action, and that this resource can be divided between tasks.

Of course, some similar sort of structure could presumably be worked into a classical model. So the naturalness of the quantum explanations of these empirical facts is not a decisive consideration. In the context of classical modelling the success of the quantum model suggests the possible virtue of conceptually separating the brain process into two processes in the way that the quantum model automatically does. But a general theory of nature that automatically gives a restrictive form is superior to one that needs to introduce it ad hoc.

Additional supporting evidence comes from the studies of the effect of the conscious process upon the storage of information in short-term memory. According to the physics-based theory, the conscious process merely actualizes a course of action, which then develops automatically, with perhaps some occasional monitoring. Thus if one sets in place the activity of retaining in memory a certain sequence of stimuli, then this activity can persist undiminished while the central processor is engaged in another task. This is what the data indicate.

Pashler remarks that "These conclusions contradict the remarkably widespread assumption that short-term memory capacity can be equated with, or used as a measure of, central resources."(p.341). In the theory outlined here short-term memory is stored in patterns of brain activity, whereas consciousness is associated with the selection of a subensemble of quasi-classical states that are compatible with the consciously accepted course of action. This separation seems to account for the large amount of detailed data that bears on this question of the connection of short-term-memory to consciousness (p.337-341).

Deliberate storage in, or retrieval from, long-term memory requires focussed attention, and hence conscious effort. These processes should, according to the theory, use part of the limited processing capacity, and hence be detrimentally affected by a competing task that makes sufficient concurrent demands on the central resources. On the other hand, "perceptual" processing that involves conceptual categorization and identification without conscious choice should not interfere with tasks that do consume central processing capacity. These expectations are what the evidence appears to confirm: "the entirety of...front-end processing are modality specific and operate independent of the sort of single-channel central processing that limits retrieval and the control of action. This includes not only perceptual analysis but also storae in STM (short term memory) and whatever may feed back to change the allocation of perceptual attention itself." (p. 353)

Pashler describes a result dating from the nineteenth century: mental exertion reduces the amount of physical force that a person can apply. He notes that "This puzzling phenomena remains unexplained." (p. 387). However, it is an automatic consequence of the physics-based theory: creating physical force by muscle contraction requires an effort that opposes the physical tendencies generated by the Schroedinger equation. This opposing tendency is produced by the quantum Zeno effect, and is roughly proportional to the number of bits per second of central processing capacity that is devoted to the task. So if part of this processing capacity is directed to another task, then the applied force will diminish.

Pashler speculates on the possibility of a neurophysiological explanation of the facts he describes, but notes that the parallel, as opposed to serial, operation of the two mechanisms leads, in the classical neurophysiological approach, to the questions of what makes these two mechanisms so different, and what the connection between them is (p.354-6, 386-7)

After analyzing various possible mechanisms that could cause the central bottleneck, Pashler (p.307-8) says "the question of why this should be the case is quite puzzling." Thus the fact that this bottleneck, and its basic properties, come out naturally from the same laws that explain the complex empirical evidence in the fields of classical and quantum physics, rather than from some ad hoc adjustment of theory to data, means that the theory has significant explanatory power.

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