

David L. Wilson

Mind–Brain Interaction and Violation of Physical Laws

If mind is not a part of the physical universe but is able to influence brain events, then violations of physical laws should occur at points of such mental influence. Using current knowledge of how the nervous system functions, the minimal necessary magnitude of such violations is examined. A variety of influences that could produce action potentials is considered, including the direct opening of sodium channels in membranes, the triggering of release of neurotransmitter at synapses, the opening of postsynaptic, ligand-gated channels, and the control of neuromodulation. It is shown that the magnitude of the disturbance required is significantly greater than allowed for under quantum-mechanical uncertainty. It is concluded that violations of fundamental physical laws, such as energy conservation, would occur were a non-physical mind able to influence brain and behaviour.

I: Introduction

There are hypotheses of the relationship between mind and brain which do not accept a physical or material explanation for processes such as consciousness and volition. Such hypotheses include various forms of dualism and some more extreme emergence hypotheses (Broad, 1951). It has been argued that any hypothesis proposing that non-physical minds exist, and that such minds play an active role in influencing physical events, requires violation of physical laws (Wilson, 1976; 1995). Nevertheless, some scientists retain such views, as do a great number of non-scientists. In this paper I explore the issue of violation of physical law by asking how minimal such a violation can be. That is, how little can a non-physical mind interfere with physical events while still influencing brain events adequately to allow for volition, willing, etc.?

One could argue that any violation of a physical law is a concern, so why should this issue of the minimum necessary magnitude of such violations be considered important? One reason relates to whether such violations would be detectable. Could such violations occur at a level that is not detectable, or is it at least possible, in principle, that a test for the violations could be devised?

Another reason for asking how minimal such violations can be is that the magnitude and type of violation necessary might influence the acceptability of the notion by some individuals. For instance, some might be more concerned about a violation of conservation of energy than a disturbance below the level of quantum-mechanical uncertainty.

There are several laws and theories of physics that will be considered in this paper. One is the first law of thermodynamics, or energy conservation, which states that energy can neither be created nor destroyed. The second law of thermodynamics states that entropy, a measure of disorder, cannot decrease in a closed system—things get more disordered with time. The principle of conservation of momentum, for our purposes, can be stated as: a particle's mass times its velocity is a constant in the absence of applied forces. Finally, a fundamental principle of quantum mechanics is that events related to collapse of a wave function, or events occurring under quantum mechanical uncertainty, occur randomly. An example of the last principle is the random decay of radioactive atoms: non-random decay would be a violation of physical law.

I will begin by asking what minimal level of energy is required to cause nerve cells in the brain to fire action potentials. Most simply, volitional acts by a non-physical mind would supply such energy. However, I will also briefly consider whether a non-physical mind might harness, rather than supply, such energy during volitional acts, and will ask whether other physical laws would necessarily be violated by such acts of a non-physical mind. I will also examine earlier models that claimed that non-physical control of brain processes could occur without violation of any of the conservation laws of physics.

II: How the Brain Works

I will assume that today's neuroscience gives us a reasonable view of how the nervous system works. In particular, conscious mental functions such as volition would somehow have to produce action potentials (nerve impulses) in neurons. Such action potentials are signals that transmit information along axons and, in most neurons, initiate the process of synaptic transmission of a chemical signal to follower (postsynaptic) cells. Action potentials are necessary to bring about muscle contractions, which produce all behaviour, from simple movements to coordinated actions and speech.

Action potentials are produced by opening sodium channels in neuronal membranes, which allow the movement of sodium ions across the membrane. Action potentials also involve potassium channels, but we can ignore that complexity for the purpose of this analysis. The flux of sodium ions through the sodium channels produces a voltage change across the membrane. The resulting action potential self-propagates along the axon. The sodium channels are voltage-gated in that they can be opened by changes in the voltage across the membrane. Other channels, such as those at the synaptic connections between neurons, can indirectly induce an action potential by allowing ions to move across the membrane, which alters the voltage, and thereby induces the opening of the voltage-gated sodium channels that produce the action potential.

III: Mind–Brain Interaction Mechanisms

I will first consider what minimally would be required of a non-physical mind to trigger a single action potential in a single neuron. There are a number of points in the process that must be considered. Then I will go on to ask how many such events would be needed to generate volitional acts such as speaking or moving hands and fingers.

a. Opening sodium channels

Perhaps the simplest way of causing an action potential would be by opening enough voltage-sensitive sodium channels to trigger an action potential directly. The opening of sodium channels involves a conformational change in the membrane protein that allows sodium ions to pass across the membrane. The conformational change is normally triggered by a reduction in the magnitude of the resting potential across the membrane of the neuron (a depolarization).

The opening of sodium channels through direct conformational change requires energy. That requirement for energy, if met by a non-physical mind, would violate the first law of thermodynamics (energy would be created). Such a violation might go undetected if the energy required, coupled with the time during which it would need to be available, were low enough that it could be “hidden” under quantum-mechanical (Heisenberg) uncertainty. That possibility is considered in Appendix A, below, and is determined not to be the case. That is, the opening of even one channel for an adequate period of time requires an energy input that is orders-of-magnitude greater than possible under quantum-mechanical uncertainty. In addition, causing an action potential would usually require the opening of a number of such channels.

Can the requirement for energy be met by a non-physical mind harnessing existing energy? That is a question that I will discuss later in this paper.

b. Altering voltage gradients

A second way to open sodium channels would be by altering the voltage across the membrane. This voltage change would trigger the voltage-gated sodium channels to open. A voltage gradient is a potential-energy gradient, and thus, in the simplest case, would require the expenditure of energy to modify. Such modification might occur, for instance, by moving charges. Enough positive charges on the inside of the membrane could be moved towards the membrane, and/or enough negative charges away from the membrane, to depolarize to threshold.

A nerve cell typically generates an action potential when its axon hillock region has a membrane potential that reaches threshold, an area that would contain a number of voltage-gated sodium channels. In Appendix A I show that just modifying the voltage gradient over a single channel, a much smaller area than an axon hillock, requires too much energy to be ‘hidden’ under the uncertainty principle. The maximum possible time period for such an energy increase, as allowed by the uncertainty principle, would be too brief to allow for any ion flow.

Given our knowledge of neurophysiology, actions at the level of quantum mechanical uncertainty do not appear to be adequate to generate action potentials by the above mechanisms. It would thus appear that a non-physical mind, which generated action potentials by supplying the energy necessary either to directly open

sodium channels or to indirectly open such channels by altering voltage gradients, would violate the first law of thermodynamics. However, there are other ways of generating action potentials and other ways for non-physical mind to influence brain which still must be considered.

c. Synaptic transmission

1. The presynaptic neuron

Synaptic transmission involves the release of a chemical transmitter from the presynaptic terminal. The chemical transmitter is stored in membrane-bound packages, called vesicles, in the presynaptic terminal. Synaptic transmission involves the linkage and fusion of one or more synaptic vesicles with the presynaptic membrane, releasing the chemical transmitter from the presynaptic cell. Once released, the transmitter interacts with receptors on the postsynaptic cell to cause changes in membrane potential of that cell. Those changes, if great enough, can result in an action potential in the postsynaptic neuron. The fusion process that releases the transmitter is complex and appears to involve the action of several proteins and the hydrolysis of ATP (Rothman and Sollner, 1997).

An influx in calcium ions through the presynaptic membrane triggers the release of synaptic transmitter. The entry of calcium ions into the cell results from the opening of voltage-gated calcium channels in the presynaptic membrane. The opening of such calcium channels is normally brought about by the change in membrane potential caused by an action potential in the presynaptic neuron. Considering all of the events involved in synaptic transmission, the opening of the calcium channel would appear to represent the point of minimum energy requirement. An alternative view of Beck and Eccles (1992), that the release process itself represents such a point of minimal energy requirement, will be considered in section c3, below. The opening of a single calcium channel involves a change in conformation of the protein that forms the channel, allowing a net flow of calcium ions into the cell. However, this is the same kind of event that was considered in Appendix A for the direct opening of sodium channels, and the calculation would be the same. In fact, genetic evidence suggests that voltage-gated sodium and calcium channels share a common mechanism of gating (Koester, 1991).

Thus, again, a necessary violation of energy conservation, well outside of the limit of quantum mechanical uncertainty, would result from non-physical mind opening even one such channel. In addition, the opening of a single calcium channel would not usually be adequate to allow enough calcium into the presynaptic terminal to assure release of synaptic transmitter. At a typical synapse, a considerable number of the channels open at about the same time, causing a thousand-fold rise in local calcium concentration in less than a millisecond.

There is yet a further complication for any non-physical mind. The transmitter is stored in synaptic vesicles. The release of synaptic transmitter from a vesicle is an all-or-nothing event. The typical number of vesicles whose contents are released at a synapse depends on the type of synapse. Several hundred can be released at a nerve-muscle synapse to trigger a single muscle contraction. In the brain, some synapses might release only one synaptic vesicle in response to an action potential, but the

release of one vesicle alone would not usually be enough to cause an action potential in the postsynaptic neuron, as discussed below.

How many synapses need to be activated to assure that the postsynaptic neuron generates an action potential? That would depend upon the state of the neuron. If, at the moment of interaction by a non-physical mind, the neuron were poised just below threshold, then a single vesicle released at a single synapse might do it. But a typical neuron has a membrane potential that is varying with time, as it receives input from a variety of presynaptic neurons forming, typically, thousands of synapses on the receiving neuron. That neuron can be firing action potentials many times per second. Most presynaptic neurons form a number of synapses on each of their follower cells. Single synapses can be unreliable. The release of synaptic transmitter from a few vesicles from a single presynaptic neuron produces a postsynaptic potential of only a few hundred microvolts (Hille, 1992). Many millivolts of potential change are required to raise the membrane potential from resting to threshold for production of an action potential. Thus, to assure that the intervention by a non-physical consciousness is effective, transmitter release from a considerable number of excitatory synapses would appear to be required, and, in some instances, would need to be coupled to the suppression of the action of inhibitory synapses on the same neuron.

Eccles (1970) has proposed that neurons that are sensitive to input from a non-physical mind could be poised with a membrane potential so close to threshold that stimulation from synaptic transmitter released from a single synaptic vesicle would be adequate to cause an action potential. There are several problems with this view. First, such a neuron would be very unstable, firing randomly due to small fluctuations in normal input. Second, there are no known neurons that maintain a constant membrane potential, within tens of microvolts, just below threshold for production of an action potential. Thus, the ability of mind to influence brain would be limited to those times when appropriate neurons were near to threshold, but not close enough to “fire” without additional (non-physical) input. Third, there is no known mechanism whereby a neuron could maintain its potential just below threshold and within such precise limits. Most brain neurons appear to have rapidly changing membrane potentials due to changes in synaptic inputs, metabolic alterations of ion channels, and to changes in the activity of electrogenic pumps, such as the sodium-potassium ATPase.

2. The post-synaptic neuron

If we examine the postsynaptic membrane as another possible site for intervention by a non-physical mind, we find similar limitations. The trigger points for production of change in the membrane potential in the postsynaptic cell are the ligand-gated ion channels that are activated by binding synaptic transmitter molecules. While the details of the conformational changes that are involved in opening such ligand-gated channels have not been determined, this kind of channel has been identified as consisting of proteins in several different cases (Hille, 1992). Thus, the general mechanism is similar enough to the voltage-gated channels that the considerations in the first part of Appendix A hold. Furthermore, the opening of a single ligand-gated channel would not usually be adequate to trigger an action potential. A considerable number of such channels located at more than one synapse would usually be required (Hille, 1992).

3. The Beck and Eccles Models

Two specific models have previously been proposed to explain how a non-physical mind might generate volitional acts without violation of the conservation laws of physics. The earlier model of Eccles (1970) proposed that synaptic vesicles had a great enough uncertainty of location under the uncertainty principle that they would be able to move to the presynaptic membrane for exocytosis. Eccles (1970) had calculated an uncertainty of distance of 5 nanometers over a millisecond of time. It was pointed out that there was an error in the calculation (Wilson, 1976) since the equation that Eccles used was based on the assumption that the vesicle was in a vacuum, not in the viscous medium of a presynaptic terminal. Just given the viscosity of water, the actual uncertainty in location of a synaptic vesicle is on the order of one picometer (Wilson, 1993), which is four orders-of-magnitude smaller than the Eccles (1970) estimate, and is a very small distance, about one percent of the width of an atom.

The second, more recent model was developed by Beck and Eccles (1992; see also Eccles, 1994). They propose that volitional acts of a non-physical mind momentarily increase the probability of exocytosis of synaptic vesicles in presynaptic terminals. They further propose that this can occur without the violation of conservation laws of physics because of the nature of the mechanism of synaptic transmission. They propose that synaptic vesicles are packaged in a presynaptic vesicular grid (PVG) that is paracrystalline. Further, they propose that the trigger mechanism (by which a synaptic vesicle fuses with the presynaptic membrane and releases its content of synaptic transmitter) involves bringing the PVG into a metastable state from which exocytosis can occur. They argue that the transition to the metastable state is by a quantum transition. With these assumptions, they conclude that vesicle exocytosis is a quantum mechanical event, and propose that a non-physical mind can influence the quantal selection process. Were such a model accurate, the actions of mind would at least violate the requirement for randomness in such quantum mechanical processes.

In addition, the model of synaptic vesicle release presumed by Beck and Eccles (1992) is not a likely or reasonable model given our current knowledge of the mechanism of synaptic transmission (Sollner and Rothman, 1994; Jahn and Sudhof, 1994; Matthews, 1996). While that knowledge is still being developed, and details are not firmly established, the evidence does not support a model of transmitter release that involves the transition of a PVG to a metastable state. Instead, specific active zones at the presynaptic membrane have been recognized as the sites of release of synaptic transmitters (Kandel, 1991). Synaptic vesicles do cluster adjacent to such active sites, and the synaptic vesicles appear to be connected by cytoskeletal components, such as actin filaments. However, rather than being a PVG in a metastable state, the vesicles must actually be released from the cluster before docking and fusing at the plasma membrane. Influx of calcium into the presynaptic terminal is the triggering event for transmitter release, and the calcium appears to be involved in several different events related to synaptic transmission (Burgoyne and Morgan, 1995). One is the release of the individual vesicles from cytoskeletally linked pool, and another is the fusion of the vesicles with the plasma membrane at the active zone. Both of these events appear to involve the binding of calcium to proteins, followed by conformational changes in the proteins. The first event is a calcium-calmodulin activated process that disrupts the linkage of the vesicles by actin filaments, releasing one or more vesicles from the cluster of vesicles. Calcium is thought to play a further role in the actual docking of

the vesicle to the plasma membrane, triggering release of the transmitter. Many of the proteins involved in these processes have been identified, and detailed models, with some experimental support, have been developed (Sollner and Rothman, 1994; Littleton and Bellen, 1995; Jahn and Sudhof, 1994; Matthews, 1996; Martin, 1997). It is thought that phosphorylation of a synapsin (one of the proteins), triggered by calcium, frees the vesicle to move into the active zone. Other proteins mediate recognition of vesicle and release site (Sollner and Rothman, 1994). In brief, current evidence and data indicate that the events involved in synaptic transmitter release require, at least, the same kind of conformational changes in proteins described earlier in this article. The modification of such events by a non-physical influence would require violation of conservation laws of physics, either energy conservation, as discussed above, or other conservation laws, as discussed below in the section on harnessing energy. There is no evidence favouring the Beck and Eccles model that synaptic transmission is the result of quantum mechanical selection events among states occurring in paracrystalline arrays of synaptic vesicles. Without that model being correct, their hypothesis concerning how a non-physical mind might act collapses.

Summing-up this section, non-physical mind acting through synaptic transmission appears to require energy, at well above a quantum-mechanical level, and confronts other complexities if the likely need to activate a number of such synapses is taken into account. Finally, there are more than ten trillion synapses in a single human brain. We have not considered how a non-physical mind could identify exactly which ones to activate, and whether such identifications might require further violations of physical laws.

d. Neuronal modulation

In addition to opening ion channels directly, some neurotransmitters, including norepinephrine, serotonin, dopamine, and some neuropeptides, act as modulators of nerve activity. These modulators produce biochemical changes in postsynaptic cells, which alter the longer-term sensitivity of the neurons to other synaptic input. Such biochemical events offer another point for mental influence, as many of these neuromodulatory processes act through a cascade (a series of biochemical reactions), altering enzymatic activity, and allowing for a considerable amplification of the signal within the neuron. Such amplifying cascades are similar to the ones operating with hormones. In neurons, the end products can include modified ion channels, whose sensitivity to future synaptic inputs can be altered.

Were a non-physical mental influence able to alter an early event in the cascade, greater change would be generated than similar actions later in the cascade. In Appendix B I explore the magnitude of energy that would be required to initiate a cascade, and find that it appears to be significant, and certainly not allowable under the uncertainty principle. A violation of energy conservation would again be necessary.

There are other limitations of modulation of neuronal activity which make it unsuitable as a point for volitional influences from a non-physical mind. Modulation serves more as an amplifier than an initiator of action. It may be important in setting one's mood or arousal, but modulation alone does not cause neurons to fire action potentials—it merely adjusts the response level of neurons to other inputs. Thus, it cannot take part in the specifics of decision making or volitional action. The probabil-

ity of firing action potentials in certain situations could change, but the initiation of action that volition would seem to entail is more like a signal than the amplification of the signal.

Furthermore, the above would require that the neurons capable of initiating volitional acts possess the necessary receptors and biochemical machinery of neuromodulation.

Finally, the time course of such modulatory actions would appear to be too slow. Modulatory influence has a time course that is considerably slower than voltage-gated or ligand-gated actions, typically having an initiation time that is measured in seconds (Hille, 1992). Volitional acts, such as the pressing of a button in response to a flash of light, can be complete in tenths of a second. In brief, for several reasons, the control only of these neuromodulatory synapses would be inadequate for volitional control of particular actions.

e. Self-generation of action potentials by neurons

Some neurons have special channels, typically potassium and calcium channels, that allow for the self-generation of action potentials. Many of these neurons are pacemaker cells, similar to the kind of pacemaker cells that are found in the heart. They have an oscillating membrane potential that periodically depolarizes the cell to threshold, resulting in an action potential, or a burst of several action potentials.

We need to consider the possibility that non-physical mind might act through the modulation of such channels. However, the mechanism for such self-generation of action potentials appears to be similar to the modulation mechanism described above (Hille, 1992). Thus, the analysis in Appendix B serves to show that the level of disturbance required directly to influence this mechanism by a non-physical mind would similarly require violation of energy conservation. In addition, the number of neurons exhibiting pacemaking activity appears to be even smaller than those containing the machinery for neuromodulation. Finally, as with modulation, the time course would be slow and unable to account for rapid mental influences.

IV: Harnessing Energy

In all of the above considerations, the level of energy required for a non-physical mind to trigger volitional acts was estimated. One might ask whether a non-physical mind might avoid violation of the law of conservation of energy by harnessing existing energy to bring about the required changes in protein conformation or voltage gradients.

For instance, a non-physical mind might cause changes in the direction of motion of enough ions in the vicinity of a sodium channel to generate the voltage change needed to cause the voltage-gated sodium channel to open. In this case it would appear that a much larger number of individual events would have to be influenced (as thousands of ions and molecules individually have their directions altered), but the individual influences might not have to violate energy conservation if each molecule retains its kinetic energy unchanged during its alteration of direction of motion, and if the resulting change in the potential energy of the local voltage gradient is offset by a change in heat energy, or other form of energy.

However, in this and all such cases that I can imagine, such harnessing of existing energy sources would require the violation of other physical laws. In the particular case above, consider the selective, directional movement of ions with specific charges on them—positively charged in one direction, negatively charged in the opposite direction—over a brief period of time, generating a significant shift in membrane potential. A variant of a Maxwell’s demon, or a number of such demons, would appear to be necessary for such alterations of motion. Such demons were originally given the ability merely to open a trap door, allowing faster moving gas molecules to pass in a given direction. The general idea of a Maxwell’s demon has been well studied (Leff and Rex, 1990), and it is recognized that the actions of such demons violate the second law of thermodynamics. In addition, in our case, the volitional demons could not just use trap doors because the demons would have to change the direction of movement of ions (or the direction of movement of other molecules that might collide, or not, with the ions) in a liquid. Minimally, such changes in the direction of motion of ions or molecules would violate conservation of momentum. Thus, with this one example, both the second law of thermodynamics and the principle of conservation of momentum would appear to be violated. Furthermore, the need for a non-physical mind to act, individually, on many ions or molecules would add to the complexity of the volitional interaction. Thousands of select, individual interactions would appear to be required just to initiate the opening of a single membrane channel.

A demonstration that laws of physics other than energy conservation would always be violated by a non-physical mind “borrowing” energy from existing sources to generate an action potential is beyond the scope of the present paper. However, the view that such violations would always occur does not appear to be unreasonable given the ability of physical laws to account for the movements of ions and molecules. Thus, indirectly producing the conformational changes needed to produce action potentials, by events that result in harnessing the required energy, appears only to shift the problem of violation of physical laws to those earlier events that volitional acts would influence, and to compound the number of possible events that would have to be individually controlled.

V: How Many Action Potentials for a Volitional Act?

Up to this point we have been considering what is needed to trigger a single action potential in a single neuron. For a volitional act to be carried out, how many action potentials are needed in a given neuron, and how many different neurons must initiate action potentials?

In order to cause muscles to contract, the brain must generate action potentials in spinal cord motor neurons. Each action potential in a spinal cord motor neuron will, in turn, directly trigger a twitch (brief) contraction in, typically, a few muscle fibres in a muscle. The input to such spinal cord motor neurons is complex, and comes from a number of sources. One of these sources is the primary motor cortex of the brain. Volitional acts are not instigated directly at the primary motor cortex of the brain, but during volitional acts, action potentials in other brain neurons are thought to lead to action potentials in the output neurons of the motor cortex (Penfield, 1958).

Minimally, it would appear that at least one brain neuron would have to be activated for a volitional act. What is not clear today is whether a single action potential

in a single neuron would be adequate or whether a very large number might be needed. There are several reasons for the uncertainty.

It is known that voluntary movements involve the activity of neurons in various brain regions (Georgopoulos, 1991; Hanes and Schall, 1996; Snyder, et al., 1997). However, it is possible that one or a few so-called command neurons might exist and have the ability to govern volitional acts. It is known that, in some invertebrates, there are single command neurons that can trigger complex, co-ordinated behavioural responses (Stein, 1978).

Might such command neurons exist in humans, one for each of the possible volitional acts we perform, so that only one neuron would need to be triggered for each such act? If one considers the complexity and uniqueness of the motor responses related to higher-level conscious activity, and the way that we learn complex behavioural actions, the idea of a single command neuron initiating each volitional act appears inadequate, as indicated below.

The command neuron in invertebrates works well for repetitive, sequenced behaviours, such as certain forms of movement. In contrast, what often characterizes conscious volitional behaviour is new combinations of muscle contractions. Consider language. The strength of language is its ability to generate a near-infinite variety of meanings from unique combinations of words. Volitional acts can involve original, creative speech. Such new combinations of words require unique sequencing of muscle contractions. At most, one could imagine something like command neurons that could trigger output of individual words or phrases, but the unique sequencing of such words or phrases into sentences would appear to require individual disturbances of brain function by a non-physical mind for each word or phrase. At least for more complex volitional acts, the firing of a number of neurons would appear, minimally, to be required.

Another complexity in determining the number of action potentials required for volitional acts comes from studies of voluntary acts in individuals. Libet *et al.* (1983) have shown that brain activation leading to a simple voluntary act has a temporal component (readiness potential) that can be measured from the scalp, and that lasts at least one-quarter to one-half second before action. These researchers indicate that the readiness potential begins several hundred milliseconds before subjects indicate that a conscious decision to act has been made. Libet (1985) has proposed that the function of conscious will is not to initiate specific voluntary acts, but to exercise conscious veto control over the cerebral processes that precede the act. It might be argued that such control could be exercised with the activation of fewer neurons, perhaps through strategically activated inhibitory interneurons. However, the readiness potential, a measurable potential on the scalp, involves activity in a very large number of neurons. A suppression of that activity might equally well involve the firing of many neurons.

Again, we are left with considerable uncertainty about the minimal number of neurons that would need to be independently activated to generate (or veto) a volitional act. For more complex acts it would appear to be more than one, as indicated above, but we do not yet know if the minimum number for a typical act is a few or very many.

VI: Input: From Brain To Non-physical Mind

In addition, there would be a need for any non-physical mind to monitor the activity in numerous brain neurons to gain and maintain input about brain states, perceptions, feedback concerning movements, etc. Thus, any non-physical mind would have to have some means of detecting the state of firing of neurons. In this paper we have gained some sense of the minimal level of disturbance that would be required of a non-physical entity to take action in the physical world, but we have no way of knowing how much disturbance of the physical world would be required by a non-physical entity to detect the state of brain neurons. However, the difficulty that such an entity would face should be obvious. For instance, if perceptions are something occurring in a non-physical mind, and result from “input” to the mind from the brain, then the mind would need to be able continually to monitor millions of neurons whose locations are spread through large regions of the cortex (Crick, 1994).

VII: Discussion

Mind-brain interaction is not the only instance for which some scientists have proposed hypotheses that require violation of currently accepted physical laws. The steady-state hypothesis of the universe (Bondi, 1952), which offered an alternative to the big-bang hypothesis, required the ongoing production of matter throughout the universe, a violation of conservation of energy. That hypothesis has been largely discarded, and a similar fate may await dualistic, interactionist hypotheses of the relationship between mind and brain. However, for those who support monistic views, it will be necessary to produce a physical explanation for consciousness and volition, a challenge much discussed but not yet met.

The above considerations outline what, minimally, would be necessary for a non-physical control of brain function sufficient for conscious acts and volition. There appears to be no way that a non-physical mind could act without violating physical laws. Furthermore, there appears to be no obvious way, consistent with our knowledge of neurophysiology and neurochemistry, for such a non-physical mind to bring about volitional acts by altering brain events only at a level within quantum-mechanical uncertainty. In each case examined, any effective actions by a non-physical entity would produce violations of one or more of the principles or laws of physics. Even were a minimal interference, under the uncertainty principle, shown to be possible, it would not allow a non-physical mind to influence brain without the violation of physical laws because any events occurring within quantum-mechanical uncertainty are required to be random. The patterned firing of action potentials in neurons that appear to be required by volitional actions would be highly non-random.

What the analysis reported here makes obvious is that the uncertainty principle leaves one very little to work with at the level of an individual neuron, and even at the level of individual membrane channels or enzymes within neurons. The design of experiments to detect violations of physical laws caused by non-physical, mental influences would obviously be quite difficult. Nevertheless, were a non-physical mind to influence events in brains, I conclude that it would not be able to ‘hide’ under quantum-mechanical uncertainty.

In summary, our current understanding of brain function has reached a stage such that violations of physical laws appear to be necessary if a non-physical mind is to influence brain. Beyond the seemingly necessary violation of physical laws, any such non-physical entity would require some means of selectively influencing the appropriate channels or synapses among the many trillions existing in the brain — no mean task.

For those who believe that free will must be totally independent and free of physical causes, the idea that physical laws must be violated should not be taken as a negative but almost as an expectation, especially to the extent that physical laws appear to specify a universe that is either determined or randomly probabalistic. If a non-physical mind exists, the research project for the next century should be to explore the impact of such non-physical influences—where in the brain does such influence occur and what laws are broken?

Of course, there are other hypotheses of the relationship between mind and brain. The postscript in Crick (1994) gives a description of what the feeling of free will might entail under a monistic view. Under such monistic views, volitional acts are brain acts and do not require initiation by a non-physical entity. Some argue that such views leave volition a mere illusion. In this paper I have attempted to base my arguments on our current understanding of physical laws and knowledge of neurobiology. It is exciting to consider the possibility that a solution to the problem of consciousness might give us better insight into the nature of matter (Cairns-Smith, 1996) as well as free will. Our scientific world-view remains incomplete without that solution.

Appendix A: Opening Gates On Membrane Channels

a. Directly opening gates

Each sodium channel can be viewed as having a gate which opens the channel in response to a depolarization of the voltage across the membrane. When the channel is open, sodium can flow through the channel. The voltage-gated sodium channel is a membrane protein. Proteins are chains of linked amino acids. In the simplest model, the gate can be viewed as an arm of the protein, a part of the chain. One recent model of how the sodium channel works (Catterall, 1988) is considerably more complex, and involves the rotation of regions of the protein that form alpha-helices. Each alpha helix is proposed to be linked to a series of positive charges, and breaks, rotates about sixty degrees, and then remakes shifted linkage points. The rotation of a set of these coils changes the shape of the protein so as to produce an open channel. There are other models of how the voltage-gating opens a channel in the membrane (Hille, 1992), but independent of the particular model, the measured magnitude of gating currents supports considerable movement of a significant piece of the protein (Papazian and Bezanilla, 1997). It is also thought that all three of the major kinds of voltage-gated channels; sodium, calcium, and potassium, use the same general mechanism, based on similarities in their amino acid sequence (Koester, 1991). For our purposes, the movement of one short arm on an amino acid chain will be used as a model. Is the energy required to move such an arm significantly greater than what would be available through quantum-mechanical uncertainty?

From the standpoint of quantum mechanics, how far can this arm or gate move without being detectable by the uncertainty principle? The uncertainty principle states that:

$$(\Delta E)(\Delta t) > \frac{h}{2\pi}$$

where: ΔE is uncertainty in energy
 Δt is uncertainty in time
and h is Planck's constant

is the approximate maximum uncertainty. So, for a non-physical influence to be undetectable, the uncertainty in the product of energy and time involved in the process of moving the gate must be less than this, or,

$$(\Delta E)(\Delta t) < \frac{h}{2\pi}$$

Several different kinds of forces or bonds are involved in determining the conformation of a protein, including hydrogen bonds, ionic bonds, and covalent disulphide bonds. A fourth kind of force that can be involved consists of hydrophobic interactions, but these actually relate to the formation, or lack of formation, of hydrogen bonds by water molecules surrounding the protein. Such hydrophobic interactions are involved, for instance, in determining the membrane-buried part of channel proteins. For our purposes, such hydrophobic interactions can be viewed as related to hydrogen bonding.

One or more of the above four bonds or forces will be involved in maintaining a particular arm of a protein in a particular position, but if there is to be stability in the shape of the protein, enough force must be involved that the arm does not 'flap' open and closed due to random thermal motions. The weakest of the above forces is the hydrogen bond, which is ten to twenty times weaker than a typical ionic or covalent bond. Although surely an underestimate of the forces involved, given the need to maintain a stable conformation, let's consider the case where one hydrogen bond (the weakest of the above) is all that is involved in holding the channel in a closed configuration. Under the uncertainty principle, how long can the channel be open (hydrogen bond be broken) and go undetected under the uncertainty principle? The energy involved in breaking hydrogen bonds is about 20 kJoules/mole. For a single hydrogen bond this amounts to

$$20 \text{ kJ} / 6.02 \times 10^{23} = 3.3 \cdot 10^{-20} \text{ Joules.}$$

Inserting this value as ΔE in the above formula from the uncertainty principle and solving for Δt gives

$$\Delta t < 3.2 \times 10^{-15} \text{ sec.}$$

This is such a very brief period of time for the channel to remain open that no ions would have time to pass through the channel. The time required just to open a membrane channel appears to range from tens of microseconds to fractions of a millisecond (Hille, 1992).

Since the uncertainty principle involves the product of energy change and time, one could increase the time available by reducing the energy required. Thus, to allow the channel to open for a millisecond under the uncertainty principle would entail reducing the energy involved by a factor of about one trillion! It should be clear that

the direct opening of a single channel by a non-physical mind could not escape undetected under the uncertainty principle.

b. Changing voltage across the membrane

There is a second way to view the problem, namely, to look at the magnitude of the energy involved in the change of potential across the membrane. Consider just a single channel in the membrane. A rough estimate of the minimal size of the patch of membrane whose potential must change is a square area, 100 angstroms on a side, centred on the channel (this area is not so much larger than an individual channel plus immediate surrounding area that most greatly influences electrical potential). An estimate of the amount of energy required to bring that small patch from resting potential to a potential that will trigger the opening of the channel is given below.

Typical capacitance for a neuronal membrane is 1 microfarad per square centimetre. The difference in potential between resting and threshold is about 25 millivolts. The energy involved in generating a change of about 25 millivolts in potential, per square centimetre is given by:

$$\frac{1}{2}C(\Delta V)^2$$

where C is capacitance
and ΔV is 25 millivolts.

Multiplying by the estimate of the minimum area required at a single channel, $(100 \text{ \AA})^2$, gives:

$$\text{Energy} = 3.1 \times 10^{-22} \text{ joules.}$$

Inserting this as ΔE in the Heisenberg uncertainty equation, gives

$$\Delta t < 3.3 \times 10^{-13} \text{ seconds}$$

which is too brief, by many orders of magnitude, to allow for any significant change in the conformation of the channel protein and initiation of flux of sodium, which requires fractions of a millisecond, not fractions of a picosecond (Hille, 1992). Thus, there is insufficient time under the uncertainty principle for the flux of sodium ions through the channel, given the energy change required to open the channel. Once again, there is a failure to 'hide' under the uncertainty principle by many orders-of-magnitude.

Appendix B: The Biochemical Approach

How much energy is required for the initiation of the cascade that results in neuro-modulation? The influence, to be most effective with the least energy expenditure, should occur at or near the beginning of the cascade. We will consider only a single triggering of the cascade, although this probably would be quite inadequate to bring about the desired level of modulation.

What energy is required for the single triggering of a cascade? To answer this question we need to examine the details of how such cascades are initiated (Schwartz and Kandel, 1991). In all cases, the binding of a neuromodulator to receptors on the membrane causes a conformational change in a protein receptor. This change is like that considered above for ligand-gated ion channels. The next step in all known cases of

neuromodulation consists of the activation of a G protein by the altered receptor. The G protein has its conformation altered by this interaction, and as a result, binds a molecule of GTP in place of GDP. Later steps in modulation differ, but all appear to involve, at the least, conformational changes in proteins, and for the cascade amplification to be significant, often involve the phosphorylation of proteins, which requires even more energy than a simple conformational change. Thus, the influence of a non-physical mind on the early stages of neuromodulation would involve the same kind of conformational adjustment considered in the first part of Appendix A, above, with the same conclusion applying. Once again, the conclusion is that, by any reasonable mechanism, the energy requirement would be significantly greater than allowed for under the uncertainty principle, and the first law of thermodynamics would be violated by action of a non-physical mind.

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