S & CB (2010), **22**, 133–149 0954–4194

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Determinism, Brain Function and Free Will

The philosophical debate about determinism and free will is far from being resolved. Most philosophers (including Christians) are either compatibilists, asserting that determinism is compatible with free will, or libertarians, arguing that free will requires a fundamental indeterminism in nature, and in particular in brain function. Most libertarians invoke Heisenbergian uncertainty as the required indeterminism. The present paper, by a neurobiologist, examines these issues in relationship to biblical teaching on the brain-soul relationship. It distinguishes different levels of determinism, including genetic and environmental determinism, and argues that these are incomplete, whereas the physical (or 'Laplacian') determinism of brain function is almost total. In particular, it is argued that the attempt to support the libertarian concept of free will on the foundation of Heisenbergian uncertainty applied to the brain is problematic for both conceptual and quantitative reasons.

Key words: free will, brain, neuroscience, quantum theory, soul, monism, dualism

The fact that the laws of nature are deterministic, apart from tiny effects at the quantum level, raises many questions. Was the entire future of the universe determined at the moment of the big bang? Are miracles possible? Can intercessory prayer make any sense in a deterministic universe? Is God on compulsory sabbatical leave as a result of his own impersonal laws? And can free will be real when our brains obey the laws of physics? These are all important questions, but this essay will focus on the last one, that of free will and determinism.

Determinism at different levels

Determinism can be considered at various levels including: *physical determinism*, resulting from the fact that the laws of physics are (almost) deterministic; *social determinism*, the thesis that people are trapped in a web of social constraints; *psychological determinism*; *environmental determinism*; *genetic determinism*; and so on. All these levels are important, for both theoretical and practical reasons, but I here focus on *physical determinism*, because I consider that this is the level where the problem of determinism is most acute. As is argued below, genetic determinism, or even the combined determinism of genes and external environment is only partial, whereas physical determinism may be (almost) total.

Genetic determinism of our brains and personalities is only partial

Genetic determinism says that the genotype determines the phenotype. Nobody doubts that many of our physical characteristics, such as height and eye colour, are largely determined genetically. But what about brain development? What about personality?

The complexity of the human brain is far too great for every detail of its interconnections to be specified by the genes. The human genome contains theoretically about 6.2×10^9 bits of information, calculated from the number of nucleotide pairs (3.1×10^9), each worth 2 bits, in both coding and noncoding DNA). The amount of this information that can actually be used is probably several orders of magnitude less. This figure is an absolute upper limit; it cannot be increased by particular devices such as alternate splicing. It follows that there is far too little information in the genome to specify the detailed connections of a person's 10^{11} neurons, each with hundreds or thousands of synaptic contacts.

It is therefore no surprise that the brains and personalities of identical twins differ, as is the case also with lower animals that are genetically identical (see below). Conventionally the differences between genetically identical organisms are attributed to influences from the external environment, but I shall argue that there are additional causes.

Determinism by a combination of genes and environment

By environmental influences, I mean all external influences on the organism, ranging from intrauterine conditions to education. Unlike determinism by genes alone, this combined determinism is often considered to be total, a prison from which we can never escape. I agree that this combined determinism is indeed very considerable, and it is commonplace for students of the determinants of behaviour to assume that the variance in a population (of humans, or mice, or fruit flies…) is entirely due to a combination of genetic factors and environmental ones.

But as soon as you get down to understanding the underlying biology, this seems unlikely. As mentioned above, there is nowhere near enough information in the genome to specify all the details of brain connectivity. Environmental influences are certainly not going to provide all the missing information, important though they are. Several authors including myself[1] have drawn attention to the fact that chance events beyond the control of either genes or environment influence many aspects of brain development. As the growing ends of axons and dendrites (called growth cones) advance, they are constantly putting out feelers ('filopodia') to recognise molecular guidance molecules along

1 Clarke, P.G.H. *Perspect. Biol. Med.* (1981) 25 (1), 2-19.

the way. Their growth can be studied, and they can be seen to be constantly making minor changes in direction, as if they are finding their way on a trial and error basis. Most reach more or less the right destination, but the precision is not total. Some (about 1%) make gross mistakes; for example, axons growing from the eye to the brain sometimes turn the wrong way at the optic chiasm, the place where the two optic nerves meet. Some grow to the wrong side of the brain, and others fail even to reach the brain, growing back down the other optic nerve. Far larger numbers (up to 40% in some cases) reach approximately the correct part of the brain, but make more subtle errors (e.g. they may grow to the wrong part of the correct target nucleus). The brain has a well developed signalling system to recognise such errors and eliminate them. If axons fail to obtain a correct signal from appropriate target neurons, the axon degenerates, and in some cases the neuron may die.[2] Thus, our brains develop, not by a rigidly prespecified programme, but by a more approximate process involving imprecision everywhere, gross mistakes occasionally, and elimination of faulty elements at various inspection points along the cellular production line.

The above examples concern events at the cellular level, but it has been argued that there is indeterminacy at the molecular level too. Many molecular processes occurring in cells are currently understood as stochastic events. For example, the binding of a transcription factor (TF) molecule to a particular sequence of DNA (to initiate transcription, i.e. gene copying) involves the apparently random diffusion of many such molecules. One happens to reach the appropriate DNA sequence, whereas many others do not. Typically there may be thousands of TF molecules diffusing in the cell nucleus, but only one of them will reach the appropriate sequence on a particular strand of DNA. The details of which TF molecule will get there, and precisely when, is not specified genetically. When the TF molecules are numerous, the details will not matter, but when they are relatively few in number, it may be a matter of chance whether the TF binding sequence gets bound, and if so when. We still do not know how important such chance factors are for the overall functioning of organisms, but recent attempts at modelling suggest they can be very important.[3] This further underlines that the most extreme forms of genetic determinism are implausible at the cellular level. At every level, genetic specification is only approximate.

Studies of genetically identical animals

This interpretation is supported by studies of isogenic (genetically identical) animals. Even in humans, the brains of monozygotic twins differ morphologically.[4] They differ much less than the brains of dizygotic twins, but they do dif-

2 Clarke *op. cit.*, (1).
3 Pedraza, J.M. & van Oudenaarden, A. *Science* (2005) 307 (5717), 1965-9.
4 Schmitt J.E., Eyler L.T., Giedd J.N., Kremen W.S., Kendler K.S., Neale M.C. *Twin Research and Human Genetics* (2007) 10 (5),683-694.

fer, and so do the intellectual abilities and psychological characteristics of identical twins. Some of these differences are probably due to environmental factors, which act even prenatally; for example, one twin may receive a richer blood supply and therefore be better nourished in the womb. But even when environmental factors are minimised, differences still occur, as has been shown in isogenic animals reared under the same conditions. For example, in isogenic daphniae, even though the position, size and branching pattern of each optic neuron is remarkably constant from animal to animal, there is nevertheless some variability in their connectivity.[5] Similarly, in isogenic grasshoppers, there is variability in the positions of neurons and in the branching patterns of their dendrites – as much, in fact, as in heterogenic clutches.[6] Also, in genetically identical specimens of the tropical fish *Poecilia formosa* (Amazon Molly), it is almost random whether the optic nerves or the Mauthner cell axons cross left over right or right over left.[7] Even in lowly nematode worms, whose development is considered to be much more tightly controlled genetically than that of more complex species, there are differences between the nervous systems of isogenic worms.[8] Since the environments of these different isogenic animals were essentially identical, the variability probably reflects developmental events below the resolution of genetic control, tiny fluctuations that have been called *developmental noise*.

In an excellent book, Finch and Kirkwood[9] have reviewed the consequences of this *developmental noise* in both development and ageing in a wide range of species including humans. They make a strong case that 'chance' events, beyond the combined control of genome and environment, make a major contribution to the differences between individuals.[10]

Physical or 'Laplacian' determinism

What then causes the differences between isogenic insects and fish reared in similar conditions? According to Newtonian physics, *everything* is determined. What if we could study the behaviour of every atom, every electron, would we not then have to conclude that determinism is total? I shall call this *physical*

5 Levinthal F., Macagno E., Levinthal C. *Cold Spring Harbor Symposia on Quantitative Biology* (1976) 40:321-331.
6 Goodman C.S. *J. Comp. Neurol.* (1978) 182(4),681-705.
7 Levinthal *op. cit.*, (5).
8 White, J.G., Southgate, E., Thompson J.N. & Brenner S. *Phil Trans R Soc Lond Biol* (1976) 275: 327-348.
9 Finch, C.E. & Kirkwood, T.B.L. *Chance, Development and Aging,* New York and Oxford: Oxford University Press (2000).
10 I am not claiming that this incompleteness of biological (genes plus environment) determinism solves any philosophical problems related to free will. Some philosophers (e.g. Galen, Strawson) have argued that indeterminism is just as much a problem for free will as determinism. But that is not the subject of this essay.

determinism; it is sometimes called *Laplacian determinism* because Laplace was well known for his view that the entire universe works like clockwork. I consider that physical determinism is the most fundamental form of determinism, and it is at this level that I shall focus the rest of this essay, with emphasis on physical determinism of the brain.

Physical determinism has long been considered a problem. When Epicurus (341 – 271BC) famously proposed that 'the atoms swerve', it was partly because he considered this was needed for humans to be free.

In the seventeenth century, Descartes wrestled with the implications of the new Newtonian philosophy, and realised that its application to the human brain raised major philosophical problems. As a dualist, he was naturally concerned with how the soul could act upon the brain without contravening the deterministic laws of physics. For him, *animals* were hydraulic machines, in which the driving fluids were 'animal spirits' (from the Latin *anima*, a soul); despite their name, he envisaged these as being decidedly physical and material. He believed that the nerves constituted the hydraulic system, down which the flow of the animal spirits was controlled by filaments that operated tiny 'valvules' in the nerves and in the ventricles of the brain. He considered that external stimuli moved the skin that in turn pulled on the filaments opening valvules to release the flow. Ultimately this would affect the muscles, producing movement. Descartes' idea was not limited to simple movements. He tried to analyse emotions like fear and love as being due to the way animal spirits were induced to flow as a result of external events. Human reflex actions and emotions were explained on the same mechanical basis as in animals, but human voluntary behaviour required an interaction between the material automaton and the immaterial 'rational soul'. Descartes maintained that this occurred in the pineal gland, where the rational soul redirected small tissue movements so as to regulate the flow of animal spirits. In an attempt to make this compatible with Newtonian laws, he proposed that this redirection involved a change in the *direction of motion* of the animal spirits but not their speed. We now know that Descartes' attempt is invalid, because momentum is a vector and its conservation applies in every direction.

For this reason, many modern attempts to preserve freedom and humanity against the supposed straightjacket of physical predictability and determinism invoke either chaos theory to undermine predictability even when physical determinism applies,[11] or quantum indeterminism. This essay focuses on the latter[12] and deals with chaos only as applied to quantum effects.

11 Polkinghorne, J. *Science and Providence: God's Interaction with the World*, Boston: Shambhala (1989).
12 For Christians there are further problems, less often discussed, of how God acts in history and how the Holy Spirit communicates with the believer. Important though these questions are, they are not discussed here for lack of space.

Philosophical approaches to physical determinism and free will

This paper does not attempt to break any new ground philosophically, but it is necessary at least to summarise what the main philosophical positions are.

To many people it seems obvious that physical determinism is incompatible with free will. If our brains work mechanistically, then our behaviour must be predetermined, so how can we be free? How can we be responsible for our choices if they were decided before we made them? How can we be responsible for our behaviour if it was determined not by ourselves, but by the impersonal laws of physics and chemistry? This view is called *incompatibilism*; it is conventionally subdivided into two radically opposed positions: *libertarianism*, which affirms free will and denies determinism; and *hard determinism*, which denies free will and affirms determinism. But many philosophers disagree with incompatibilism, adopting the contrary view, which is called compatibilism. Thus we have three classical positions.

1. *Compatibilism* ('soft determinism'): Determinism is compatible with free will and human responsibility (e.g. Spinoza, Hobbes, Hume, Daniel Dennett).
2. *Libertarianism*: We do have free will, and this is incompatible with determinism (e.g. Reid, Kant, Robert Kane, Richard Swinburne).
3. *Hard determinism*: The past completely determines the future, including the future of our own brains. Free will is therefore an illusion (e.g. Holbach, Nietzsche; most modern philosophers reject this label).

This list is not of course exhaustive. For amateurs (like myself) who wish to go into the subject in more detail, libertarian philosopher Robert Kane's recent book[13] gives a very clear and even handed introduction to the different positions, which include the particularly pessimistic one of Galen Strawson, who maintains that both determinism and indeterminism are incompatible with free will. Some of the same ground is covered in ref. [14]

Problems of defining of free will

One's choice among the above positions is intimately linked to how one defines free will. Some people incorporate their philosophical assumptions into their very definition of free will. For example, the Free Dictionary gives a compatibilist definition: 'The power of making free choices unconstrained by *external* agencies' (italics added). In contrast, the Handbook of Psychological Terms gives a blatantly libertarian definition: 'The choices which are said to have no

13 Kane, R. *A Contemporary Introduction to Free Will*, Oxford: Oxford University Press (2005).
14 Murphy, N. & Brown, W.S., *Did My Neurons Make Me Do It?*, Oxford: Oxford University Press (2007), chap. 7.

necessary determination from the nervous system or from any other physical cause.'

Many thinkers have commented on the problem of definition. For example, Einstein once wrote:

> Honestly I cannot understand what people mean by free will. I have a feeling, for instance, that I will something or other; but what relation this has with freedom I cannot understand at all. I feel that I will to light my pipe and I do it; but how can I connect this up with the idea of freedom? What is behind the act of willing to light the pipe? Another act of willing? (A. Einstein, 1932).

Philosophers have long been aware of these problems, but the definition of free will is still a subject of debate among them. Some argue that the very term *free will* is unfortunate, and prefer to speak of *freedom of action*. All agree that human responsibility is at the heart of the issue.

Free will and ideas of the soul

One's preference for a compatibilist or a libertarian position is likely to be linked to one's beliefs about the brain-mind relationship and the soul. A Cartesian dualist, conceiving the soul as a separate nonphysical entity that interacts with the brain, will require some degree of indeterminism in the brain-machine to provide leeway for the soul to act on the brain. In contrast, a monist, perhaps a dual aspect monist like Malcolm Jeeves,[15] will probably think in terms of a deterministic brain, a machine without loose screws. There are exceptions, however; for example Forster and Marston[16] accept a monist position on biblical grounds but argue for indeterminism.

As has been argued several times in this journal (e.g. [17]), the dualist notion of an eternal nonphysical soul that is so widespread in our society is not considered by most theologians to be the biblical one. It comes from the ancient Greeks, notably from Plato, as is illustrated in the following quotation:

> Does not death mean that the body comes to exist by itself, separated from the soul, and that the soul exists by herself, separated from the body? Socrates, in Plato's *Phaedo*.

This Greek notion of the immortal soul was developed by the neoplatonists and became deeply rooted in Western Society and Christian thinking. But most modern scholars accept that the biblical notion of man is different. In the Old Testament, the word that is most often translated 'soul' is *nephesh*, whose pri-

15 Jeeves, M. *Science and Christian Belief* (2004) 16(2), 101-122.
16 Forster, R. & Marston, P. *Reason, Science and Faith*, Crowborough: Monarch (1999).
17 Booth, D. *Science and Christian Belief* (1998) 10(2), 145-162; Green, J.B. *Science and Christian Belief* (1999) 11, 51-63.

mary meaning is simply *life* or *vitality*, with the underlying connotation also of *movement*. Furthermore, the word translated 'spirit' (*ruah*) in the Old Testament carries the basic idea of air in motion. In many cases it simply means, and is translated, 'wind', but it can also refer to the 'breath of life' that the whole animal creation shares with man (Gen. 6:17). When translated spirit, it usually expresses the vitality of the mind as expressive of the whole personality (Pss. 32:2; 78:8), or it may refer to human inclinations and desires (e.g., Hos. 4:12). Thus, neither *nephesh* nor *ruah* necessarily implies dualism. Admittedly, both are described occasionally as leaving man at death, but never as existing separately from the body. Thus, although there is still some debate on the subject, most scholars consider that the Old Testament sees man as a unity.

In the New Testament, it is more difficult to find out what is meant from the analysis of words, because the original manuscripts were written in Greek, and the available words were all heavily charged with the dualistic overtones of Greek philosophy. There is therefore more debate on this question, but the majority view of theologians is that the New Testament writers also emphasise the unity of the human person, and do not teach the idea of a disembodied soul. Thus, *psyche*, which is the New Testament equivalent of *nephesh*, carries meanings ranging from life and desire (in St Paul's letters) to the whole personality. Most strikingly, the New Testament doctrine of the resurrection of the body is very far from the Platonic concept of an eternal, immaterial soul with the potential to exist in isolation from the body. This is particularly clear in I Corinthians, chapter 15. Here, St Paul first affirms the physical resurrection of Jesus, and that 'those who belong to Christ' will likewise be raised. He then goes on to analyse the various uses of the word 'body', showing that its meaning can vary, and he explains that after the dead are raised, their body will be a 'spiritual body', very different from the previous 'natural body' (or 'physical body'), but a body nonetheless. His notion of a 'spiritual body' is radically different from the Platonic notion of an eternal, disembodied soul. Indeed, he states that the physical comes first, then the spiritual. Elsewhere he writes: 'God… who alone is immortal' (1 Tim. 6:16). Nowhere does the Bible countenance the notion of a disembodied soul or an intrinsically eternal soul.

Admittedly, many great Christian thinkers have been dualists (and neoplatonists) including Origen and Augustine, Luther and Calvin, and Descartes; and dualism, often very different from that of Plato and Descartes, still finds support from modern philosophers and theologians including J. P. Moreland and J. W. Cooper. But in post-Reformation times various scholars have opposed dualism quite explicitly. For example, Joseph Priestley, the British conconformist minister who achieved scientific eminence by isolating 'dephlogisticated air' (oxygen), held essentially the biblical view described above. He maintained that the common dualism between matter and spirit was due to the contamination of biblical Christianity by Greek philosophy. In his *Disquisitions Relating to Matter and Spirit* (1777), he gave sophisticated arguments that the matter-spirit duality should be collapsed and that God worked through causal chains that were neither material nor immaterial in the traditional senses of these words. His arguments were partly scientific, partly philosophical, and partly theological. Among the latter was an objection against the idea of an immortal soul, because it rendered the doctrine of the Resurrection superfluous.[18] More recently, Anglican theologian Austin Farrer wrote in reaction to the dualistic ideas of neurophysiologist John Eccles (see below): 'We will have nothing to do with the fantastic suggestion, that what the supersensitive "reactors" in the cortex react to, is the initiative of a virtually disembodied soul.'[19]

Thus, Christians can be dualists or monists, just as they can be libertarians or compatibilists. But philosophers (Christian or not) who side with dualist/interactionist libertarianism are nowadays usually *quantum* libertarians.

Quantum libertarianism

The notion that quantum (Heisenbergian) indeterminism might provide a basis for free will was proposed already in the 1930s by the physicists P. Jordan (discussed in ref. [20]) and Eddington, and has continued to be proposed by philosophers[21] and scientists.[22] I shall call this approach *quantum libertarianism*.

Heisenberg's Uncertainty Principle

Most readers will be aware that one of the widely accepted consequences of wave mechanics is *Heisenberg's Uncertainty Principle*, according to which there is a fundamental limit to the precision with which certain pairs of physical quantities can be measured. One such pair is the momentum and position of a particle. If h is Planck's constant, and imprecision is expressed by Δ, then Δmomentum x Δposition $\geq h/4\pi$. There is no limit to the precision with which the momentum alone of the electron, or its position alone, might be measured; but any gain in the precision of measurement of one member of the pair will inevitably be offset by decreased precision for the other member. Another such pair is: $\Delta E.\Delta t \geq h/4\pi$, where E is energy and t is time, and we shall use this below. Since h is very small indeed, Heisenbergian uncertainty is irrelevant to macroscopic objects such as golf balls; but it is very relevant to microscopical entities such as electrons.

18 Brooke, J.H. *Science and Religion: Some Historical Perspectives*, Cambridge: Cambridge University Press (1991).
19 Farrer, A. *The Freedom of the Will*, London: A & C. Black (1958).
20 Walter, H. *Neurophilosophy of Free Will*, Cambridge Mass. and London: MIT Press (2001).
21 Kane, R. *The Significance of Free Will*, Oxford: Oxford University Press (1996); Searle, J.R. *Freedom and Neurobiology*, New York: Columbia University Press (2007).
22 Beck, F. & Eccles, J.C. *Proc. Natl. Acad. Sci.* (1992) 89, 11357-11361; Glimcher, P.W. 'Indeterminacy in brain and behavior', *Annu. Rev. Psychol.* (2005) 56, 25-56; Schwartz, J.M., Stapp, H.P., & Beauregard, M. 'Quantum physics in neuroscience and psychology: a neurophysical model of mind-brain interaction', *Phil. Trans. Roy. Soc. B* (2005) 360, 1309-1327.

Heisenberg's principle was initially proposed as a practical limitation to measurement, but many physicists and philosophers have argued that it goes far deeper than mere practicalities, establishing a fundamental indeterminism in nature. This interpretation has been vigorously disputed by many others including Einstein, who made in this context his famous remark that 'God does not play dice'. The fundamental equation of quantum physics, the Schrödinger equation, is in itself fully deterministic, and the indeterminism arises only in the transition between the quantum level description and the macroscopical one. Nevertheless, many philosophers have seized on Heisenbergian uncertainty as an argument against physical determinism. They treat it as a kind of cloud cover in which small perturbations can occur 'unnoticed' by the watchful eye of nature's laws. In the following paragraphs I shall provisionally accept this interpretation to explore its consequences for brain function, but would emphasise that the starting assumption is already controversial.

Quantum libertarians propose that mind-directed changes occur 'hidden' within the cloud cover of Heisenbergian uncertainty. According to standard quantum physics, such hidden effects are assumed to be random, but the unconventional proposal of quantum libertarianism is that they are *non-random*, directed by the mind (or soul etc.).

Quantum libertarianism at the synapse

Among those who attempted to extend this indeterminism to the brain and free will was Nobel prizewinning neurophysiologist Sir John Eccles, who throughout his long and productive career persistently advocated an essentially Cartesian form of dualism,[23] although he sought more plausible sites of mind-brain liaison than Descartes' proposal of the pineal gland.[24]

Eccles invoked Heisenbergian Uncertainty to provide a way for the mind and will to modify brain-function without violating physical laws. His idea was that it provided enough flexibility in the otherwise rigid chain of cause and effect for mental events to be able to influence brain events, and he saw this as necessary for us to be free agents.

To be relevant to conscious decision-making, the mind-brain liaison would need to influence the brain's electrical activity rather directly, and Eccles proposed that this occurs in synapses (junctions between neurons) of the cerebral cortex. He also postulated, rather arbitrarily, that the cortex is divided into open modules (responsive to mental events) and closed modules (unresponsive). There is no experimental evidence for Eccles' propositions, but given the known importance of the cerebral cortex for conscious thought and decision-

23 Eccles, J.C. *The Human Psyche*, Berlin: Springer (1980).
24 Eccles, J.C. *Proc. Natl. Acad. Sci.* (1992) 89, 7320-7324.

making, and the critical role played by synapses in neural function, they seem a reasonable starting point for speculation.

In the 1970s and 1980s, Eccles argued that the crucial Heisenbergian uncertainty would be in the position and velocity of *synaptic vesicles*, tiny membranous bags whose fusion with the cell membrane causes their content of neurotransmitter molecules to be released into the narrow synaptic cleft (space between two neurons). He thought this uncertainty could be sufficient to allow dualistic interactions affecting synaptic fusion with the membrane. This view was criticised by neurophysiologist David Wilson,[25] who argued (correctly in my opinion) that the vesicles were many orders of magnitude too large for this to work.

Eccles then teamed up with physicist Friedrich Beck to present a more sophisticated model of neurotransmitter release in which they argued that quantum indeterminism could be important.[26] I shall not discuss here the biological details of the Beck-Eccles model, some of which are no longer accepted (e.g. the notion that transmitter release involves the transition of a paracrystalline presynaptic grid to a metastable state). Moreover, it has since become clear that the movement of vesicles to the cell membrane and their fusion with it are rigorously controlled; before fusing with the membrane they are 'docked' close to it by a complex of proteins, and the final fusion is only possible when one of these proteins (usually synaptotagmin) changes its conformation as a result of interaction with calcium. As argued by Wilson,[27] it is more plausible (or at least less implausible) to postulate Heisenbergian effects on the control of synaptic calcium concentration rather than on the movement of synaptic vesicles. But the following argument, which is adapted from Wilson,[28] shows that Heisenbergian effects are too small even to affect synaptic calcium.

Quantitative application of Heisenbergian uncertainty to synaptic function

We consider the possibility that Heisenbergian uncertainty might allow a chemical bond to be modified in an ion channel in the synaptic membrane. This could be a calcium channel, influencing synaptic calcium concentration directly, or a sodium channel that influenced it indirectly through changes in electrical potential. According to Heisenberg's principle, there is a limit to the precisions of energy (E) and time (t) given by $\Delta E.\Delta t \geq h/4\pi$ where $h= 6.63 \times 10^{-34}$ J.s. In other words, an energy change ΔE can be 'hidden' for a time Δt providing ΔE is of the order of $h/4\pi\Delta t$. To have even a minimal effect on the synaptic function Δt would need to be at least 10 microseconds, probably much more.

25 Wilson, D.L. *Behav. Brain Sci.* (1993) 16,615-616.
26 Beck, F. & Eccles, J.C. *op. cit.*, (22); Beck, F. *Int. J. Neural Systems* (1996) 7,343-353.
27 Wilson, D.L. J. *Consciousness Studies* (1999) 6(8-9), 185-200.
28 Wilson *op. cit.*, (25).

Substituting this value gives a ΔE of the order of 5.2×10^{-30} Joules. This is about 200,000 times too small to disrupt even a single Van der Waals interaction, the weakest of all the chemical bonds ($E = 1 \times 10^{-24}$ J). Even if, unrealistically, we took Δt as the time of a single ion to cross the channel (about 10 nanosec.), ΔE is still 200 times too small.

Other possible sites for Heisenbergian effects

The above arguments focus on synaptic ion channels, but apply equally to any solution involving changes in molecular bonds. But what about other loci? Might the calculations come out more favorably for the possibility of Heisenbergian effects if applied to some other cellular structure? We don't know, but currently it seems hard to formulate suitable hypotheses.

One much discussed site for quantum effects (a more general concept that includes Heisenbergian effects) is the microtubules, very fine tubes, about 20 nm in diameter, that run down the insides of axons, and are known to be involved in transporting proteins and other molecules from the cell body to the axon tip or vice versa. The microtubule hypothesis was originally proposed, by Penrose and Hameroff, as part of a theory that the brain works as a quantum computer. They were not concerned with Heisenbergian uncertainty or free will, but some authors have suggested the hypothesis could be adapted to the latter purpose. The scientific and philosophical reasons for proposing microtubules as a site for quantum effects are too complex to be dealt with here.[29] Few neurobiologists take the microtubule hypothesis seriously, and some trenchant criticism is provided in ref. [30].

I share the general scepticism about quantum effects in microtubules (whether applied to quantum computation or adapted to Heisenbergian uncertainty and free will), but I admit that more work is required to analyse whether Heisenbergian effects in other cellular events might affect brain activity. Possibilities include: the binding of individual calcium ions to calcium-sensing molecules such as synaptoptagmin; local changes in postsynaptic membrane potential that might affect the triggering of an action potential; or events along the axon that might affect the speed of the action potential and its time of arrival at the synapse.

An inadequate counterargument about sensitivity to Heisenbergian effects

The hypothesis that neural functioning could be sensitive to quantum effects is sometimes argued on the grounds that the absorption of a very few photons

29 Lahoz-Beltra, R., Hameroff, S.R., & Dayhoff, J.E. *Biosystems* (1993) 29,1-23; Penrose, R. *Shadows of the Mind,* Oxford: Oxford University Press (1994).
30 Grush R. & Churchland P.S. *J. Consciousness Studies* (1995) 2(1), 10-29.

can affect retinal function.[31] It has indeed been well known, since the 1940s, that the extreme sensitivity of human vision in faint light implies that a single rod photoreceptor can respond to just one or two photons of light. True though this is, it confuses the energy of a photon with the uncertainty of its energy. The ΔE calculated above (5.2×10^{-30} J) is about 10^{-13} times smaller than the energy available in a single photon of (blue-green) light (4×10^{-17} J).

Thus, attempts to free the brain from the shackles of deterministic law by means of Heisenbergian uncertainty falter because of the smallness of the uncertainty. An answer to this problem has recently been sought in the fashionable field of *chaos theory*.

Amplification of Heisenbergian uncertainty by deterministic chaos

There is no universally accepted mathematical definition of chaos, but in rough terms a chaotic system is one that is extremely sensitive to initial conditions or perturbations. As a result of this property, chaotic systems (like the weather) are in practice unpredictable over a long period, even though they are deterministic. The field of chaos research has roots in the work of Poincaré at the end of the nineteenth century, but it took off in the 1960s and has since become a major field. It has been deeply analysed by mathematicians and computational modellers, and chaos has been reported, or predicted to occur, in many different situations in physics, chemistry and biology. Of immediate relevance to our present concerns, it has been claimed to occur in the electric activity of the brain.

Since the 1980s, numerous electrophysiological studies of action potentials in various brain regions have been interpreted as evidence for chaotic processes.[32] It has even been argued that chaotic dynamics can be detected in the electroencephalogram recorded from the scalps of awake humans, and that switches between chaos and non-chaos can be diagnostic of normal versus abnormal function. As a note of caution, I should add that it is technically very difficult (perhaps impossible) to prove rigorously from a series of action potentials or waves recorded from the brain that the underlying process is truly chaotic. All that can be said is that there is sufficient evidence to convince many scientists that chaos sometimes occurs in brain activity.

The relevance of chaos to quantum libertarianism is that it is sometimes claimed to provide a means of amplifying the tiny indeterminism available from quantum theory (for references see [33]). It is argued that if the mind were to exert even a slight influence (within the limits of Heisenbergian Uncer-

31 Penrose, R. *The Emperor's New Mind*, Oxford: Oxford University Press (1989), pp. 400-401; Forster and Marston *op. cit.*, (16).
32 Skarda, C.A. & Freeman, W.J. *Behav. Brain Sci.* (1987) 10,161-195.
33 Kane *op. cit.*, (21) p.129.

tainty) on brain activity, the small change could be enormously amplified if the brain dynamics were chaotic. Hence, the non-physical mind might act on the physical brain to change conscious experience and/or behaviour. The chaos responsible for the amplification could be in the electrical activity of brain neural networks (as discussed above) or conceivably at an intracellular level, where chaos is likewise claimed to occur.[34]

A major difficulty with this approach is that combining chaos theory with quantum theory is problematic. *Quantum chaos* has been studied for two decades, but its very existence is debated, because of the mathematically predicted 'quantum suppression of chaos'; if the equations of a chaotic system are combined with Schroedinger's equation, the chaos is suppressed. The causes of this seem to be only partly understood, but have been linked to the fractal nature of the behaviour of chaotic systems, to the fact that quantum systems cannot display classical trajectories on a finer scale than that of Planck's constant, and to the fact that Schrödinger's equation gives solutions that are periodic or quasi-periodic and hence incompatible with chaos.[35] Hobbs[36] faced up to the quantum suppression problem and gave provisional arguments that it might be solvable. More recently the pendulum has swung back in favour of quantum chaos, at least in some situations, because of evidence over the last few years that the quantum suppression of chaos can itself be suppressed by another quantum effect, the phenomenon of *decoherence* caused by interaction between the quantal system and its environment.[37] But I doubt that that quantum chaos, resurrected by decoherence, can provide for fundamental indeterminism in the sense required by quantum libertarianism, because this requires the environment to be considered as an external element outside the quantum-level description. A quantum-level description that included the entire interacting environment would not be subject to decoherence. And there are further problems, as discussed below.

Two further problems with the amplification hypothesis

Quite apart from the problems of quantum chaos, the proposal that soul-induced fluctuations might be amplified, whether by chaos or by other means, to provide the changes in brain activity needed for libertarian free will is problematic for three further reasons.

34 Houart, G. Dupont, G. & Goldbeter, A. *Bull. Math. Biol.* (1999) 61(3):507-530.
35 Hobbs, J. Chaos and indeterminism. *Canad J Philosophy* (1991) 21,141-164; Koperski, J. *Zygon* (2000) 35, 545-559.
36 Hobbs *op. cit.*, (33).
37 Berry, M.V. 'Chaos and the semiclassical limit of quantum mechanics (is the moon there when somebody looks?)', in Russell, R.J., Clayton, P., Wegter-McNelly, K. & Polkinghorne, J. (eds.) *Quantum Mechanics: Scientific Perspectives on Divine Action, Vol. 5*. Vatican City: Vatican Observatory Publications and Berkeley CTNS (2001).

First, as mentioned above, the Schrödinger equation is fully deterministic, and the indeterminism arises only in the transition between the quantum level description and the macroscopical one. The difficulties that this raises for amplification or ultrasensitive quantum detectors in the brain were discussed by Penrose.[38]

Secondly, could the chaos-induced changes be specific enough to provide free will? Even without amplification, the step from indeterminism to free will requires the unconventional interpretation that Heisenbergian indeterminism is not really indeterminism at all, but a kind of cloud cover permitting the soul or mind to *determine* brain activity unnoticed. Thus, we are asked to accept without evidence that what everybody believed was random is in fact directed and meaningful, and further that the directedness is maintained even after enormous amplification (by chaos or other means). In the current state of knowledge this seems decidedly far-fetched.

Thirdly, brain physiology has (and needs) built-in resistance to small fluctuations. Brain cells live in a warm (310°K), wet environment where they are continually buffeted from within and without by the random movements that all molecules make because of their thermal energy. This energy is given by:

$E_{th} = 0.5k_B.T.n$, where
n = degrees of freedom = 3
k_B = Boltzmann constant = 1.38×10^{-23} J/°K
T = 310°K

whence $E_{th} = 6.4 \times 10^{-21}$ J (much larger than our previously calculated $\Delta E \sim 5.2 \times 10^{-30}$ J)

Thus, the thermal (and hence kinetic) energy of the molecules is 9 orders of magnitude greater than the energy change that can be hidden by Heisenbergian uncertainty. But brain cells (and other cells) have to be resistant to the buffeting due to thermal energy. And if chaos is to amplify tiny mindinduced fluctuations, it will presumably amplify also the far greater fluctuations due to thermal energy, as Beck and Eccles[39] recognised. Indeed, despite differences in approach, Beck's quantitative conclusions are similar to mine: that Heisenbergian uncertainty can only be relevant to brain events occurring in the picosecond range or still faster (e.g. electron transfer). The radical difference between us is that Beck thinks that Heisenbergian uncertainty in such rapid events may affect brain functioning, whereas I think this most unlikely. Beck[40] cites evidence for this in the response of photobacteria to light, but there appears to be no evidence in relation to brain function.

38 Penrose *op. cit.*, (28), pp. 348-352.
39 Beck & Eccles *op. cit.*, (22).
40 Beck, F. *Adv. Consciousness Res.* (2001) 29, 83-116.

A similar resistance to perturbations may exist at the network level as well, because single-pulse microstimulation of a cortical neuron has always been found to affect only neurons receiving direct connections from it without disrupting the overall cortical activity. Libertarian philosopher Robert Kane proposes exactly the opposite, however, for critical moments of decision. Citing theorists such as Henry Stapp and Gordon Globus he writes: '… conflicts of will [may] stir up chaos in the brain and make the agent's thought processes more sensitive to undetermined influences…'.[41] While several studies have been published on the electrophysiology of decision making, there is no direct evidence about brain activity during conflicts of will. An involvement of chaos cannot currently be excluded, but it seems to me that extreme sensitivity to minor fluctuations at the moment of choice would make the decision making excessively vulnerable to arbitrary factors ranging from irrelevant neural inputs to changes in blood pressure.[42]

Uncertainty about uncertainty

Finally, I would reiterate the warning given above, that the very starting point of this discussion on quantum libertarianism – the use of Heisenbergian uncertainty to obtain ontological indeterminism – is open to debate. A detailed consideration of this much-discussed topic is beyond the scope of this essay, but I would briefly mention that there are at least two kinds of problem.

On the one hand, a minority of physicists argue for an interpretation of quantum theory in terms of a fully deterministic theory.[43] On the other hand, even for those who accept fundamental indeterminism in the transition from the quantum-level description to the macroscopical one, the deterministic nature of the Schrödinger equation may still raise problems for ontological interpretation.

Conclusion

Brain determinism by genes plus environment is incomplete, but at the lower level of physical law determinism does seem to be complete apart from the tiny degree of indeterminism that results from Heisenbergian uncertainty. Quantum libertarianism attempts to ground our freedom of action on this scanty foundation, arguing that this quantum-level indeterminism may manifest

41 Kane *op. cit.*, (21).
42 Decision making by the selection of one of a set of different chaotic attractors would be a separate issue.
43 One class of such theories involves hidden variables at the sub-quantum level, as advocated in the writings of the late David Bohm (*Wholeness and the Implicate Order*, London: Routledge & Kegan Paul, (1980)); The question of whether the many worlds interpretation of quantum mechanics is deterministic is beyond the scope of this essay.

itself in cerebral functioning. This paper draws attention to quantitative and conceptual problems with this approach.[44]

Acknowledgements

I am indebted to many colleagues, especially Simon Bernèche, for advice on physics and biophysics, and to Stuart Judge, Bastian Peter, Marc-André Dupertuis and Peter Bussey for their helpful comments on the manuscript.

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44 This article is adapted from a lecture given by the author at a joint CiS/ASA conference 'New Frontiers in Science and Faith' (Edinburgh, August 2007).