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Quantum Stochasticity and (the End of) Neurodeterminism

1 Introduction

Free will is a “scandal in philosophy” (Doyle 2011). However, free will is no scandal for contemporary mainstream neuroscience. Most neurobiologists believe that there is no such problem or that neuroscience has already solved the problem of free will or is on the way to solving it by fully elucidating the neuronal mechanisms of human decisions. A completely mechanistic explanation of “free” decisions would make them causally dependent on neuronal activity and thus not free. Hence most neuroscientists consider free will an illusion (e.g. Wegner 2003) or they adopt a compatibilist view, believing that free will can exist even in the fully mechanistic machine called the human brain. Many neurobiologists would agree with Francis Crick who famously said that

> “You”, your joys and your sorrows, your memories and your ambitions, your sense of personal identity and free will, are in fact no more than the behavior of a vast assembly of nerve cells and their associated molecules (Crick 1994, 3).

Although new ideas and concepts are emerging (e.g. Van Regenmortel 2004, Noble 2006), reductionism and determinism are still the major paradigms in current biology, including neurobiology. “[Physicists] invented the deterministic-reductionistic philosophy and taught it to the biologists, only to walk from it themselves” (Loewenstein 2013). The dominant belief is that “anything can be reduced to simple, obvious mechanical interactions. The cell is a machine. The animal is a machine. Man is a machine” (Monod 1974, IX).[1] In this article, I am going to argue that the mainstream Newtonian view of the human brain as a sophisticated machine is challenged by new findings in neuroscience and in the rising field of quantum biology.

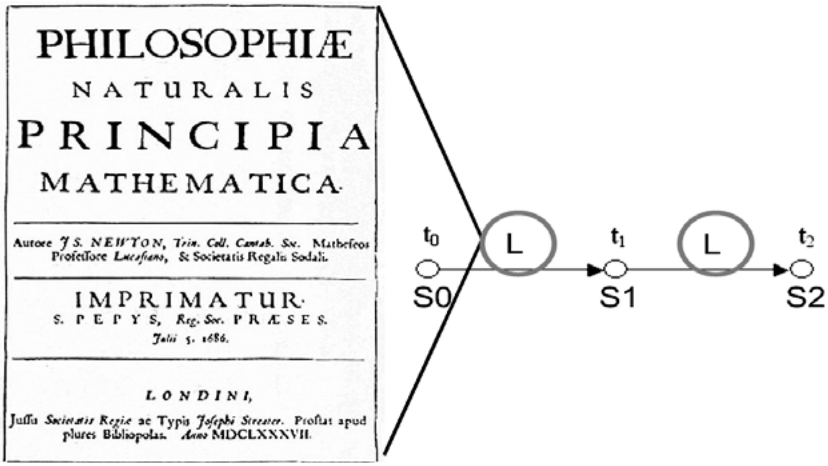
1 Unfortunately, scientists are often not aware that their fully deterministic and reductionistic view of the world is a philosophical (metaphysical) view, and not a scientific view based on purely empirical or logical evidence (cf. Jedlicka 2005).

2 Definition of neurodeterminism

In the early 19th century, inspired by Newtonian physics, Pierre-Simon Laplace expressed the deterministic world view in his famous description of what is now known as *Laplace's Demon*: an intelligent being that knows completely the state of the world (all forces acting in the universe and the position of all particles) at one moment and can calculate its whole future development:

> We ought to regard the present state of the universe as the effect of its antecedent state and as the cause of the state that is to follow. An intelligence knowing all the forces acting in nature at a given instant, as well as the momentary positions of all things in the universe, would be able to comprehend in one single formula the motions of the largest bodies as well as the lightest atoms in the world, provided that its intellect were sufficiently powerful to subject all data to analysis; to it nothing would be uncertain, the future as well as the past would be present to its eyes (Laplace 1814, 19).

Following Laplace, we can define a *deterministic system* as a system whose behavior is constrained in such a ways that its inputs and initial state fully determine its next state or output. In other words, "[t]he world is governed by (or is under the sway of) determinism if and only if, given a specified way things are at a time *t*, the way things go thereafter is fixed as a matter of natural law" (Hoefer 2010). On the contrary, a stochastic or indeterministic system can be defined as a system whose inputs and initial state do not fully determine its next state or output. Expressed in a more formal way, if *S* is a complete description of the state of our world at a given time *t* and *L* is a complete description of all laws of nature (e.g., the laws of Newtonian mechanics), then *S* and *L* together logically imply a complete description of the entire history of our world following *t*:



In such a deterministic world, all events are the necessary consequences of the previous states and the laws of the universe. For instance, in the deterministic scenario, the formation of the planet Earth and the extinction of dinosaurs would be simply an inevitable consequence of the state of the universe at the time of the Big Bang and of the deterministic laws of physics.

Neurodeterminism can be seen as a special case of cosmic determinism, because *SB*, the state of the brain and its environment (inputs) at a given time *t*, is a part of the state of the world *S* and thus is along with *S* fully governed by the antecedent states of the world and its laws *L*. This definition is similar to the description of neural causation by the neuroscientist Wolf Singer:

> If neuronal processes are the basis and cause of all mental phenomena and if brain processes follow the laws of nature, then the principle of causality must hold for neuronal interactions. Even though there is noise and interference, each state of the brain is then a necessary consequence of the immediately preceding state. Since decisions are the consequence of special brain states, our concepts concerning the independence of will are likely to require some revision (Singer 2009).

3 The incompatibility of neurodeterminism and responsibility

Are free will and moral responsibility compatible with (neuro)determinism? Many influential thinkers are compatibilists (Mckenna 2009), for example Daniel Dennett (2003) or Harry Frankfurt (1969). However, a strong argument has been raised against the compatibility of free will, moral responsibility and determinism. It is called the consequence argument:

> If determinism is true, then our acts are the consequence of laws of nature and events in the remote past. But it's not up to us what went on before we were born, and neither is it up to us what the laws of nature are. Therefore, the consequences of these things (including our present acts) are not up to us (Van Inwangen 1983, 56).

If all our acts are unavoidable consequences of the laws of nature and of events before our birth then we are not free to choose between alternative courses of action. We cannot do otherwise. Therefore, we have no moral responsibility for our actions. This is an indirect consequence argument (Jäger 2006) for the incompatibility of moral responsibility and determinism because it relies on (1) the incompatibility of free will and determinism ("free will incompatibilism") and (2) the principle of alternative possibilities (PAP). PAP states that we are morally responsible for what we have done only if we could have done otherwise (Frankfurt 1969). Using PAP it is possible to make the logical step from "free will incompatibilism" to "moral responsibility incompatibilism". However, PAP has been attacked by Harry Frankfurt and other compatibilist (Frankfurt 1969, see also McKenna 2009). Nevertheless, it is possible to construct direct consequence arguments for the incompatibility of moral responsibility and determinism which do not depend on the validity of PAP. Christoph Jäger has recently formulated three versions of such a direct consequence argument (Jäger 2006). The strongest version can be formulated in nontechnical terms as follows:

SO is the description of the state of the universe as it was at a time point before human beings appeared in the history of evolution. *L* is the description of the laws of the universe, and *A* is the description of some arbitrarily chosen human action that happened (or is going to happen). The argument consists of one inference rule ("Boethius' principle") and three steps. Boethius' principle is the following: From "p and no one is responsible for the fact that p, and it is necessary that p implies q" it can be inferred: "q and no one is responsible for the fact that q". The rule is valid for all p and q in a deterministic universe in which all human cognitive acts (desires, beliefs) and behavioral actions are fully determined. The reformed consequence argument draws a devastanting conclusion from two premises and Boethius' principle:
1. *SO* and *L*, and no one is responsible for the fact that *SO* and *L* (premise 1)
2. It is necessary that *SO* and *L* imply *A* (premise 2, which follows from determinism)
3. *A* and no one is responsible for the fact that *A* (conclusion, based on 1, 2 and Boethius' principle)

The consequence argument is powerful because premise 2 is based on determinism and premise 1 is difficult to refute.[2] So the only plausible way of criticism is to attack the inference rule.

The present version of the consequence argument has three important advantages over previous versions of the consequence arguments: (1) it does not require PAP, (2) Boethius' principle is immune against the usual criticism of the inference rules used in consequence arguments[3] and (3) Boethius' rule makes the argument also immune against counterexamples based on overdetermination (Jäger 2006).

2 But see an interesting rejection of premise 1 based on multiple-pasts compatibilism in Aaronson 2013, 24.

3 For a discussion of the validity of the inference rule β, see e.g. Vihvelin 2011.

In sum, the consequence argument shows that compatibilists do not have many plausible options defending the compatibility of determinism and moral responsibility.[4] And since neurodeterminism is just a special case of cosmic determinism, the consequence argument denies also the compatibility of neurodeterminism and moral responsibility. If our universe were a machine governed by deterministic laws and initial conditions, then our brain would be also a machine (a computer), and, consequently our experience of conscious will and moral responsibility would be only an illusion.

4 The exorcism of Laplace's Demon by quantum theory

If determinism is incompatible with moral responsibility, then the most important empirical question is the following: Is our world deterministic? There was not much hope for free will or moral responsibility in the times of Newtonian physics. But then came the quantum revolution. Theories and experiments in quantum physics strongly support the indeterministic nature of our universe. Quantum theory is indeterministic. The development of the quantum state of a physical system is governed by the deterministic wave function. However, according to most interpretations of quantum mechanics, the result of a quantum measurement (which corresponds to a collapse of the wave function) is undetermined. Thus, quantum measurements generate objectively indeterminate events: their cause is nothing or something outside the physical world (Satinover 2001, 101). Even with full knowledge of the state of a quantum mechanical system, it is not possible to predict (calculate) the result of a measurement, only its probability. There is no underlying mechanistic cause (within the physical world) for the specific actual outcome of a measurement when there are several possible outcomes.

There are two alternative options for a deterministic interpretation of quantum theory.[5] But both have their weak points. (1) The many-worlds interpretation has

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4 Is indeterminism compatible with moral responsibility and free will? Indeterminism alone is not sufficient for responsibility and free will, but the consequence argument shows that indeterminism is a necessary condition (*a conditio sine qua non*) for responsibility and free will. A fully indeterministic world with no deterministic laws would not be compatible with responsibility, since in a purely random and chaotic universe we would not have any control over our acts. Thus, a universe with a mixture of partial determinism and partial indeterminism is required for moral responsibility.

5 Interpretations of quantum mechanics can be classified into three groups depending on which serious troubles with probability. According to the many-world interpretation, all outcomes are actualized. But “[o]nce you give up the distinction between actuality and possibility saying that all possible realities are equally actual, the notion of probability becomes meaningless” (Putnam 2005). (2) The most popular hidden variable theory is Bohmian mechanics which “buys its ‘determinism’ via the mathematical device of pushing all the randomness back to the beginning of time” (Aaronson 2013, 23). In sum, we can say with Scott Aaronson that

> [P]hysical indeterminism is now a settled fact to roughly the same extent as evolution, heliocentrism, or any other discovery in science. So if that fact is considered relevant to the free-will debate, then all sides might as well just accept it and move on! (2013, 23)

The quantum revolution in the direction of indeterminism was shocking to many physicists. Einstein famously said that God does not play dice. However, it seems that God plays dice after all. Quantum theory has performed a successful exorcism on Laplace’s Demon. And there are good reasons to expect that future physical theories will also contain quantum indeterminism (e.g. Banks 1997). Quantum indeterminacy is relevant to the problem of free will because it has swept away Newtonian physical determinism (Barr 2003). Of course, quantum theory has not proven that free will exists. However, it has shown that the classical determinism of Laplace can no longer be plausibly used as an argument from physics against free will. Thus, quantum theory opened new ways to reconcile human freedom with the laws of physics (Weyl 1932).

5 Two arguments against the quantum brain hypothesis

Quantum physics has shaken classical determinism. However, whether and how it can shake neurodeterminism is far from clear and straightforward. It is true that the only objectively indeterministic processes in the physical world are quantum processes. But does quantum indeterminacy affect the dynamics of neuronal networks? Does quantum physics allow the brain to exploit indeterminate quantum

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the following three assumptions is denied (Brüntrup 2008, 60): 1. Development of a physical system in time is fully governed by the wave function (→ collapse–of–the–wave–function theories). 2. There are no hidden variables (→ hidden variable theories). 3. Measurements always provide a single definite outcome (→ many-worlds interpretation).

events? These are key empirical questions. There are two main arguments which are usually raised against the quantum brain hypothesis:

1. Neuronal signaling molecules, neurons and neural networks are *too large* for quantum phenomena to play a significant role in their functioning. The conventional wisdom is that all *quantum events* are *averaging out*, so that fluctuations among quantum particles are not important. As expressed by Daniel Dennett:

> Most biologists think that quantum effects all just cancel out in the brain, that there's no reason to think they're harnessed in any way. Of course they're there; quantum effects are there in your car, your watch, and your computer. But most things—most macroscopic objects—are, as it were, oblivious to quantum effects. They don't amplify them; they don't hinge on them (quoted in Penrose 1996, 251).

Christoph Koch and Klaus Hepp (2006), too, identify the large size of neuronal objects and the huge number of particles involved in neuronal signaling as one of the critical weak points of quantum brain hypothesis:

> Although brains obey quantum mechanics, they do not seem to exploit any of its special features. Molecular machines, such as the light-amplifying components of photoreceptors, pre- and post-synaptic receptors and the voltage- and ligand-gated channel proteins that span cellular membranes and underpin neuronal excitability, are so large that they can be treated as classical objects. [...] Two key biophysical operations underlie information processing in the brain: chemical transmission across the synaptic cleft, and the generation of action potentials. These both involve thousands of ions and neurotransmitter molecules, coupled by diffusion or by the membrane potential that extends across tens of micrometres. Both processes will destroy any coherent quantum states. Thus, spiking neurons can only receive and send classical, rather than quantum, information. It follows that a neuron either spikes at a particular point in time or it does not, but is not in a superposition of spike and nonspike states.

2. The second important criticism is that the interaction of neuronal molecules, neurons or neuronal networks with their noisy, wet and warm environment will destroy any nontrivial quantum states such as superpositions or entanglements. If this were true, only trivial quantum effects could be present in the nervous system. But what is the difference between trivial and nontrivial quantum effects? Trivial quantum effects provide the basis for the structure and chemical properties of molecules and they are ubiquitous (also in cars and watches). Hence, trivial quantum effects are crucial for the basic biochemistry of neuronal molecules, but when considering the neuronal function, these trivial quantum features can, allegedly, be ignored and the molecules important for neuronal signaling can be treated as essentially classical. All interesting coherent quantum states which are necessary for any nontrivial quantum computation (Davies 2004) can, allegedly,

exist only in well isolated quantum states and are rapidly destroyed by the environment. Since the brain is "a 300-degrees Kelvin tissue strongly coupled to its environment" (Koch, and Hepp 2006), decoherence will prevail and no neuronal quantum computation will be possible. Because of the extremely high speed of environment-induced decoherence, the brain "should be thought of as a classical rather than quantum system" (Tegmark 2000).

6 Towards quantum neurobiology

The two arguments against the hypothesis that quantum dynamics play a nontrivial role in the nervous system seem convincing and are accepted by most scientists. However, a growing body of empirical evidence indicates that the second argument is false and that the first argument is also very likely false. Exciting recent research shows that *nontrivial quantum effects* are present *in biological systems*—and not just in spite of, but sometimes because of, the interaction with the noisy and warm environment. Furthermore, because the brain is a *complex nonlinear system* with high sensitivity to small fluctuations, it is likely that it can *amplify* microscopic *quantum effects*. Specifically, there are two alternative but interrelated ways in which quantum events may influence the activity of the brain (Satinover 2001, 210; see also Jedlicka 2009): (1) Nontrivial quantum effects can speed up the computational processes in living organisms at the microscopic level. (2) Nonlinear chaotic dynamics can amplify lowest-level quantum fluctuations upward, modulating even larger-scale macroscopic neuronal activity.

What is the experimental evidence for these two claims?

(1) Contrary to expectations, nontrivial quantum processes have been observed in living systems. Recent experiments provide evidence for unexpectedly long-lasting quantum coherence in the electron transfer which is involved in photosynthesis.[6] This quantum-mechanical process is thought to improve the efficiency of energy transfer in photopigment molecules (Panitchayangkoon, et al. 2010). The pigment molecules seem to implement an efficient quantum algorithm to find the fastest route for the light-induced excitation of electrons (Sension 2007; but see also Tiersch et al. 2012). Quantum coherence has been found in photosynthetic bacteria as well as in marine algae. This suggests that evolution has been able to select and exploit quantum-mechanical features for fast and efficient computation in two evolutionary distinct organisms. Another

6 Engel et al. 2007; Lee et al. 2007; Collini et al. 2010; Panitchayangkoon et al. 2010; Sarovar et al. 2010.

example of quantum dynamics in living systems has been found in photoreceptors, which are important for vision. Photoreceptor cells of the retina contain a protein called rhodopsin. Experiments using high-resolution spectroscopic and nuclear-magnetic resonance techniques revealed coherent quantum waves in the rhodopsin molecule (Wang et al. 1994; Loewenstein 2013). As summarized by Werner Loewenstein (2013):

> Quantum mechanics, not classical mechanics, rules the roost at this sensory outpost of the brain.

Quantum effects have been described also in the olfactory system. Electron tunneling has been suggested to play an important role in the detection of odorants by olfactory receptors (Huelga, and Plenio 2013). Avian magnetoreception is yet another example of potentially beneficial quantum effects in biology. Long-lived quantum entanglements in the cryptochromes of the retina seem to support the sensitivity of a bird's eye to magnetic fields (Huelga, and Plenio, 2013; Arndt et al. 2009; Ball 2011). In addition, quantum tunneling has been observed in other biomolecules, such as enzymes or motor proteins (Hunter 2006). Most importantly, contrary to the long-held view, under some conditions, the strong coupling to the noisy and warm environment is able to promote rather than hinder long-lasting quantum coherence in biological systems (Plenio, and Huelga 2008; Huelga, and Plenio 2013). Because of the accumulating evidence that quantum phenomena need to be considered explicitly and in detail when studying living organisms, quantum biology has recently emerged as a new field at the border between quantum physics and the life sciences (Ball 2011).

> Physicists thought the bustle of living cells would blot out quantum phenomena. Now they find that cells can nurture these phenomena—and exploit them (Vedral 2011).

So far, we have focused on nontrivial quantum processes in sensory cells. But are nontrivial quantum effects also present elsewhere in the nervous system? It is very likely, but direct experimental evidence is still missing. Where should we look for further instances of neuronal quantum effects? There are many stochastic neuronal mechanisms which may be driven by quantum events. Although it is true that "the main sources of neural noise are forces that can be characterized as thermal and chaotic rather than quantum in nature" (Sompolinsky 2005, 31), quantum physics is expected to shape at least some stochastic events in the brain, such as the opening of ion channels (Vaziri, and Plenio 2010). In this way microscopic quantum events might affect electrical signals in neurons, as proposed by Paul Glimcher (2005):

> [T]hese data suggest that membrane voltage is the product of interactions at the atomic level, many of which are governed by quantum physics and thus are truly indeterminate events. Because of the tiny scale at which these processes operate, interactions between action potentials and transmitter release as well as interactions between transmitter molecules and postsynaptic receptors may be, and indeed seem likely to be, fundamentally indeterminate.

It is in itself important that quantum coherence in living organisms has been experimentally demonstrated at the microscopic level. But what are the spatial and temporal limits of these quantum effects? Can we discover quantum coherence in more than just a few molecules? How long can it persist? Some quantum brain proposals, focusing on explaining consciousness (Hameroff, and Penrose 2014), would require coherent quantum waves on much larger and longer scales than those found so far. The honest reaction to the questions just posed is that we do not know the answers to them and that only future research can provide those answers.

(2) If it turned out that quantum effects cannot be observed in living systems at the macroscopic level, would that mean that living systems can be fully described by classical physics? Or is there another plausible way in which small-scale quantum effects—there is evidence for their occurrence (see (1))—might influence large-scale neuronal activity and behavior? Yes, there is. The common view that minuscule fluctuations, including quantum events, cancel out in larger systems need not be true in highly nonlinear systems like our brain. The nervous system can be seen as a nested hierarchy of nonlinear complex networks of molecules, cells, microcircuits and brain regions. In iterative hierarchies with nonlinear dynamics (at the edge of chaos), small (even infinitesimal) fluctuations are not averaged out, but can be amplified. Quantum fluctuations on the lowest level of scale may influence the initial state of the next level of scale, while the higher levels shape the boundary conditions of the lower ones. This hierarchy of nested networks with many feedback loops exploits rather than cancels out the quantum effects:

> [Q]uantum dynamics alters the final outcomes of computation at all levels—not by producing classically impossible solutions but by having a profound effect on which of many possible solutions are actually selected (Satinover 2001, 210).

In his essay on free will and neuroscience, Haim Sompolinsky has also mentioned this possibility:

> Chaos within the brain may amplify enormously the small quantum fluctuations […] to a degree that will affect the timing of spikes in neurons (2005, 32).

Similarly, even Christof Koch, one of the major critics of quantum brain ideas, had to admit:

> What cannot be ruled out is that tiny quantum fluctuations deep in the brain are amplified by deterministic chaos and will ultimately lead to behavioral choices (2009, 40).

The quantum amplification mechanism has been adopted also by Scott Aaronson, whose recent "freebit" theory of free will "postulates that chaotic dynamics in the brain can have the effect of amplifying freebits to macroscopic scale" (2013, 38).[7] A similar theory has already been proposed by Pascual Jordan (1938).

What is the evidence for the proposal that the brain is a complex nonlinear system, capable of chaotic dynamics? Beggs and Plenz (2003, 2004) provided experimental evidence that neuronal networks can produce complex patterns of collective activity, which are called *neuronal avalanches*. These avalanches have a characteristic distribution: Each avalanche engages a variable number of neurons, but, on average, many more small avalanches are observed than large ones. This indicates that neuronal networks are poised *near criticality* (near phase transition, see Beggs and Timme 2012) and are prone to displaying emergent *complex* activity (Chialvo 2010). Similar results supporting *criticality* in the brain have been obtained on a larger scale from fMRI data (e.g. Deco, and Jirsa 2012). In general, we can observe three types of dynamics in the brain: 1. *ordered/subcritical* dynamics consisting of oscillatory synchronous activity with the characteristic features of high coordination and low variability, 2. *random/supracritical* dynamics consisting of asynchronous irregular activity with low coordination and high variability, and 3. *complex/critical* dynamics with high coordination and high variability. Brain states exhibiting *complex/critical* dynamics are the most interesting ones because they support the most efficient information processing (Beggs and Timme 2012). At the critical point between order and disorder (i.e. at the edge of chaos and instability), neurons can communicate best, since at that point they are coordinated but not stuck in a certain state for a long time and can establish long-range dynamical correlations. Furthermore, neuronal networks in near critical states display, because of the largest fluctuations, the largest repertoire of network activity. Finally, at the critical point, the highest sensitivity to small fluctuations (e.g. London et al. 2006) is observed: even a single neuron perturbation has a small but non-zero chance to trigger an avalanche. As pointed out by Dante Chialvo (2010), there are convincing Darwinian reasons for supposing that (parts of) our brains operate near the critical point: In a *subcritical* world, everything would always be uniform, there would be nothing new to learn and hence no critical and plastic brain would be needed; memories might as well be unchanging. In a *supracritical* world, everything would always be changing with

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7 But see also criticism of this quantum amplification idea in Clarke 2014.

no regularities to be learnt. No long-term plasticity and memory would be of any help. In our *critical* (complex) world, surprising events do occur, but regularities, too, are present so that the brain needs to register but also to update the stored memories.

> [B]rains seem "balanced on a knife-edge" between order and chaos: were they as orderly as a pendulum, they couldn't support interesting behavior; were they as chaotic as the weather, they couldn't support rationality (Aaronson 2013, 48).

Thus, it is highly plausible that small quantum fluctuations can be amplified, since brain activity can develop to the critical point: the point of complex neuronal dynamics. Interestingly, recent calculations suggest that quantum coherence can become long-lived in complex systems which are in a critical state between chaos and regularity—at the edge of quantum chaos (Vattay et al. 2014). Thus, the intricate interplay between quantum effects and nonlinear complex dynamics is able *a)* to generate new persistent quantum-chaotic patterns at a microscopic scale, *b)* to amplify quantum effects to a macroscopic scale (Satinover 2001, 209). How exactly the indeterminacy of complex quantum dynamics of the brain is embedded in classical neuronal mechanisms of decision making (Rolls 2012) remains to be determined. But we can conclude with Hermann Weyl:

> We must await the further development of science, perhaps for centuries, perhaps for thousands of years, before we can design a true and detailed picture of the interwoven texture of Matter, Life, and Soul. But the old classical determinism of Hobbes and Laplace need not oppress us any longer (1932, 65).

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