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HARALD ATMANSPACHER AND STEFAN ROTTER

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1. Introduction

A number of philosophers nourish the hope that studies of brain behaviour will resolve the question whether the brain is a completely deterministic machine, or a generator of stochastic states with indeterminate connections.[1] Although brain science is mainly concerned with how particular phenomena are described best, philosophical issues often refer to the real, ontic nature of these phenomena.

In this paper we analyse the different ways to describe brain behaviour with the goal to provide a basis for an informed discussion of the nature of decisions and actions that humans perform in their lives. As will become clear, this is a difficult task, and we are far from solving it with currently available knowledge. But it is worthwhile to locate some major stumbling blocks and address approaches intended to remove or circumvent them.

Much of the material that we are going to present has been extracted from a previous publication (Atmanspacher and Rotter 2008) which we recommend for readers who desire to see more details. Here we try to reduce formal and technical details to what we think is necessary for proper understanding. Moreover, we restrict ourselves to brain states and their dynamics exclusively and exclude any relation to the mental. An earlier review with similar focus has been published by Glimcher (2005).

[1] We use the terms 'stochasticity' and 'stochastic behaviour' as synonymous with 'randomness' and 'random behaviour'. The notion of randomness seems to be favoured in the Russian tradition, whereas stochasticity is more frequently used in the Anglo-American terminology.

The article is organized in a straightforward fashion. In Section 2 we outline a number of concepts exhibiting how many subtle details and distinctions lie behind the broad notions of determinacy and stochasticity. These details are necessary for a sound and fertile discussion, in Section 3, of particular aspects relevant for the characterization of brain states and their dynamics.

Our basic notion is that the descriptions of brain behaviour currently provided by neuroscience depend on the level and context of the descriptions. There is no clear-cut evidence for ultimately determinate or ultimately stochastic brain behaviour. As a consequence, we see no solid neurobiological basis to argue either in favour of or against any fundamental determination or openness of human decisions and actions.

2. Between determinacy and stochasticity

In this section some elementary concepts are introduced that are crucial for an informed discussion of determinacy and stochasticity, but are often used with vague associations, or badly defined specifications, or both. The terms *determinateness* and *determinism* are used to distinguish between the determinacy of *states* of a system (or classes of such states) and its *dynamics* (or classes of its dynamics), respectively.[2] By way of characterizing these terms, closely related notions such as error and variation, causation and prediction are addressed which serve important purposes particularly in the description of complex systems. Then the concepts of stochasticity, randomness, chance, and the role that probability plays in their context are outlined, and techniques of how to represent stochastic processes deterministically and vice versa are described.

An important further issue is the difference between *individual* and *statistical* descriptions of a system. It is tightly related to one of the most fundamental questions concerning the status of scientific theories: the distinction between epistemological and ontological statements (Scheibe 1974; Atmanspacher and Primas 2003). Epistemology comprises all kinds of issues related to the knowledge (or ignorance) of information gathering and using systems. By contrast, ontology refers to the nature and behaviour

[2] The terminology is adopted from Jammer's discussion of Heisenberg's usage of these terms (Jammer 1974).

of systems as they are (or may be assumed), independent of any empirical access.

2.1 State determinateness

States of a system to which *epistemic descriptions* refer are called *epistemic states*. The mathematical representation of such states encodes empirically obtainable knowledge about them. If the knowledge about states and their associated properties (also called observables) is expressed by probabilities in the sense of relative frequencies for a statistical ensemble of independently repeated experiments, we speak of a *statistical description* and of *statistical states*. Insofar as epistemic descriptions refer to a state concept encoding knowledge, they depend on contexts of observation and measurement. Therefore, descriptions of properties or observables associated with an epistemic state are *contextual*, i.e. context-relative.

States of a system to which *ontic descriptions* refer are called *ontic states*. They are designed as (idealized) exhaustive representations of the mode of being of a system, i.e. an ontic state is 'just the way it is', without any reference to what any observer does or does not know about it. The properties (or observables) of the system are understood as *intrinsic*. As *individual states*, ontic states are the referents of *individual descriptions*. The ontic state of a system is represented by a point x in its state space Ω. The associated intrinsic observables define the coordinates of the state space. The state of a system is *determinate* if it is point-wise represented and, as a consequence, the observables are sharply defined.

An epistemic (statistical) state is characterized by a probability measure μ over Ω. Such a representation of epistemic states (and their associated observables) generally requires a partition of Ω into subsets A. It refers to our knowledge as to whether an ontic (individual) state x is more likely to be in some subset A rather than in others. This limit on the informational content of an epistemic state μ can be due to two basically distinct reasons. First, it can be due to 'objective' influences such as uncontrollable perturbations originating from the system's environment or intricate interdependencies among its internal constituents. Second, it can be due to 'technical' reasons such as the imprecision of measurements or the fact that any decimal expansion of real numbers has to be truncated somewhere for computational purposes.

In the second case, the epistemic state encodes the reduced amount of knowledge about an individual ontic state that results from explicitly epistemic procedures. We use the notion of *error* to address this situation. Error characterizes the scatter of measured or rounded values of an observable with respect to an assumed 'true' value in an ontic state. Variation, on the other hand, refers to a distribution of ontic states, each of which is characterized by a 'true' value of one of its associated observables. This is the situation in the first case above.[3] In complex systems, epistemic states and the corresponding distributions generally include both error and variation.

In quantum systems, the situation is even more complicated since even observables associated with ontic states are usually not dispersion-free, meaning that ontic quantum states are generally indeterminate. This is related to the non-commutativity of observables in quantum theory, giving rise to 'blurred observables' (Schrödinger 1935) that prevents a point-wise representation of an ontic quantum state. This idea of an 'objective vagueness' has been picked up under terms like 'Verschmiertheit', 'properties lacking sharp values', 'ontic blurring', 'objective fuzziness', 'unsharp properties'. This must not be confused with fluctuations or statistical spreads, amounting to variations due to supposed valuations by point functions.

2.2 *Dynamic determinism*

The temporal evolution of an ontic state $x \in \Omega$ as a function of time $t \in \mathbb{R}$ is a trajectory $t \mapsto x(t)$; the ontic state $x(t)$ determines the intrinsic observables that a system has at time t exhaustively. The temporal evolution of an epistemic state μ corresponds to the evolution of a subset $A \subset \Omega$ over time. The concept of an individual trajectory of an individual, ontic state is lost within a purely epistemic description.

The evolution is time-reversal invariant, if for every solution $f(t)$ of the equations of motion also the function $f(-t)$ is a solution. In this case, the evolution of the system is called both forward and backward *deterministic*. In such a case, there is no preferred direction of time. Fundamental physical laws (e.g. in Newton's mechanics, Maxwell's electrodynamics, relativity theory) are time-reversal invariant in this sense. (Note that fundamental physical laws are also time-translation invariant, such that no instance in time is distinguished and, thus, there is no nowness in physics.)

[3] From the perspective of statistical modelling, the two situations are known as fixed-effect modelling (with errors) versus random-effect modelling (with variation). Within a stochastic approach, the latter case is sometimes characterized as doubly stochastic.

Phenomenological physical theories such as thermodynamics contain a distinguished direction of time where the time-reversal symmetry of fundamental laws is broken. This leads to an evolution that is either forward or backward deterministic. The breakdown of both time-translation invariance and time-reversal invariance is necessary to distinguish first a particular instant in time t (nowness) and then, relative to this instant, two temporal domains called past and future. In this way, a *tensed time* can be generated which differs fundamentally from the *tenseless parameter time* of physics.

For a discussion of notions such as *causation* and *prediction*, concepts that are more specific than the concept of determinism, tenseless time alone is insufficient. Among several varieties of causation, this applies particularly to *efficient causation* in the sense of cause-effect relations that are conceived on the basis of a well-defined ordering relation between earlier and later states. This ordering is also significant for the notion of prediction (and retrodiction).

Specifically intricate types of dynamics arise in classical systems that are today known as deterministic chaos. The behaviour of chaotic systems in this sense is governed by deterministic equations, yet it is not predictable to arbitrarily high accuracy because, roughly speaking, it depends sensitively on the accuracy with which initial conditions are known. This is sometimes popularly referred to as the so-called 'butterfly effect', but a much better example is the mechanical three-body problem, e.g. in the motion of celestial bodies. Quite innocently looking equations of motion, simply integrable for two gravitationally coupled bodies, become exceedingly difficult to solve if only one body is added.

In the theory of complex systems, chaotic behaviour is characterized by an intrinsic instability with respect to changes of initial conditions. This instability can be quantified by so-called Lyapunov exponents or, more compactly, by the Kolomogorov-Sinai entropy of the system. Positive values of these quantities indicate that small variations of initial conditions become exponentially amplified as a function of time. They define a finite 'predictability horizon', giving rise to the notion of 'weak causation' for chaotic systems. For instance, the orbits of many smaller bodies of the solar system (asteroids, moons), subjected to the combined gravitational perturbations of the major planets, are chaotic and unstable on million-year timescales.

But even in the absence of chaos, indeterministic processes may occur at particular instances of time, whose simplest prototypes are bifurcations.

When a stable, non-changing state of a system becomes unstable, it typically relaxes into one among several neighbouring stable states at a so-called critical bifurcation parameter. Various kinds of bifurcations are known today – their common characteristic is that small fluctuations at the critical point play a significant role for the behaviour of the system beyond that point. In a general sense, such behaviour is generic for all kinds of decision processes where a selection (choice) among two or more alternatives is at stake.

The time evolution of the state of a quantum system is strictly deterministic if it is described by the Schrödinger equation. Issues about determinacy arise if individual quantum states are considered. For instance, measurement processes on quantum systems in superposition states are not describable by the deterministic Schrödinger equation – in this sense they are indeterministic. Although the epistemic state of the system after measurement is determinate, the ontic superposition state prior to measurement is indeterminate in the sense that the observables characterizing it are not dispersion-free.[4]

On the other hand, the applicability of the Schrödinger time evolution is, strictly speaking, limited to the case of isolated systems. For the dynamics of open quantum systems, stochastic influences by the environment have to be taken into account. This, however, is usually done by classical noise rather than genuine quantum stochasticity.

2.3 Probability and stochasticity

The concept of determinism cannot only be contrasted with causation and prediction. An important arena with its own tradition is the tension between deterministic and stochastic behaviour. Roughly speaking, stochastic behaviour is what is left if one tries to describe the world in deterministic terms.

In the theory of stochastic processes, the indeterministic behaviour of a system is described in terms of stochastic variables $x(t)$, parametrized by time $t \in \mathbb{R}$, whose distribution $\mu(x, t)$ represents an epistemic state. The description of a system in terms of individual trajectories $x(t)$ corresponds

[4] Note that here and elsewhere in this article we refer to states and observables of quantum systems rather than quantum events. The reason is that there is no well-defined and consistent notion of an event in quantum theory. This makes it notoriously difficult to relate philosophical discussions focusing on events to quantum theory and its results.

to a point dynamics of an ontic state, whereas a description in terms of the evolution of the associated measure $\mu(x, t)$ corresponds to an ensemble dynamics of an epistemic state.

The limiting cases of infinite and vanishing predictability indicated in the preceding section correspond to special types of stochastic transition matrices. For instance, singular stochastic processes are completely deterministic and allow a perfect prediction of the future from the past. The general case of limited predictability is covered by the notion of a regular stochastic process. Particular complications arise where sequences of states or observables are not stationary, or where limit theorems of probability theory (central limit theorem, law of large numbers) do not apply. This is typically the case in complex systems.

The dichotomy of ontic and epistemic descriptions is also prominent in the theory of stochastic differential equations. For instance, Langevin-type equations generally treat stochastic contributions $\xi(t)$ in addition to a deterministic flow in terms of fluctuations around the trajectory of a point x in phase space. Such a picture clearly reflects an ontic approach. On the other hand, the evolution of epistemic states μ, e.g. in terms of drift and diffusion, is typically described by Fokker-Planck-type equations.

2.4 Deterministic embedding of stochastic processes

It is not surprising that deterministic processes such as fixed points or periodic cycles can be considered as special cases of more general formulations in terms of stochastic processes. This is easily understandable if all entries in a stochastic transition matrix are either 1 or 0, thus representing deterministic transitions among states. What comes somewhat as a surprise is the converse, namely that stochastic processes can be understood in terms of deterministic processes. This has been accomplished by means of a mathematical theory of so-called natural extensions or dilations of stochastic processes (see Gustafson 1997 for an overview).[5]

The significance of this important result can be illustrated in the following way. A system that is originally described stochastically, e.g. due to uncontrollable interactions with its environment, can be extended into its environment until all relevant interactions are integrated in the

[5] Note: this theory proves that deterministic embeddings of stochastic processes exist; it does not give an explicit and unique prescription of how to construct them.

behaviour of the system itself. This leads to an increasing number of degrees of freedom, enabling an integration of all previously stochastic behaviour into an overall deterministic dynamics. The price to be paid is a phase space of considerably higher dimensions, which has to cover all degrees of freedom that were treated as noise in the stochastic formulation.

If deterministic and stochastic dynamics can be rigorously transformed into each other, it follows that corresponding *(epistemic) descriptions* cannot be taken as indicators of determinacy and stochasticity as *(ontic) features of nature*. The dilation theorems mentioned above show that the gap between the two is often a matter of convenience or convention. If a stochastic description of a system seems to be appropriate, this can be due to deliberately regarding interactions with its environment as noise, or due to lacking knowledge about underlying observables and corresponding laws of nature. Conversely, certain idealizations that ignore fluctuations or perturbations of a system can lead to a deterministic description.

3. Brain behaviour: deterministic or stochastic?

The brain is a complex network comprising a very large number of interconnected nerve cells (neurons), and an equally large number of supporting cells (glia cells). Neurons send signals to each other in the form of electrical impulses (action potentials), using specialized extensions of their cell body (axons and dendrites). The axon of the sending neuron forms specialized junctions (synapses) with the dendrites of the receiving neurons. At the synapse, a presynaptic action potential triggers the release of neurotransmitters (e.g. glutamate) into the synaptic cleft. The transmitter is then bound to specific receptors in the postsynaptic neuron. This, in turn, induces a brief electrical signal in the postsynaptic neuron, which can be either excitatory or inhibitory, depending on the transmitter-receptor pair used for signal transduction. The balanced action of thousands of excitatory and inhibitory inputs to every neuron determines its activation and, in view of the high degree of recurrency found in most parts of the brain, also its contribution to the overall brain dynamics.

Different aspects of neurodynamics are salient for brain activity at different levels of resolution, as for example ion channels, neurons, or networks of neurons. Therefore, the corresponding conceptual frameworks and mathematical models present a picture of neurodynamics that is quite non-uniform. Sweeping from microscopic over mesoscopic to macroscopic components of the brain, deterministic, chaotic or stochastic descriptions can each be adequate. The proper choice for one of them is usually motivated by arguments concerning which features are important and which aspects have little or no relevance at each particular level.

This entails that it is often premature – and always risky – to draw general conclusions from neurodynamics for the organism by taking only a single level of description into account. In fact, an interpretation derived from models at one level may be contrary to the conclusions obtained from another level. Different scenarios at the level of stochastic subcellular biophysics, at the level of quasi-deterministic isolated neurons and at the level of large chaotic networks yield different conclusions.

A number of issues that were, and still are, intensely discussed at the level of individual neurons (often referred to as the micro-level of brain activity) will be outlined in Section 3.1. Although ion channels, which are essential for the functioning of neurons, are best described stochastically, the reliability and precision of individual neurons suggests a deterministic picture. Section 3.2 addresses the complex dynamics of recurrent cortical assemblies or networks (of several thousand recurrently coupled neurons), characterized by apparently irregular activity but presumably reflecting deterministically chaotic dynamics. This so-called mesoscopic level of brain activity is the level at which neural correlates of mental representations are assumed.[6]

3.1 Ion channels and individual neurons

Stochastic dynamics are prevalent in brain activity observed at a microscopic level. Consequently, probabilistic methods play a prominent role for modelling phenomena in this realm. In particular, the essential molecular components of electrical activity in nerve cells, the so-called ion channels, open and close stochastically and are effectively described by Markov processes (Sakmann and Neher 1995). Such models assume a probability (rate) associated with each possible transition, and modulatory

[6] The neural correlate of a mental representation can be characterized by the fact that the connectivities, or couplings, among those neurons form an assembly confined with respect to its environment, to which connectivities are weaker than within the assembly. A simple mechanism for the formation of such assemblies was proposed by Hebb (1949) and has been considerably refined by the concept of spike-timing dependent plasticity (Gerstner *et al.* 1996; Markram *et al.* 1997) in recent years.

parameters (like the membrane potential at the spike initiation zone, or the concentration of neurotransmitters in the synaptic cleft) may influence these transition probabilities. Almost-determinate (almost-deterministic) behaviour is reflected by state (transition) probabilities close to 0 or 1, respectively.

The function of intact neurons relies on large populations of ion channels rather than few individual ones. The compound ion currents resulting in larger membrane patches and whole neurons have greatly reduced fluctuations as compared to single-channel currents. This averaging or smoothing of signals associated with (lower-level) ion channel populations is due to the independent, uncorrelated operation of its constituents. As a consequence, the classical (higher-level) description of single neurons and their dynamics including action-potential generation is both determinate and deterministic, first described by Hodgkin and Huxley (1952) in terms of non-linear deterministic differential equations. Not only was this formal description found very adequate for isolated nerve cells, subsequent physiological experiments also demonstrated that real neurons can be extremely reliable and precise. In fact, it was demonstrated that neurons effectively operate (under certain conditions) as deterministic spike encoders (see Bryant and Segundo 1976; Mainen and Sejnowski 1995).

Both notions, reliability and precision, address epistemic issues of predictability horizons and the form of distributions. They avoid ontic connotations or commitments which need to be clarified if one speaks about determinacy and stochasticity. Reliability and precision are useful to express the relevance of particular phenomena on a microscopic level (e.g. stochastic ion channel openings) for the dynamics on a more macroscopic level (e.g. the operation of nerve cells), and the degree of control that can be exerted either by the system itself or by an experimenter. It cannot be denied, though, that chance phenomena characterize the operation of some subcellular building blocks of neurons in an essential way. These aspects, however, do not seem to play an important role for the functioning of neurons, and even less so for the dynamics of the large networks that they constitute.

This is not surprising to the degree to which an extension of a system into its environment often allows to simplify the description of its dynamics, e.g. by averaging procedures. As indicated in Section 2.4, this can lead to a deterministic description if enough stochastic interactions are integrated, i.e. if the system is considered globally enough. In this way, the stochastic dynamics of ion channels underlying the behaviour of individual neurons 'averages out' so as to yield a highly precise and reliable deterministic description of neurons.

Any distribution characterizing a state can in principle be interpreted as due to genuine chance (ontically) or due to ignorance (epistemically). This ignorance, or missing information, can in turn be deliberate, e.g. in order to disregard details that are inessential in a particular context, or it can be caused by uncontrollable perturbations. At the ion channel level, where quantum effects must be expected to occur, an ontic interpretation in terms of indeterminate states is possible or likely.

However, the fact that the stochastic dynamics of ion channels typically yields highly reliable and precise neuronal behaviour suggests that any potentially genuine micro-stochasticity is inefficacious at the neuronal level (and even more so at the network level). Therefore, statistical neuronal states are assumed to be of epistemic nature and genuine indeterministic contributions to the dynamics of neurons seem to be of low relevance. After all, the representation of the neurodynamics in a neuronal state space amounts to a fairly well-defined trajectory of quasi-ontic states.

3.2 Neuronal assemblies and recurrent networks

The activity of cortical neurons *in vivo*, i.e. embedded in networks, is generally characterized by highly irregular spike trains (Softky and Koch 1993). The standard deviation of inter-spike intervals is typically close to the mean interval, a property which is also shared by Poisson processes (cf. Tolhurst *et al.* 1981). This reminiscence of a random phenomenon raises the question which components of single-neuron activity can be considered as a signal, and which aspects must be classified as random noise (Shadlen and Newsome 1998).

Detailed models of input integration in neurons conceive the membrane potential process as a continuous-valued stochastic process like a one-dimensional random walk (Gerstein and Mandelbrot 1964; Tuckwell 1988). Irregular spike trains then correspond to strongly fluctuating membrane potentials observed in intracellular recordings *in vivo* (Azouz and Gray 1999). Comparison with *in vitro* recordings (most afferents cut off) strongly suggests that irregular spike trains *in vivo* are actually caused by complex, but deterministic synaptic interactions among the neurons in the network, and that they are not a result of noise processes extrinsic or intrinsic to the network.

Different from the many kinds of stochastic or probabilistic modelling of brain dynamics, observations of simple deterministic dynamics, e.g. periodic processes such as in EEG signals during epileptic seizures, are exceedingly rare. However, the irregularly looking complex dynamics of recurrent networks of neurons comprising both excitatory and inhibitory cells have been identified as features of deterministic chaos. The idea to model neurodynamics in terms of deterministic chaos goes back to early work of Freeman (1979); see also Amit (1989). It has been of increasing influence over the decades (see, e.g., van Vreeswijk and Sompolinsky 1996; Jahnke *et al.* 2009), and today there is general agreement that deterministically chaotic processes play an important role to understand the dynamics of the brain at various levels.

The dynamics of a chaotic system takes place on a subspace of the state space that is called an attractor. However, this holds only *cum grano salis*, namely if the transient motion from initial conditions on to the attractor can be disregarded. If such transient motion is not negligible, or if there are many attractors between which the system spends considerable amounts of time, the situation becomes quite complicated. For instance, Kaneko (1990) observed *long-time (super-) transients* in studies of complex coupled map lattices, and Tsuda (2001) proposed the scenario of *chaotic itinerancy* with many coexisting quasi-stable 'attractor ruins' for neurodynamics. Recent work of Zumdieck *et al.* (2004) demonstrates that long chaotic transients may abound in complex networks.

In such involved situations, observed irregularities of time series are due to a combination of deterministic chaos and random fluctuations which are hard to disentangle. It is, therefore, often practical to look for an overall stochastic description, for instance in terms of diffusion equations, stochastic point processes, or otherwise. Corresponding analyses (based on a Fokker-Planck-type diffusion approximation) of single-neuron dynamics in the high-input regime showed qualitatively different types of mean field dynamics of recurrent networks, depending on the strength of external inputs and on the relative strength of recurrent inhibition in the network (Brunel and Hakim 1999).

However, this does not imply that the nature of the process is fundamentally stochastic. Mixtures of deterministic and stochastic processes can obviously be described by stochastic evolution operators, although there may be underlying features of hidden determinism. As outlined in Section 2.4 above, even the opposite is possible: systems that are described deterministically can have underlying features of hidden stochasticity as well. But no matter whether the described features are hidden or apparent, they remain epistemic and do not justify conclusive ontic implications.

3.3 Quantum stochasticity in neural activity: a pertinent example

Since stochastic descriptions can generally be transformed into deterministic descriptions, it is an important issue whether or not there is a *genuinely* stochastic neuronal dynamics for which a (hidden) deterministic interpretation can be excluded. To all our present knowledge this is the case for stochastic quantum processes, for which the Schrödinger dynamics breaks down so that they are to be conceived as ontologically indeterministic.

Although the neurobiological literature does not refer to quantum phenomena a lot, it would be premature to assume that indeterministic quantum processes do not occur on relevant scales in the brain. A fairly concrete and detailed suggestion of how stochastic quantum processes could play a role is due to Beck and Eccles (1992), later refined by Beck (2001). This proposal refers to particular mechanisms of information transfer at the synaptic cleft.

The information flow between neurons in chemical synapses is initiated by the release of transmitters in the presynaptic terminal. This process, called exocytosis, is triggered by an arriving nerve impulse with some small probability. Thermodynamics or quantum mechanics can be invoked to describe the trigger mechanism in a statistical way. Examining the corresponding energy regimes shows that quantum processes are distinguishable from thermal processes for energies higher than 0.01 eV at room temperature (Beck and Eccles 1992). Assuming a typical length scale for biological microsites of the order of several nanometers, an effective mass below 10 electron masses is sufficient to ensure that quantum processes prevail over thermal processes.

The detailed trigger mechanism proposed by Beck and Eccles (1992) is based on the quantum concept of quasi-particles, reflecting the particle aspect of a collective mode. Skipping the details of the picture, the proposed trigger mechanism refers to tunnelling processes of two-state quasi-particles, resulting in indeterministic quantum state collapses. It yields a probability of exocytosis in the range between 0 and 0.7, in agreement with empirical observations.

However, processes at single synapses can hardly be correlated with 'active' decision processes, whose neural correlates are widely assumed to be coherent assemblies of neurons. The same problem appears if, according to Eccles's original intention, it is suggested that quantum processes in the brain provide an entry point for mental states to act causally on neural states. Most plausibly, *prima facie* uncorrelated random processes at individual synapses would result in a stochastic rather than a coherent network of interacting neurons (Hepp 1999). Although Beck (2001) has indicated possibilities (such as quantum stochastic resonance) for achieving coherent patterns at the level of assemblies from fundamentally random synaptic processes, this problem has not been resolved so far.

3.4 Punctuating brain determinism with quantum processes?

More generally speaking, most relations among different levels of neural description are only poorly understood. Yet there are some basic features that apply to most of these relations. For instance, higher (aggregated) level activity typically operates on longer timescales than lower level activity. This entails that fast variability at lower levels typically becomes irrelevant for the slower variability at higher levels. Since indeterministic quantum processes are assumed to occur on low levels (e.g. in synaptic processes, as proposed by Beck and Eccles), this is an argument against their implications at higher levels.

Hameroff and Penrose (1996), and also Stapp (Schwartz *et al.* 2005), have speculated about coherent quantum states at higher levels, but their proposals lack the empirical details necessary to evaluate them seriously. Moreover, it has been argued repeatedly that decoherence processes lead to the decay of such coherent states on timescales much shorter than those of neurobiologically relevant processes, so that neural systems essentially behave quasi-classically.[7]

Since higher-level neural activity has been found to exhibit deterministic chaos, i.e. a sensitive dependence on initial conditions, in particular situations, it has been proposed to consider quantum states as such initial conditions. The idea is that a small deviation due to an indeterminate quantum state could make a (huge) difference for the future course of neural activity, even on longer timescales. Does this idea work?

[7] Recent work on particular mechanisms of 'recoherence' (Hartmann *et al.* 2006; Li and Paraoanu 2009), re-establishing coherence in the presence of decohering interactions with a warm and noisy environment, might hold interesting new aspects in this respect, worth exploring in more detail.

First, quantum states playing the role of perturbations of initial conditions introduce limitations on predictability (specifiable by the Kolmogorov-Sinai entropy of the relevant attractor) but the chaotic dynamics itself is classically deterministic. Second, initial perturbations are amplified exponentially only on the attractor, so that its size represents an additional limit for long-time state changes. (Perturbations large enough to push a system out of its attractor are possible but unlikely for quantum fluctuations as expected in the brain.)

Another possibility for faint quantum states to introduce effective changes arises at intrinsically unstable states, for instance at bifurcation points. If a system happens to be at an unstable point, say, at the boundary between two attractors, any arbitrarily small fluctuation decides which of the two attractors the state of the system will relax into. However, the efficacy of small fluctuations in this sense is naturally weakened in the presence of additional, typically classical noise. So again, although possible in principle, it is hard to conceive a scenario in which quantum stochasticity becomes relevant for brain activity at a mesoscopic level correlated with decisions and actions.

Assuming the in-principle possibility that quantum states may make a difference, would this contribute to a better understanding of decision processes? Punctuating brain determinism by quantum stochasticity leads to stochastic changes at best, and this is certainly not how an active decision or action is understood. If quantum stochasticity were relevant only at a micro-level of brain activity, it is easy to argue that it becomes irrelevant (averaged out) at the mesoscopic assembly level. If quantum stochasticity were efficacious *directly* at the mesoscopic level, this would change the picture considerably – but at present this seems doubtful because rapid decoherence would destroy quantum effects too fast to be relevant for the comparably slow timescales of the assembly dynamics.

4. Conclusions

The intricate relations between determinacy and stochasticity raise strong doubts concerning inferences from neurobiological descriptions to ontological statements about the extent of determinism in the brain. These doubts are amplified by the observation that even the kind of description that is suitable depends on the level of brain activity one is interested in. As we move from microscopic (subcellular, membrane-bound molecules) to mesoscopic (neuronal assemblies) and macroscopic (large networks or populations of neurons) levels, completely different kinds of deterministic and stochastic models are suitable and relevant.

These difficulties abound for neurobiological descriptions of the brain as a classical system. So what about quantum states, genuinely (namely ontologically) stochastic states that must be assumed to occur in the brain as they occur everywhere else? As we have shown above, the difficulties of how to understand relations between levels of brain activity become even more pressing, in part because quantum noise is likely exceeded by stronger classical noise, and in part because it is expected only in particular low-level neurobiological processes. It is not overly deprecatory to assess the situation as largely inscrutable.

If, on the other hand, quantum effects are regarded as entry points for any kind of indeterminate or indeterministic influences in an otherwise deterministic system, everything depends on the nature of these influences. Assuming non-physical, e.g. mental, forces acting on neural activity (as proposed by Beck and Eccles 1992) leads into completely unexplored territory – to say the least.

All these (and more) complications entail that well-founded arguments to defend the position that neurobiology 'is' deterministic, or that it 'is' not, are hardly available. Our bottom line is that pretentious claims as to deterministic or indeterministic brain activity are unfounded, and so are the consequences drawn from them. This bears significance with respect to all kinds of problems related to decisions and actions – which are beyond the scope of this article though.

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