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Physics of Consciousness

Wlodzislaw Duch
Department of Computer Methods, Nicholas Copernicus University,
ul. Grudziadzka 5, 87-100 Toruñ, Poland.
duch @ phys.uni.torun.pl

ABSTRACT

Conscious experience is an experience, i.e. a particular relaxation of mind/body system. Mental events are stable reverberations of sets of neural cell assemblies. Dynamical models based on this assumption allow to explain a large body of empirical evidence, such as the content of consciousness in dynamical illusions and subjective ordering of events in experiments with short-time direct stimulation of neurocortex.

1 Introduction

Great progress in understanding of biochemical and neurological mechanisms has not yet lead to the comparable progress in understanding of higher cognitive functions of the mind. So far only very few attempts that aim at a unified theory of cognition have been made. They came from the artificial intelligence perspective. Probably the first was John Anderson's Act* model developed in the past 20 years. The model has three types of memories, declarative, procedural and working memory, and although it is just a formal model, with no ambitions for biological justifiability, it is quite successful in modelling a variety of high level cognitive phenomena, such as memory effects, priming, or even learning simple programming techniques and theorem proving. Another project, Model Human Processor (MHP), was started at Xerox PARC company as a model to design human-machine interfaces. Allen Newell, a co-author of the MHP project, wrote a book "Unified theories of cognition" [1] promoting the view that there is enough empirical evidence from cognitive psychology and neuropsychology to create many alternative unified theories of cognition. His own attempt was based on an expert system called SOAR, a system using production rules and symbol processing, certainly rather implausible as a model of mind/brain activity.

Computational neuroscience provides a better path for understanding the brain/mind functions. Attempts to link theoretical computer simulations with experimental approaches have been quite successful but somehow restricted to lower-level cognition (cf. [2,3]). First books on the theory of dynamical systems applied to the early stages of human development appeared recently (cf. [4]). A very interesting attempt based on modular neural networks applied to categorisation and learning has been published by Murre [5]. His CALM (Categorisation And Learning Module) networks, inspired by the cortical minicolumns, are one of the first successful attempts at cognitive modelling with some biological justification. Such cognitive models (cf. [6]) are concerned with many interesting psychological phenomena, such as various memory effects, recognition, priming, lateral inhibition, conditioning, categorisation, learning, attention, reinforcement, optimisation or motoric control. Quite recently consciousness became a popular subject (cf. [7-10]) but the discussion of this elusive phenomenon has been kept on a rather philosophical level. A few notable exceptions include the "global workspace" model of Baars [11], Theory of Neuronal Group Selection [12] and a relational theory of mind [13].

In this paper I will try to stay firmly grounded in empirical evidence. The noun "consciousness" does not refer to anything in particular, it is not a thing we can talk about, it is rather an experience or many different experiences that we label as "consciousness". The first problem in the research on consciousness is to clearly define what the real problem is. What should we explain?

2 Understanding Consciousness

Some physicist think that a unified *Theory of Everything* (TOE) will explain consciousness together with everything else (cf. Penrose [14] writing on consciousness, quantum gravity and unified field theories), but since they do not define what they want to explain (Penrose writes that "consciousness is indeed something") it is not clear what do they mean. Of course such belief goes along the respected reductionist tradition of physics: to understand something means to reduce it to more fundamental (physical) concepts and build models that are based on such concepts. However, in case of consciousness this is not and never will be sufficient! The reason is rather subtle but not hard to follow. Understanding depends not only on the ability to draw logical conclusions but also on relation of these conclusions to our experiences. Understanding of classical physics agrees with our sensory experiences. Understanding in quantum mechanics refers to abstract objects, such as the wavefunction, and since these objects are not directly accessible to our senses the feeling that we really understand is very hard to achieve. Foundations of physics are plagued with never ending discussion on “what does it really means”. Understanding of the mind in abstract, physical terms derived from quantum mechanics or quantum gravity is not satisfactory because we have direct perception of the mind while we do not have such perception of quantum wavefunctions. What does an abstract understanding have to do with me, with my experience of being conscious? Suppose that we find a nice equation describing the behaviour of mind, an analogue of Schrödinger equation for the mental events. Mathematicians may be happy with it but it will never reach the world of my personal experience. One may say that we already have such an explanation: the dynamics of excitations of neurons in the brain produces the mind. Do we understand our self better if a field of “psychons” is postulated [10] and individual minds are treated as activations or vertices of such field?

This is not where the real problem lies. The real, hard problem is to understand the first person experience, consciousness as an experience. Consciousness is a particular experience related to thoughts about myself. I am, I see, I observe, an interplay of the “I”, a subject, and an object, or contents of consciousness. No fundamental physical theory can tell us about this feeling or make it less mysterious in our direct experience. This is where we find the limit of external description, or limit of our modelling power - the ultimate understanding must refer to the personal experience, not just to words pointing at an experience. Books in the perennial wisdom tradition are full of paradoxical descriptions referring to this point: we cannot explain the basic experience of being. We cannot learn this experience of conscious feeling from books, it is a first person experience. Serious consideration of this point leads directly to the mystical traditions, particularly Buddhist schools of “mind cultivation”, such as Chan in China or Zen in Japan, schools that claim “a special transmission, beyond words, from mind to mind”. Various states of consciousness, their pathologies and transformations have been described by transpersonal psychology in details [15]. Thus “explaining consciousness” one should define at which level of human development should it be explained since conscious experiences of an infant, a child, an adult and a Zen monk are quite different.

Some authors (cf. [16]) make sharp distinction between the primary and reflective consciousness. Primary consciousness is simpler and involves walking awareness of the sensory stimuli. The problem in this case is to determine why certain phenomena are reported as conscious while others are processed sub-consciously by the brain. Reflective consciousness is related to the self-reflection and involves concepts connected with the representation of “I” or “myself”. A distinction is also made between the phenomenal and psychological consciousness. Phenomenal consciousness refers to the “existence of some phenomenal quality”, i.e. to the first-person experience, while psychological use of the word “consciousness” may refer to the awakeness, introspection, reportability, self-consciousness, attention or knowledge (awareness) of something. From the philosophical point of view it is the phenomenal consciousness that is hard to explain. I am convinced that the explanation given here is not restricted to psychological consciousness only because it concerns the mechanisms of the uniqueness of “what it is like to be” (cf. Nagel, in [7]) but this is a very subtle problem.

This particular feeling that we usually label “I am” is at the root of the consciousness riddle. To label experiences we do not have to be conscious - optical character recognition software labels the visual experiences of a scanner attached to the computer. Language abilities have nothing to do with this. This feeling cannot be reduced to logical or symbolic processes, changing the potentials or modifying the synaptic conductivities; it comes from relaxation of the whole mind/body system, from close associations of the concepts “I, me” with activations of the subcortical brain structures, hormone system and in effect the whole body. Mind events are not reducible to physicochemical processes, they depend on the content of the inner world resulting from the individual social history, emergent levels of organisation too subtle to investigate at the physical level. In principle everything is reducible to neurophysiological events, but it is true only in the same sense as in principle biology is reducible to chemistry and chemistry reducible to physics. In practice we are far from reducing phenomenology of biology to chemical interactions. Interesting, complex phenomena require their own phenomenology and our goal may be at most to find the link between psychological concepts and neurophysiological brain events, not to reduce psychology to neurosciences.

3 Requirements for a good theory of consciousness

Several attempts have been made to determine what is needed to make a good theory of consciousness. Chalmers [17] reduced the requirements for a good theory of consciousness to three points: explain the first person experience, the qualia and the mental content. He tries to show that phenomenological consciousness cannot be reduced to (does not supervene on) something physical. He argues that this follows from the logical possibility of zombies, i.e. systems that are in all respects human-like but do not feel anything. Such argument assume from the beginning that consciousness is not a physical phenomenon. The position of behaviourists claiming that consciousness is just brain and body states is quite coherent and immune to such arguments. The real problem from this point of view is to explain why do we hold to various illusions about our self, but this is a psychological, not a philosophical problem. Solution to this problem is hard because it requires good theory of infant development, formation and maintenance of theories about our self. Gray [16] has formulated four requirements for a “transparent” theory. It should explain how conscious experiences 1) evolved 2) what survival value they confer 3) how do they arise out of brain events and 4) how do they alter behaviour.

As a step towards a theory of consciousness fulfilling these requirements I will sketch here an approach that seems to solve most of the problems. In “A Treatise on Human Nature” written in 1740 David Hume wrote: “Mind is nothing but a heap or collection of different perceptions, unified together by certain relations...”. The augmented behavioural position - all experiences are nothing else but mind/brain/body states - is perfectly coherent. In the process of development we create many theories about our selves based on false convictions that something else is needed to explain our experience (cf. Cartesian Theatre of Dennett [8]). Any argument that there is something non-physical involved starts from an assumption that consciousness is non-physical. Although this may be our deep conviction hard evidence to support this extraordinary claim is missing.

To connect certain brain events with mental or conscious events one should start from neuropsychological data, point out which events in the brain are labelled as conscious and be able to predict the contents of conscious experience. For behaviourists this is a sufficient explanation. It is hard to describe higher cognition at the same level of theory as basic perception, therefore the second step is to justify some approximations to the real brain dynamics, introducing a specific language for a theory of mind. This language [18] is useful as a bridge between the brain and the mind events connecting brain's dynamics with psychological spaces.

4 Brain events and the contents of consciousness.

In recent experiments with visual perception [19] subjects were able to recognise a picture of one of 20 faces presented for only 50 ms. The neurons respond to a very brief presentation of 16 ms with activity extending up to 300 ms. This reflects the operation of a local short term memory system. Very short stimuli may have an impact on the subconscious processes (this is called *implicit learning*) and influence later behaviour. The evidence for such subliminal influences has been recently critically examined [20] and the conclusion is that the implicit learning has not yet been satisfactorily demonstrated. Such short stimuli “do not make it” to the consciousness. It shows that conscious processes should be connected with patterns of neural excitations requiring longer times to establish themselves. Conscious perception is relatively slow reaction of the whole organism. Many processes performed in parallel by the brain never become the contents of our consciousness.

At what level should we see the correlation of brain events with conscious mental events? It seems unlikely that single neurons are important for brain activity. Hebb [21] suggested that groups of neurons, or **neural cell assemblies** (NCAs), are more appropriate because they are more reliable (distributed coding) and modular networks may store more information [22]. From neuroanatomy we know that neocortex has a modular structure, with microcolumns of neurons with relatively high (a few percent) vertical connectivity with excitatory connections. Such microcolumn occupies 0.1-1 mm^2 and has between 10 and 100 thousands of neurons. Typically local axons inhibit the neighbouring microcolumns (with connectivity of a fraction of a percent) while long pyramidal cell axon collaterals spreading over several millimetres are excitatory. Correlated firing of NCAs in separated parts of the neocortex creates **transcortical neural cell assembly** (TNCA) and is activated by certain subcortical structures. Most important subcortical structures involved in this process are presented in Fig. 1.

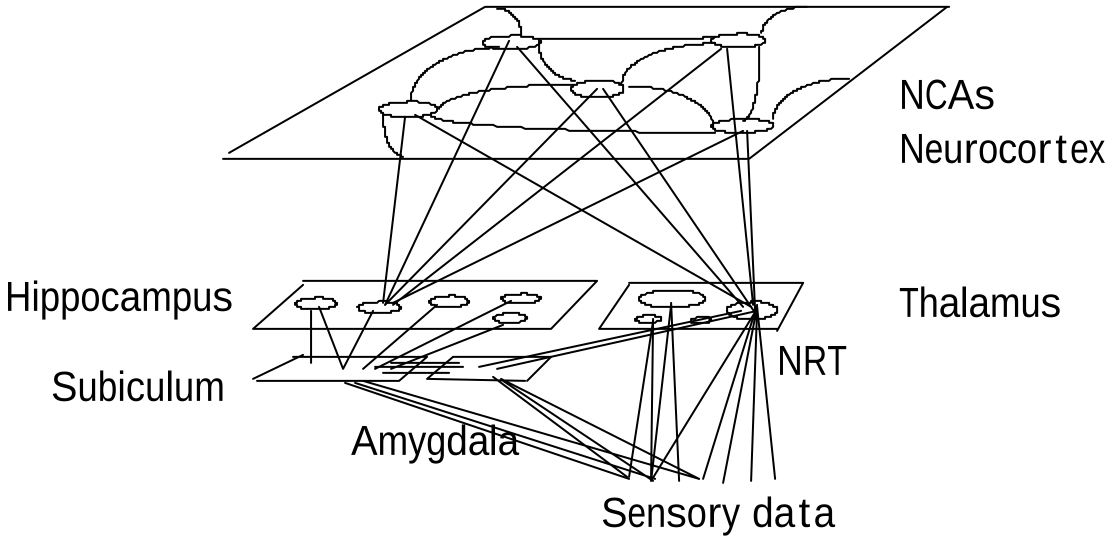

Fig. 1 Major brain structures involved in control of global dynamics responsible for conscious perception.

Hippocampus is involved in long-term memory (LTM) storage, most probably [23] it functions as an intermediate memory storage preventing catastrophic interference of new memories with compressed representation of episodic memories in LTM and facilitating recall of recent memories. This recall is really a reinstatement of the same neuronal activity as the activity during the original experience. Enthorinal cortex and subiculum belonging to the hippocampal formation seem to be involved in selective attention [16]. Thalamus controls emotions and attentional processes, especially nucleus reticularis thalami (NRT) regulates the flow of information between the cortex and thalamus. Almost all sensory information reaches the neurocortex via NRT. Signals from the topographic sensory maps reach LTM in neurocortex, hypothalamus and hippocampus and thalamus. Emotional reactions evoked by stimulation of thalamic structures, such as the pleasure reactions during stimulation of lateral thalamus and fear reactions during stimulation of amygdala, control the dynamics of brain processes, adding values to mental events categorised by hippocampus coupled with frontal, temporal and parietal cortex. I will argue here that it is precisely the dynamics of TNCAs due to the rhythmic activations of cortical NCAs by subcortical structures that is correlated with short term memory and mental events. Modulation of the EEG activity in form of moving waves has been observed (Newman and Baars [11]) leading to very subtle wave phenomena. Whittington *et al.* [24] studied synchronisation in thin slices of live brain tissue and found the neuroreceptors (belonging to the class of metabotropic glutamate receptors) responsible for the 40 Hz oscillatory activity of the network. Synchronisation of these oscillations over wide distances in the brain provide a potential solution to the problem of binding features of sensory experiences analysed by different areas of the brain. Experimental data is explained by the theoretical model [24] of inhibitory neurons driven by excitatory activations of pyramidal cells.

There is much noise in the brain, neurons are not reliable elements and to be a robust controller of the body the brain cannot allow rapid reactions to all short transition patterns of neural excitations. The speed of information processing is optimised by the evolution and is a compromise between fast information processing in dangerous situations and minimisation of energy consumption by the brain. The main parameter carrying information in the brain is the average frequency of spiking. It is simply impossible to avoid noise in the brain and yet our conscious experiences are coherent and stable. In artificial neural networks controlled noise is frequently added to the input data to obtain more robust adaptation, smooth the irregular data and solve hard optimisation problems. In effect networks learn prototypes rather than exactly the data presented, and meaningful generalisations become possible. What counts as a recognition in recurrent neural network is a stable attractor state, not the transition states that do not carry information (cf. [2]). In the real brain also stable (~0.1-1 sec.) patterns of excitations are most important for information processing therefore conscious experiences should be connected only with such stable patterns.

Formation of stable patterns of excitation in the dynamical system in which noise is important is a slow process. Specialised areas of the brain analyse different features of sensory experiences compressing information that reaches the high-level decision mechanisms and becomes conscious experience. Compression of information is a very general and important mechanism. The results of various low level feature analysers are bound together in conscious experience. In the visual system alone there are many separate areas analysing colours, shapes and motion. Damage to some of these areas may selectively remove features of conscious experience leaving for example only perception of colour. Signals from the low-level perception areas activate frontal and parietal neural cell assemblies via long axons of the TNCAs and stimulations by the subcortical structures. Evolution slowed these processes by crossing all major nerve pathways (left hemisphere controlling and receiving input from the right part of the body and vice versa). Creation of stable patterns of activities in such a large brain areas require times of the order of at least tenth of a second. In brains and in neural networks learning, or forming of new memory objects, is slow, but recognition is quick. Episodic memories are represented by attractor states of the brain, i.e. the structure of TNCA stable wavefronts (dependent on the synaptic conductivities) is formed and the relaxation of the mind/body states remembered as “an experience”.

5 Experimental evidence

NCAs are needed to explain short-term memory, including sensory buffers such as the phonological working memory persisting for up to 2 seconds [25]. A preliminary experimental evidence for the existence of TNCAs has been presented very recently using neurolinguistic techniques [26]. Coherent activation of neurons in visual cortex has been observed in several experiments (Newman and Baars [11], [27]). TNCAs are also needed to explain various experiments in cognitive psychology. Temporal law of associative learning is “one of the major unsolved challenges in the study of brain mechanism of learning and memory” [28]. In a typical experiment conditioned stimulus (CS), such as a tone, is paired with unconditioned stimulus (US), such as an air puff to the eye causing the eye to blink. Best learning requires in this case a time delay of 0.2-0.5 second between the CS and US. If both stimuli are applied at the same time no learning occurs. This is what one should expect if associative learning is done via conscious, high-level response requiring formation of TNCAs.

More direct confirmation of the association of TNCAs with conscious experience comes from analysis of neuropsychological experiments. Excitation of a large number of neurons by stimulating neocortex with electrodes leads to many inhibitory and excitatory neural signals. Pumping energy to such system pushes it into highly excited chaotic state until the energy gets dissipated from the system and it settles in one of the stable attractors. In effect each time the same microcolumn is stimulated different memories will be invoked and experienced. It would be very interesting to know how many different memories may be invoked by stimulation of one cortical region. Even if the brain receives and processes sensory information if TNCAs patterns are not formed (cf. the 'blindsight' cases or cases of hysterical blindness [8]) this information is not experienced consciously. Masking of conscious perception have been studied in details. In the metacontrast phenomenon [8] a coloured disk is flashed for 30 ms on a screen, followed by a ring that wipes out conscious experience of the disk. One may observe neural excitations due to the first stimulus and see how the second stimulus changes these excitations, preventing the TNCA from reaching an attractor state corresponding to the conscious perception of the disk. If a whole series of confusing stimuli is presented then a stable attractor of the TNCA excitation may not be reached for a second or longer, each new stimulus forcing the system into a new pattern before the old becomes firmly established and episodic memory engaged. The long time-scales in the cutaneous rabbit, Kohler's colour Phi or similar experiments [8] are understandable and it should be possible to compute these times predicting when experience will become conscious.

A series of experiments performed by B. Libet in the last 30 years [29] provides the best evidence for linking the global dynamics of the brain with conscious perception. Short 0.2 msec. electrical pulses of frequency ν were applied to somatosensory cortex of awake patients (up to 60 pulses per second). The minimal current that is noticed as a tingling sensation decreases with increasing frequency $I \sim 1/\sqrt{\nu}$ for ν between 8 to 240 Hz. Conscious sensation occurs 0.5-1 sec. after application of the first pulse at the current intensity near the threshold level. Minimal I values causing conscious sensation sharply increase when trains of pulses are shorter than 0.5 sec. For a single pulse minimal currents are an order of magnitude higher than for 1-second train of 30 pulses. For trains of pulses longer than 1 sec. the minimal current decreases with the frequency of pulses per second but does not decrease with length of the pulse train. These quantitative observations [29] are explained by energetic criteria: conscious sensations require enough energy delivered to the cortex to excite TNCAs and enough continuous power (if $I \sim 1/\sqrt{\nu}$ then $I^2\nu \sim$ power=const) to support them. It takes energy to create stable TNCA excitations and time is needed to transfer this energy. This relationship is so simple because in Libet's experiments the stimuli were plain electrical excitations. For weak impulses, at the threshold of invoking the experience, 500 ms is necessary for conscious experience. Signals with complex structure may excite TNCAs at much lower currents. Readiness potentials appear 550 ms before the motoric action, subjectively felt intention about 200 ms before. Similar estimations were given by Taylor (1995, submitted to *Consciousness and Cognition*) where the nature of competitive neural processes leading to awareness is discussed.

Libet's experiments [29] on “backward referral in time” created real confusion (cf. [8]). An electrical pulse is applied to the somatosensory cortex and a single pulse is applied to the skin about 0.5 sec. after the direct cortex stimulation. All subjects reported conscious perception of the later skin stimulation as earlier than the sensation invoked by the direct cortex stimulation. Libet interprets it as referring the conscious perception of the direct stimulation 0.5 second back in time. Applying electrical stimulus to the medial lemniscus or in the thalamus area up to 0.5 seconds after the neocortex was stimulated gives the same wrong subjective perception of temporal order as does the skin stimulus. From the TNCA point of view the solution of these paradoxical observations is obvious: pumping energy is a necessary condition but to reach a global TNCA attractor state a number of NCAs in different parts of neurocortex should be active at the same time. Direct stimulation of thalamic structures or of the skin (with signals relayed to the cortex also by thalamus) creates proper TNCA excitations without any delay. In the language of dynamical systems one may say that the time to reach the attractor state in a phase space of high dimensions depends not only on the energy but also on the precision of pointing into the attractor's basin. I do not know about any other plausible explanation of these observations.

6 Summary

Conscious experience is an experience and as all experiences is a particular combination of brain and body states. Reflective consciousness involves the concept of self but is not different in principle from the primary consciousness. **Ego** - a complex of mind objects related to the representation of self - develops and controls the dynamics of other mind states. Conscious experiences are controlled by the self-interest of the ego complex, influencing the hypothalamic structures controlling emotions. The gap between perception and action enables reflection on what we our doing and enables more refined actions. Lower animals follow genetic programs stored in their midbrain structures; higher animals and humans have a chance to break out of this instinctive behaviour. **The evolutionary value** of consciousness is great indeed. Chance to observe and experience the **qualia** associated with our action and **modify** the behaviour enabled to build superego on the top of ego complex of mind objects. It improved the collaboration of the groups of prehumans and enabled them to create complex societies. The ultimate grounding of our conscious experiences is inseparable from the body [30]; not only the nervous system but also the hormone system is involved. Ego qualia are special because they are related to strong emotions, the self-preservation instinct, activation of subcortical structures such as amygdala controlling fear states. Ego is the centre of gravity of brain's dynamics and the mind is most stable if there is only one such centre. In terms of dynamical systems it simply corresponds to a largest and deepest basin with many attractor states. However, Multiple Personality Syndrome (MDS) is a possibility if there is strong catastrophic interference of different experiences stored in episodic memory. To avoid this destructive interferences while forming their inner world children organise their personalities around two distinct centres. Some psychiatric disorders, such as schizophrenia, may be due to problems in forming TNCAs resulting from wrong synchronisation of firing of neurons, with positive symptoms (hallucinations) appearing when certain TNCAs are activated too easily without sensory stimulation and negative symptoms (withdrawal) when they are too hard to activate. The most successful treatment for schizophrenia is based on clozapine, a drug that blocks dopamine and serotonine neurotransmitters, strongly influencing global attractor states of the brain.

The relaxation of the brain/body states, labelled as “conscious experience”, is a subtle, non-linear process based on the feedback to/from all sensory and motoric subsystems and on the feedback from those attractors of the brain's dynamics that are close to the final state representing conscious recognition of an object or a thought. Some of these relaxation processes, chosen by the selective attention mechanism, find their way to the episodic memory and are remembered as “conscious experience”. Mental events result from “frozen experiences”, they are really chunks of past experiences remembered by the brain - what else could we remember? The brain stores “chunks of experiences” and re-lives them. Mind state is an activation of these stored experiences and the experience is labelled “conscious” if the working memory requiring global brain dynamics is engaged. The essence of conscious experiences lies in exploration of a single multimodal mind object: a thought, a sound, a colour, each having many features and related to brain/body reactions in a non-linear way, leading to a particular relaxation of the organism, very individual and hence subjective. Bodily reactions in anxiety are not just symptoms but part of this experience or brain/body relaxation. Symptoms and causes are not separable. Bodily reactions, somebody's pleasures, are not something we can really imagine, although we may try to “tune ourselves” to them. Personal world stays personal although heterophenomenology [8] may give us some approximation to it if we share the same experiences. In principle there is no philosophical problem in understanding what it is like to be another being, human or animal (cf. Nagel in [7]), although in practice our brain is not capable of reinstating exactly the same states as other brains, especially brains of animals.

The approach to conscious experience sketched here explains puzzling experiments related to conscious perception, such as those discussed by Dennett [8]. Long delays and strange subjective time ordering in Libet's experiments [29] are due to the non-specific form of low-level stimulation of the somatosensory cortex, resulting in long transition times to stable attractors of the TNCAs excitations. Conscious experiences are not only due to the comparison of the current and the predicted state [16]. Dropping moment-to-moment expectations, as practised in the “mindfulness meditation” [15], decreases habituation and increases, rather than decreases, the subjective feeling of being conscious. It is a training in paying attention to all sensory data and mental events without being trapped in daydreaming. The evolutionary advantage of consciousness lies exactly in this ability to avoid inflexible behaviour patterns (based mostly on genetic learning) that animals follow. Consciousness and intelligence, adaptation to complex environment, are inseparable. Conscious experience is nothing else but the reaction of the mind/body system, reaction infinitely more subtle in sophisticated humans capable of having qualia (conscious experiences) associated with such abstract questions like “who am I”?

How to bridge the gap between the mind and the brain? Approximation to the dynamic of TNCAs leads to the feature spaces (also known as psychological spaces, conceptual spaces or mind spaces [18]). Enormously complicated phase space of the dynamical system composed of tens of thousands of neurons is replaced by a space in which attractors are represented as “mind objects” and dynamics based on activations of these multidimensional mind objects becomes much simpler. Scientific theories provide us with a series of approximations to describe phenomena at different level of complexity and the way from neurons to NCAs and TNCAs and to the psychological spaces seems to be quite fruitful way from dead matter to conscious mind.

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