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Past and future in a moment of time: the brain's biological access code to consciousness or why the human mind is not artificial

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Abstract

Dresp-Langley and Durup (2009; 2012) proposed a temporal resonance mechanism as the most parsimonious neurobiological explanation of consciousness and showed how a '*time-bin resonance model*', where temporal signatures of conscious states are generated on the basis of signal reverberation in dedicated neural circuits of the brain would be able to generate an *access code* to consciousness. Beyond a certain statistical threshold, neural signal reverberation would produce meaningful temporal signatures in terms of specific activity patterns which trigger, maintain and terminate a conscious brain state. Spatial information is integrated into topological maps at non-conscious levels through adaptive resonant matching; it is not part of the neural signature of a conscious state. The latter would consist of a purely temporal pattern code arising from long-distance reverberation and de-correlation of spatial signal contents or messages from temporal contents. Such a code would be generated through the progressively non-arbitrary selection of temporal activity patterns in the continuously developing brain. The activation threshold of the temporal signature of a conscious state solely depends on probabilistic coincidences. The temporal neural signatures of conscious states form the "natural" basis of human consciousness and involve memory circuits at deeper non-conscious levels of perceptual integration. Although social pressure may drive human consciousness in certain directions rather than others at a given moment in time, the claim that the human mind would be an artefact of such pressures is not only unsubstantiated, but ignores the whole neurobiology of what Grossberg in some of his finest work referred to as "the adaptive brain".

1. Introduction

In the last twenty years, studies of consciousness have produced a considerable bulk of theoretical and experimental work concerned with the attempt to answer two critical questions: 1) What is phenomenal consciousness and is a scientifically operational definition of this phenomenon possible, and 2) where and how is consciousness generated in the brain? Being able to answer the second question entirely depends on whether a valid answer to the first one can be given. Looking back on different approaches towards a scientific study of consciousness (e.g. Kihlstrom, 1987; Natsoulas; 1983; Dennett; 1991; Posner, 1994; Block, 1995; Revonsuo, 2000; Zeman, 2001; Dietrich, 2003; Dehaene *et al*, 2006 and others), we are left with the conclusion that a fully operational yet comprehensive definition of the phenomenon as such still poses a fundamental problem. This problem is highlighted in a recent article (see Block, 2007), where the author argues for an “abstract solution to the problem of consciousness”, pointing out that phenomenal consciousness exceeds cognitive accessibility and, therefore, the neural basis of phenomenal consciousness can not include the neural basis of cognitive accessibility. This claim takes us right back to what several authors have referred to as the “hard problem of consciousness” (e.g. Chalmers, 1996, Searle, 1998) or the seemingly insurmountable difficulty to account for how the conscious “I “ (cf. James, 1890) in experiences such as “I do”, “I feel” or “I am”, arises from biophysical mechanisms in the brain. Without any pretence of being able to answer this question, we here propose a biophysical model that dissociates cognitive performance from conscious representation by explaining how a conscious state may arise in the brain from temporal resonance of memory signals in the absence of any stimulus input or ongoing cognitive activity such as perception, attention, or conscious report. Our model relates to earlier concepts such as Edelman’s (e.g. 2003) conscious state notion, Grossberg’s (e.g. 1999) brain resonance model, and Helekar’s (1999) idea of an identity link between temporal brain activities and consciousness.

The major limitation of experimental studies of consciousness with a cognitive performance design is that they may have permitted bringing to the fore various particular conditions of expression of consciousness, but they have not advanced our understanding of how the phenomenon is actually produced by the brain. The question of consciousness and its possible neural origins has thus been reduced to looking for covert traces of a complex phenomenon in overt behaviours like guided attention, active conscious perception, and conscious report.

1.1. Consciously guided behaviour

Approaches where a specific conscious behaviour is considered as an indicator of consciousness generally consist of having human observers perform specific tasks that require focussed attention or selective memory retrieval. One of the more recent efforts in that direction would be, for example, the experiments by Dehaene *et al* (Dehaene, Changeux, Naccache, Sackur, & Sergent, 2006), where consciousness is approached in terms of what the authors call ‘conscious report’. Suggesting that a human subject is phenomenally conscious when some critical event is reliably reported, they argue that consciousness can be defined in terms of ‘access of information to conscious report’. Such a restriction of phenomenal consciousness to processes that enable information to access a certain level of conscious representation is grounded in Block’s concept of access consciousness (e.g. 1995). Examining conscious report of a human observer to unravel the mechanisms of consciousness, or access of information to consciousness, leads to several critical questions that remain to be answered. Does information that is made accessible to conscious report have to correspond to ongoing or past, to real or imagined events? Does the conscious experience that is subject to conscious report occur well before, immediately before, or during the report? How long would it be expected to last thereafter? In other words, is studying conscious perception and visual attention sufficient to understand the mechanisms that produce consciousness in the first place? The logic of scientific explanation requires that the nature of the *explanandum*, or what is to be explained, is adequately derived from the *explanans*, or explanation given, and an *explanans* can be considered adequate only in regard to the particular expression of, or dependent variable relating to, the *explanandum*. In the case of attention and perception, knowing that both are two either related or unrelated aspects of the *explanandum* (consciousness), the *explanans* is derived from conscious reports, sometimes correlated with some specific activity in the brain. The *explanans* in this case is adequate with regard to the particular perceptual process probed by the study task, but not with regard to the *explanandum* as such. Along the same line of reasoning, a neural correlate may adequately reflect brain activity related to a particular process of conscious perception highlighted by behavioural data, but is still inadequate as a “neural correlate of consciousness”.

In the search for a neural correlate of consciousness (or NCC, as in Crick & Koch, 1998), Dehaene and colleagues, whose work has received a lot of attention, employed a working model in terms of ‘subliminal’, ‘preconscious’, and ‘conscious perception’, which adopts a taxonomy proposed by Kihlstrom (1987) twenty years earlier. The authors proposed top-down attentive selection as the key to conscious perception. Phenomena such as change

blindness (e.g. Silverman, & Mack, 2006), where human observers are unable to detect important changes in briefly presented visual scenes disrupted by blinks, flashes or other visual masks just before the changes occur, are put into the category of ‘preconscious perception’. What happens in change blindness, is that observers usually fail to report what they actually see because they believe that what is there is what they have seen just before. Such belief would block the attentive selection process that would otherwise enable the new information contained in a new visual scene to access the level of conscious perception (cf. Dehaene & Changeux, 2005). Such change blindness appears to be a result of top-down inhibition of ongoing stimuli, preventing their conscious perception. In this case, the immediate data of perception cannot reach consciousness because the conscious state is filled with a dominant memory representation of a previous event. This highlights the selectivity of the brain mechanisms that make representations accessible to consciousness. Theories until now have failed to account for such selective mechanisms, which could explain how consciousness originates from the brain in the absence of cognitive performance, attention, and awareness.

Visualizing which parts of the brain are or are not activated when a human subject is or not attentively (‘consciously’) performing a behavioural task has not helped to advance in that direction. In the fourteenth century, physicians attempted to identify the *locus* of the human soul in the body. With the advent of modern functional imaging techniques, the localization of consciousness in the brain has become the pet subject of a small industry in contemporary science. While rapid technological progress, promoting the development of imaging and electrophysiological techniques, has made it possible to correlate cognitive function with increasingly precisely located neural activities and interactions in specific brain areas, such correlations do not lead us further towards understanding the genesis of conscious function in particular. Some observations may suggest that conscious activity would correlate with occipital neural activity while others seem to point toward a correlation between conscious mental events and late parieto-frontal activity (see Rees *et al.*, 2002, for a review). Even though some kind of sense may be read into such apparently largely disparate data (see Driver & Vuilleumier, 2001, or Dehaene *et al.*, 2006), fact is that the much expected breakthrough that would allow to determine the *locus* of consciousness on the basis of pictures taken from the brain during conscious task performance has not yet happened.

Lucid dreaming: dressed rehearsal in the theatre of consciousness

As pointed out already more than a century ago by William James (1890), consciousness encompasses far more than being able to effectively attend to, perceive, and describe stimuli. Baars (e.g. 1997) referred to phenomenal consciousness as the theatre of the mind, which is reminiscent of writings from the first book (part 4, section 6) of the *Treatise of Human Nature* (1740) in which the Scottish Philosopher David Hume compared phenomenal consciousness to a theatre with a scene of complex events where various different sensations and perceptions make their successive appearance in the course of time:

“The mind is a kind of theatre, where several perceptions successively make their appearance; pass, repass, glide away, and mingle in an infinite variety of postures and sensations. There is properly neither simplicity in it at one time, nor identity in different, whatever natural propension we may have to imagine that simplicity and identity. The comparison of the theatre must not mislead us. They are the successive perceptions only, that constitute the mind; nor have we the most distant notion of the places where these scenes are represented, or of the materials of which it is composed.”

Hume’s phenomenal description of successive feelings or sensations appearing as sequences in time is embedded in some contemporary views of consciousness. Less than ten years ago, the neurobiologist Ramachandran discussed the concept of ‘self’ in relation with the concept of ‘consciousness’, and emphasized that phenomenal consciousness encompasses hardly more than sequences of many distinct perceptions and sensations. Moreover, these are not necessarily related to ongoing external events or *stimuli* (Ramachandran, 1998).

Understanding conscious imagination and creative thinking, or the striking similarities between object descriptions resulting from conscious perception and from pure imagination (e.g. Kosslyn, 1994; 1999; Kosslyn *et al*, 2001), would at some stage require going beyond studying actively and consciously behaving observers. When we dream intensely, we are not attentive to *stimuli*, but we are phenomenally conscious, and sometimes we may be able to access and report these phenomenal data several hours later, when we recount our dreams over breakfast. LaBerge (1990) believes that, to the neuronal functions that produce consciousness, dreaming of perceiving and doing is equivalent to perceiving and doing. Thus, in line with Hume’s or Baars’ theatre metaphors, our dreams would be the dressed rehearsals in the theatre of our conscious mind. Such a view is supported by evidence for a functional equivalence of psycho-physiological correlates of consciousness in active wakeful observers and during lucid dreaming, which occurs in REM sleep phases. Lucid dreaming and

equivalent wakeful activities are measured in terms of relatively short EEG signal epochs indicating a specific activation level of the central nervous system (e.g. LaBerge, Levitan, & Dement, 1986). Other recent work on anesthetized patients (e.g. Drover *et al*, 2002) suggests that different levels of consciousness during anaesthesia are reliably predicted by an invariant set of changes in quantitative EEG analysis. It seems regrettable that these and similar lines of research have not received more attention from brain theories of consciousness.

Perhaps the time has come to step back and recapitulate what we have learnt and what not from the past twenty years of consciousness studies (in this regard, see also the recent critical review by Buzsàki, 2007). From the strict viewpoint of the theory of explanation, any hard evidence linking the phenomenon of consciousness to the brain is not yet available. A major constraint is imposed by Occam's razor, which describes what is commonly called the law of parsimony (*lex parsimoniae*), a principle of logic that is both ethically and pragmatically grounded in the philosophy of science of the English cleric William of Occam (14th century: "*entia non sunt multiplicanda necessitate*"). It states that the explanation of a phenomenon should resort to as few "entities" (mechanisms, processes, laws) as possible. Likewise, an entire model or system of explanation should make as few assumptions as possible and a scientific theory of consciousness would have the virtue of proposing the fewest possible functional assumptions to account for conscious brain activity enabling conscious experience.

This major constraint, together with arguments brought forward earlier herein, leave us with the conscious state notion as the most parsimonious definition of consciousness. The simplest possible postulate that there would be a specific brain state, the conscious state, adequately defines the *explanandum*. The fewest mechanisms necessary for its genesis in the brain adequately define the *explanans*.

1.3. Information processing by the brain and the conscious state notion

The notion of a conscious state (e.g. Edelman, 2003) and how it may lead to an operational approach to the problem of consciousness was discussed already ten years ago by Tononi & Edelman (1998). It encompasses the earlier definition proposed by von der Malsburg (1997) in terms of a continuous process with a limited duration. Conscious states are neither identical nor reducible to states of awareness or vigilance (see also Nielsen & Stentstrom, 2005). While they may involve cognitive processes such as memory (e.g. Cowan, Elliott, Saults, Morey, Mattox, Hismjatullina, & Conway, 2005), attention (e.g. Raz & Buhle, 2006), conscious perception (e.g. Crick & Koch, 2000; Dehaene *et al*, 2006), or volition

(Grossberg, 1999; Dehaene *et al*, 2006), these would only be possible expressions of a conscious state and are not to be confounded with the state as such. Rather, a conscious state would correspond to a specific functional state of the brain that enables the experience of phenomenal consciousness. John (2002) argued that the most probable invariant level of neural activity or coherent interaction among brain regions that can be measured when a person is in a conscious state would be the best possible approximation of NCC, or what he calls the “conscious ground state of the brain”.

Earlier studies concerned with the functional characteristics of conscious and non-conscious information processing, decision making, and action (for detailed reviews see Kihlstrom, 1987, Dehaene & Naccache, 2001, or Buszàki, 2007) have pointed towards approaching consciousness in terms of a brain state or ‘conscious state’ that would result from functional properties of neural circuitry. A conscious state appears to have two major functional characteristics, such as 1) a limited information processing capacity (e.g. Schneider & Shiffrin, 1977; Shiffrin & Schneider, 1977; Shiffrin, 2003) and 2) a unique representational content for a limited and relatively short duration (e.g. Duncan, 1980; Mangan, 2003; LeDoux, 2002; Dietrich, 2003). The content of a conscious state would be steadily updated through non-conscious processes of perception (e.g. Dresch, 1998; Bonnet & Dresch, 2001; Dresch & Fischer, 2001; Dresch & Langley, 2005), which constitute by far the largest part of all brain activity (e.g. Velmans, 1991; Gray, 2002; Pockett, 2004). Conscious information processing relies mainly on serial processing, which allows for only a very limited amount of information to be dealt with in a given time span. Most people cannot consciously follow two ideas at the same time, or consciously execute two even simple, simultaneous tasks (e.g. Cherry, 1953; Baars, 1998). Conscious ‘seriality’ undeniably constrains any possible theory of consciousness (e.g. Seth & Baars, 2005; Edelman, 2003). Non-conscious activity, on the other hand, is largely based on parallel processing and can therefore handle a lot more information (e.g. Mesulam, 1990; Hochstein & Ahissar, 2002; Mangan, 2003; Dietrich, 2003). The function of serialization in terms of an ordered list of conscious events (e.g. Page & Norris, 1998; Seth *et al*, 2006), discussed already half a century ago by Lashley (1951), is linked to the hypothesis that an event or piece of information, once made conscious, would become selectively available to other processes related to thought and speech production. This function of making non-conscious information accessible to the mind is an important achievement of brain evolution. The limited capacity of conscious processes, on the other hand, represents a major functional constraint that is revealed by numerous psychophysical data, which include data on change blindness mentioned earlier and more recent observations

on change detection (Triesch, Ballard, Hayhoe & Sullivan, 2003) showing that observers detect sudden specific changes in visual scenes only and only just in time when they need the specific information to solve a given problem. The limited capacity of a conscious state entails that it must entirely rely on working memory, which can handle the ‘magic’ number of about 7 representations (e.g. Oberly, 1928; Miller, 1956 and more recently Parkin, 1999 or Vogel, Woodman, & Luck, 2001). Such a limitation severely constrains the top-down processes that can effectively operate within the limited temporal windows of a conscious state. As proposed earlier by Mangan (2003), the pre-conscious processes at the fringe of consciousness may provide some kind of buffer, which both compensates for and regulates the limited conscious capacity. The processing capacity of the non-conscious, in contrast, may be estimated within a range of at least 10^7 bits, knowing that the optic nerve transfers 10^8 bits per second (Koch, 1997), which is infinitely more than working memory can deal with. The limitations of conscious processing are defined in terms of the representational content that is authorized to invade a conscious state at a given time. Such content would be retrieved selectively from non-conscious long-term memory, where it is stored as an integrated representation, as defined in Churchland (2002, p. 64) in terms of a “pattern of activity across groups of neurons which carry information”. A fully integrated non-conscious representation would consist of a unique activity pattern, defined by a unique temporal signal sequence, across groups of neurons.

2. The temporal signatures of conscious states

Dresp-Langley and Durup, 2009; 2012) argued that the brain genesis of a conscious state may exploit some of the functional properties of working memory to produce a specific temporal signal sequence, or temporal signature sufficient to activate and to maintain a conscious state in the brain. Such a temporal signature would fulfil a double function: it would enable the generation of a specific conscious brain state that is well distinguished from other, non-specific and non-conscious brain states, and it would provide ready accounts for both the selective nature of conscious states and the fact that they may occur in the mind more than once.

A certain class of theoretical approaches to working memory, such as the Lisman-Idiart-Jensen memory model (Lisman & Idiart, 1995, Jensen *et al.*, 1996, Jensen & Lisman, 1996, Lisman, 1998, Jensen & Lisman, 1998, Jensen, 2005) have proposed temporal mechanisms based on some of the empirical findings summarized above, postulating a

working memory with a maximum processing capacity of 7 ± 2 items, where each item is represented by the firing activity of a cell assembly (the so-called ‘coding assembly’) in a well-defined temporal window. Specific numerical predictions, for the slope of the Sternberg curve, for example, were developed on the basis of such memory models (for details, see Jensen & Lisman, 1998; 2005). Başar (1998) and Başar *et al* (2000), for example, considered cognitive transfer activities to be based on oscillations at specific temporal frequencies, combined like the letters of an alphabet to deliver a temporal code for conscious brain activity measurable through wavelet analysis of EEG or event-related potentials (ERP). While these numerical models illustrate both the plausibility and the potential power of temporal codes in the brain, there is a major difference between such models and the one we consider here to account for conscious state generation. Our theory relies on particular dynamics of temporal messages, or resonant time bin messages, produced by a complex system (the brain) within massively distributed circuits of neurons. This implies that the temporal dynamics are oscillatory, since all known resonance mechanisms are by their physical nature oscillatory, but does not lead to any predictions regarding particular frequency bands.

Taking the general assumption of a temporal code further, whenever a unique combination of temporal sequences attains a critical activity threshold, a unique conscious state would be generated, and regenerated whenever that signature is retrieved again, either by the same set of neurons or any other set capable of producing it. Such neural timing for conscious state access would rely on simultaneous *supra* threshold activation of sets of cells within dedicated neural circuits in various, arbitrarily but not necessarily randomly determined *loci* of the brain. The intrinsic topology that determines which single cell of a given circuit produces which spike pattern of a given temporal signature is, therefore, independent of the topological functional organization of the brain.

This idea that a conscious brain state is triggered by temporal signals of cells that are arbitrarily associated with any other functional properties of cells suggests a way of thinking about NCC that is radically different from that offered by most current approaches. It has the considerable functional advantage that, should some subsets of coding cells be destroyed, other subsets could still deliver the code elsewhere in the brain. Such a functional assumption is justified in the light of evidence for a considerable plasticity of functional brain organization (e.g. Wall, Xu, & Wang, 2002). The relevance of functional plasticity in regard to our model will be discussed later in greater detail.

2.1. Time windows of a conscious state

Like the temporal signal sequence or activity pattern of any single coding cell is determined by its firing activity across a certain length of time, the temporal signature of a conscious state is also linked to its duration, the so-called ‘psychological moment’ (Pöppel & Logothetis, 1986; von der Malsburg, 1999; Tononi & Edelman, 1998), with variations in the limited dynamic range of a few hundreds of milliseconds. This estimate was established on the grounds of a considerable body of psychophysical and neurobiological data would suggest (e.g. Lehmann *et al*, 1987; Lestienne & Strehler, 1988; Thorpe & Imbert, 1989; Crick & Koch, 1990; Potter, 1993; Strik & Lehmann, 1993; Gray, 1995; Pascual-Marqui *et al*, 1995; Taylor, 1996; Koenig & Lehmann, 1996; Lehmann *et al*, 1998; von der Malsburg, 1999; Bressler & Kelso, 2001; Chun & Marois, 2002). Work by Libet (1993; 2003; 2004), for example, has shown that a time minimum of about 500 ms is required for a near-threshold stimulus to produce a conscious perceptual experience. In order to analyze neural patterns in terms of the temporal codes they deliver, the duration of a conscious state is to be divided into critical time windows, or ‘bins’, the length of which would be limited by the accuracy of neuronal timing, or the lower limit of biophysics. Such a time window, or ‘bin’, is expressed through the parameter Δt which would represent the sum of standard deviations for the time delay of synaptic transmission including the duration of the refractory period. An average estimate of 6 ms for this parameter appears reasonable in light of the data available (Bair, 1999). Helekar (1999) based his calculations of a temporal code on an average duration of 3 ms for Δt , operating under the hypothesis of an average estimate of only 30 ms for a state duration, expressed in terms of t . An average estimate of 6 ms for Δt is consistent with bin durations proposed by Shastri & Ajjanagadde (1993), Moore & King (1999), or Rieke *et al* (1997). Yoshioka & Shiino (1998) suggested 10 ms and Singer (2000) times no longer than 10 ms. Interspike intervals and integration times of cortical neurons display a similar dynamic range (Eggermont, 1998). Under the simple assumption that within each such ‘bin’ there is either a signal or no signal, derived from McCullough & Pitts’ (1943) germinal work on information transmission in neural networks, the information content of each bin is 1 bit. On the basis of an average duration of 300 ms for a given conscious state, which seems more realistic than the 30 ms state duration suggested by Helekar, a 6 ms duration for a critical time window or ‘bin’ within that state, and with a deterministic signal being generated during each ‘bin’, the information content of such a conscious state would be $300/6 = 50$ bits. A similar

computation of the maximum quantity of information conveyed by a duration t with a number of temporal windows identified by a given Δt was proposed by MacKay & McCulloch (1952). Considering equal probabilities for activity (signal) and non-activity (no signal) within each ‘bin’, a conscious state of a duration of 300 ms would then generate 61 bits of content (for $\Delta t = 6$ ms). This theoretical approach is detailed in Rieke *et al* (1997), who pointed out that the neuronal systems under study approach the theoretical limit of information transmission. The figures given above may be compared with estimates of the number of visual prototypes held in memory given by Tsotsos (1990), which correspond to information contents of 17 to 23 bits. Similar time-based estimates were suggested later by Thorpe *et al* (2001) and VanRullen *et al* (2005). Recent approaches in terms of dynamic analyses of correlated oscillations in cortical areas at various frequencies (e.g. Bassett *et al*, 2006) and functional interactions between gamma and theta oscillations in different structures of the brain (e.g. Axmacher *et al*, 2006) are consistent with the estimates given here. How such purely temporal functional aspects of an immense variety of neural signals produce a temporal code for conscious state access may be understood on the basis of the functional properties of so-called reverberant neural circuits in the brain.

2.2. Reverberation, long-distance propagation, and de-correlation of signal contents

The reverberant circuits or loops that have been identified in the brain appear to have their own intrinsic topology (e.g. Abeles *et al*, 1993; Edelman, 1993; Crick, 1994; Grossberg, 1999; Constantinidis *et al*, 2002; Lau & Bi, 2005; Dehaene *et al.*, 2006). Reverberant neural activity was found in thalamo-cortical (Llinás *et al*, 1998; Llinás & Ribary, 2001; VanRullen & Koch, 2003) as well as in cortico-cortical pathways (Steriade, 1997; Pollen, 1999; Lamme, 2004; 2006). Reverberant neural activity as such is a purely temporal process that generates feed-back loops in the brain, referred to by some in terms of ‘re-entrant circuits’ (Edelman, 1989; 1993, Tononi *et al*, 1992; 1998, Tononi & Edelman, 1998; 2000, Edelman & Tononi, 2000; Fuster, 2000; Prinz, 2000; Di Lollo *et al*, 2000; Klimesch *et al*, 2001; Edelman, 2003; Robertson, 2003; Crick & Koch, 2003). Reverberation is an important functional property of the brain because without it, the conscious execution of focussed action would be difficult, if not impossible (e.g. Lamme, 2006).

Dehaene *et al* (2006) argued that conscious perception and report would rely on the extension of local brain activation to higher association cortices that are interconnected by long-distance connections and form a reverberating neuronal circuit extending across distant perceptual areas. Reverberation would allow holding information on-line for durations that

are unrelated to the duration of a given stimulus and long enough to enable the rapid propagation of information through different brain systems. In their view, conscious information processing in the brain is associated with the parieto-frontal pathways of the brain, which are protected from fast fluctuations in sensory signals and which would allow information sharing across a broad variety of cognitive processes. While we agree with Dehaene *et al*'s postulate that conscious information processing would be enabled on the basis of signal reverberation and propagation across long-distance connections in the brain, we do not think that the complex cross-talk between neural signals that is necessary to generate information sharing across a broad variety of non-conscious cognitive processes can be part of NCC. If this were the case, the brain would have to sort out a seemingly infinite number of different signals from multi-channel cross-talk to generate a stable, reliable, and unifying code for conscious state access.

A ready solution for this dilemma would be signal de-correlation, potentially enabled through long-distance reverberation and based on some critical integration threshold. De-correlation of temporal from spatial messages for capacity-limited representation within consciousness would clarify how a stable and precise brain code for conscious state access can be generated in the light of a largely plastic and diffuse spatial functional organization of the brain. De-correlation has become an important concept in neural network theory and in systems theory in general. It describes a mechanism that reduces cross-talk between multi-channel signals in complex systems (like the brain), while preserving other critical signal properties.

3. Arguments for a biological access code to consciousness

The idea of a temporal access code for conscious states as the most parsimonious link between brain and mind is justified in the light of several theoretical arguments. It might be useful here to recall that the term 'code' initially stems from information theory and may stand for both 1) an entire system of information transmission or communication (like the brain) where symbols are assigned definite meanings and 2) a set of symbols for the content of a given message (like a temporal activity pattern) within that system. One argument in favour of a purely temporal access code for conscious brain states is its undeniable functional and adaptive advantage. Its origin would most likely be epigenetic given that, during brain development, representations remain largely non-conscious for a long time before they

eventually become the subjectively and holistically experienced data of phenomenal consciousness around the age of two or three.

3.1. Plasticity of spatial functional brain organization

Sensory, somatosensory, and proprioceptive signals may instantly be perceived as the immediate data of a conscious state, eliciting what psychophysicists call sensations. The integration of such a variety of signals into brain representations, however, relies on non-conscious mechanisms, which have to be sufficiently adaptable and display a certain functional plasticity to enable the continuous updating of representations as a function of changes. Such changes are imposed on our brains day by day by new situations and experiences. Yet, to be made available to consciousness, there has to be some permanently reliable, unifying “tag” which ensures stable access across time. Grossberg (1999) referred to this problem as the “*plasticity-versus-stability dilemma*” and proposed resonant neural learning as a potential solution. While such learning quite satisfactorily accounts for non-conscious information processing by the brain, it has not helped clarify through which mechanism non-conscious brain representations would be made available to consciousness. The need for a mechanism of neural integration that explains how non-conscious representations are delivered to consciousness is highlighted further by certain neurological data, such as ERP and functional imaging data on neurological patients with unilateral neglect or extinction after unilateral brain damage. Such patients are unaware of objects or events that take place on the contra-lesional side of physical space. Depending on how far their parietal lesion extends to the occipital or temporal cortex, a more or less important amount of non-conscious perceptual processing is found to be preserved (see Driver & Vuilleumier, 2001, for a review). This suggests that localized brain damage of the parietal lobe affects the mechanisms that enable specific perceptual representations to access the conscious state level but does not affect the perceptual representations as such.

Other neurological observations severely challenge the idea that function should be fixed in specific *loci*. The ‘phantom limb’ syndrome (e.g. Ramachandran, Rogers-Ramachandran, & Cobb, 1995; Ramachandran, 1998), for example, reveals an extraordinary plasticity of topological functional brain organization. The phantom limb syndrome is a phenomenon that was already mentioned in writings by Paré and Descartes, and described in greater detail by Guéniot (1868). It has been repeatedly observed in hundreds of case studies since. After arm amputation, patients often experience sensations of pain in the limb that is no longer there, and experimental data show that a third of such patients systematically refer

stimulations of the face to the phantom limb, with a topographically organized map for the individual fingers of a hand. On the basis of similar evidence for massive changes in somatotopic maps after digit amputation and other experimental data showing that several years after dorsal rhizotomy in adult monkeys, a region corresponding to the hand in the cortical somatotopic map of the primate's brain is activated by stimuli delivered to the face (Merzenich *et al.*, 1984), Ramachandran and his colleagues proposed their 'remapping hypothesis' (e.g. Ramachandran, Rogers-Ramachandran & Stewart, 1992). The latter clarifies how spatial and topological representations are referred to other *loci* in the brain through massive cortical re-organization. The findings reported by Ramachandran and others provide compelling evidence that, despite dramatic changes in non-conscious topology, representations remain available to conscious state access and can still be experienced in terms of sensations such as pain, cold, digging or rubbing. We believe that this is so because the temporal signatures of these representations persist for some time in the brain. In the light of Dehaene *et al.*'s (2006) long-distance signal propagation hypothesis, Dresch-Langley and Durup (2009; 2012) claim that the neural code for conscious state access itself extends beyond the local sensory and somatosensory areas which receive and process input from a given part of the body, such as an arm or a leg. Long-distance propagation and reverberation would lead to the consolidation of the temporal signatures of conscious sensations resonating across the brain, and the temporal signatures could reach threshold activation levels even when signal input to the specific local sensory area is no longer delivered. Ramachandran & Hirstein (1998) reported interesting clinical observations of co-existing sensations where the patient reported that he simultaneously felt a cotton swab touching his face and a tingling sensation in a phantom digit. In the light of a temporal code for conscious state access, this observation may be accounted for in terms of an extreme case of temporarily equally likely temporal signatures during progressive extinction. Any brain code, to be stable and reliable, needs reinforcement. In the case of amputation, the brain representations of sensations relating to the amputated member are no longer reinforced and their specific temporal signatures, though they would persist for some time, are also ultimately doomed to extinction. This, however, does not happen abruptly but slowly and gradually, and for some time different temporal signatures coding for different, similar conscious sensations could, indeed, generate statistically equally likely and simultaneously experienced conscious states.

3.2. Temporal coherence and coincidence detection

In his 'neurophysics of consciousness', John (2001, 2002) suggested that a conscious state may be identified with a brain state where information is represented by levels of coherence among multiple brain regions, revealed through coherent temporal firing patterns that deviate significantly from random fluctuations. This assumption is consistent with the idea of a stable and perennial temporal code for conscious state access, despite spatial remapping or cortical re-organization. Empirical support for John's theory comes from evidence for a tight link between electroencephalographic activity in the gamma range defined by temporal firing rates between 40 and 80 Hz (i.e. the so-called '40-Hz' or 'phase-locked' gamma oscillations) and conscious states (e.g. Engel *et al*, 1992). This 'coherence index', with a characteristic phase-locking at 40 Hz, was found to change with increasing sedation in anaesthesia, independent of the type of anaesthetic used (Stockmanns *et al*, 2000). Decreasing temporal frequencies were reported when doses of a given anaesthetic were increased. Moreover, the characteristic phase-locking at 40 Hz displays coherence not only across brain regions during focussed arousal, but also during REM sleep when the subject is dreaming (Llinás & Ribary, 1993). Such coherence disappeared during dreamless, deep slow-wave sleep, which is consistent with the findings reported on deeply anesthetized patients. The fact that the temporal coherence index of a conscious state is produced during focussed arousal as well as during dreaming in REM sleep phases is fully consistent with the idea (e.g. LaBerge, 1990) that dreams and conscious imagination represent functionally equivalent conscious states.

The phase-locking at the critical temporal frequency would be achieved through intracortical reverberation, enabled by a digital event within a hybrid system, as in John's terminology (John, 2001, 2002). This hybrid system, the brain, establishes arbitrary but non-random departures from different *loci* or topological maps. These latter may undergo functional re-organization, yet, the temporal code for conscious state access remains intact. This would lead to cortico-thalamic feedback loops, or resonance loops which generate the temporal signatures of conscious states on the basis of a statistical computation of non-conscious memory events coinciding in time. Potential mechanisms explaining how such memory events are read out by non-conscious processes in the brain were discussed by Grossberg in his Adaptive Resonance Theory (1975; 1999).

3.3. Adaptive resonance theory and Grossberg's important contribution

Originally, Adaptive Resonance Theory (ART) was conceived as a theory of brain learning to explain how the brain generates and updates representations of continuously changing physical environments (Grossberg, 1975). More recently, ART was extended to account for related phenomena such as attention, intention or volition. According to Grossberg (1999), the link between these three could be described by the fact that intentions would lead to focus attention on potentially relevant internal or external events. These *foci* of attention would lead to new representations when the system (the brain) is able to validate and integrate them into resonant states, which would include, according to Grossberg, the conscious states of the brain. According to the theory, all conscious states would be resonant states, triggered either by external or internal events and mediated by either attention or volition. This claim as such, however, does not explain how non-conscious representations would become available to consciousness. In our analysis, this is a direct consequence of the fact that the theory fails to separate spatial from temporal coding. Thus, Grossberg's dilemma, which he termed *stability-versus-plasticity* dilemma and which refers to the difficulty of finding a brain code that generates representations stable enough to be safe from extinction, but sufficiently plastic to incorporate newly learnt data, remains unsolved at the level of the transition from non-conscious representation to conscious state access. His earlier theories lacked in clarity regarding which brain mechanism would select the resonant representations that are to become conscious, and it fails to explain the genesis of a conscious state in the absence of ongoing stimuli producing immediate short-term memory events.

Nonetheless, Grossberg's adaptive resonance theory plausibly explains how the brain ensures the continuous updating of non-conscious representations through a mechanism termed top-down matching, which produces so-called resonant brain states. A resonant brain state would be achieved through the repeated matching of external or internal events in short-term or working memory to internal events activating top-down representations. According to the theory, the brain is continuously confronted with ongoing internal or external representations (*bottom-up*) and therefore has to continuously generate probabilistic hypotheses to determine what all these transitory events are most likely to be and whether they are relevant. This involves matching the ongoing representations to representations stored in long-term memory (*top-down*). Coincidence of bottom-up representations and top-down representations (*top-down-matches*) would produce so-called matching signals, or coincidence signals which, when repeatedly generated, lead to resonant states in the brain. The representations generated through top-down matching would be, according to Grossberg,

coded topologically in the ‘What’ and ‘Where’ processing streams of the brain (see Grossberg, 1999 for an extensive review of the relevant physiological data), and what he calls “the resonant code” is therefore tightly linked to functional topological organization. The question of how non-consciously encoded topological information is made available to consciousness is, as already pointed out, left unanswered. These considerations and arguments lead us to propose a new model of conscious state access based on what we call time-bin resonance.

4. Time-bin resonance: the biological basis of any form of consciousness

The following postulates and model properties are brought forward:

- 1) It is claimed that only non-conscious brain processes have enough capacity to process the complex cross-talk between spatial and temporal signals originating from various simultaneously activated and functionally specific sensory areas .
- 2) The temporal signatures of conscious states are generated and consolidated in reverberating inter-connected neural circuits that extend across long distances and well beyond functionally specific topology.
- 3) The activation of a temporal signature that triggers conscious state access depends on a statistical temporal coincidence of activity patterns related to non-conscious memory events.
- 4) Such a temporal signature is de-correlated from signal contents or messages relative to so-called spatial cortical maps.

The circuitry generating a temporal signature would have an intrinsic and essentially arbitrary, but not necessarily random, topology in terms of “which cell fires first”. This intrinsic topology is determined by statistical temporal resonance principles only. While there is no empirically based description of resonators receiving, amplifying and transmitting time-patterned messages in the brain, it is nevertheless certain that a large number of physical and biophysical phenomena can be plausibly and parsimoniously explained on the basis of resonance principles or mechanisms. We believe it makes good sense that evolution would have produced brains capable of generating conscious states on the basis of such mechanisms.

4.1 General functional characteristics

It is likely that biological resonators, in contrast with “ordinary” resonance devices designed by humans, would have highly sophisticated operating principles, given that hundreds of functionally different kinds of cells exist in the brain. On the other hand, there is no reason why resonators in the brain would have to function with a high level of precision, provided that they operate according to some redundancy principle and the whole group of resonating cells producing a conscious state behaves in a statistically predictable way. Our model conception of temporal signal sequences forming a specific biophysical ‘time-bin’ pattern that activates, maintains, and inactivates a conscious state is certainly and inevitably a simplification of reality. Such a simplification does, however, not affect the internal validity of the model arguments presented here. The principal aim here is to explain how a time bin resonance system would generate conscious brain states on the basis of a relatively limited amount of neural resources.

Given the known temporal properties of conscious information processing, we suppose that conscious states may generate messages corresponding to variable contents in terms of bit sequences corresponding to variable durations. In the simplest possible model, any of these conscious states would be identified by a unique sequence of 1s and 0s. Thus, in the same way as bar codes provide the key to an almost infinite variety of things, such temporal sequences provide the key to consciously experienced brain events. A given temporal code would be generated spontaneously at a given moment in early brain development, then eventually be reproduced and consolidated during brain learning. Consolidation would be a result of repeated reverberation in cortical memory circuits, leading to resonance states which correspond to more or less specific conscious states. Once a resonance circuit is formed, it is able to generate conscious state access at any given moment in time provided there is a statistically significant temporal coincidence between activity patterns in long-term memory. As long as this threshold of statistically significant coincidence is not attained, the representations processed in the resonant circuitry remain non-conscious or pre-conscious.

Counting from a first signal, or spike, in biophysical time, the resulting temporal sequence of 1s and 0s may be described as a succession of intervals between 1's. Let us imagine a network of brain cells, or a resonator, with a functional architecture or connectivity described by the shapes of closed polygons (see Figure 1 for an illustration), with a variable number of apices and the same number of edges. Each apex of such a polygon would correspond to a neuron which can receive or emit input or output signals from and to

processors anywhere in the brain, and also along the specific tracks of a resonant circuit primed for a specific temporal signature during its development. Here, we refer to the apices of our network model in terms of dedicated principal resonant neurons (PRNs). PRNs would be part of intra- and inter-cortical networks of neurons possessing long-range connections with other neurons across large distances across the brain. Their major functional property would therefore be the capacity of resonant long-range interaction well beyond their nearest neighbours. Not all neurons in the brain appear to have this capacity.

Each edge of a polygon would represent a delay path which transmits signals from a given apex to the next, with a characteristic delay corresponding to some multiple of the elementary ‘bin’ unit (Δt , as defined earlier by others in other models discussed earlier here). The distribution of these delays should fit the proportion of 1's and 0's in typical ‘time-bin’ messages: if, for example, 1's are as likely to occur in a code as 0's, then the proportions of various delays Δt , $2\Delta t$, ..., $n \Delta t$ would be predictable. The delay paths as such would correspond to local neural architectures in the brain (e.g. Nelson, 2002; Nedergaard *et al*, 2003; Fellin & Carmignoto, 2004; Bullock *et al*, 2005; Volterra & Meldolesi, 2005; Yamazaki *et al*, 2005). Whatever the effective operational structure of such a resonance circuit, the specific temporal signatures it generates would be experience-dependent and consolidated during development. The database of long-term memory representations from which these temporal signatures arise is updated continuously through non-conscious mechanisms. The conscious experience of an event we perceive as “new” is generated by a temporal resonance pattern that is for the first time activated above the coincidence threshold. Such a pattern is built from a new and unique combination of previously non-conscious long-term and ongoing short-term memory representations.

A brain or system operating on the basis of temporal resonance principles would work as follows. All PRNs would have been primed during brain development to send signals along all delay paths originating from them, and all those receiving a signal coinciding with the next input signal would remain activated. The connections between PRNs of the circuit would thereby be potentiated, as in the classical Hebbian model. Simultaneously, signals travelling from initially activated neurons to connected cells with too long delay paths would be cancelled. Thus, once a given polygon of a resonant network is potentiated along all of its edges, it would reverberate temporally coinciding signals while amplifying resonant connections across populations of resonant neurons within massively parallel neural networks in the brain. This model assumption is biologically plausible in the light of physiological evidence for both intra – and inter-cortical connectivity across large distances in the primate

brain. The representational power of such a distributed temporal code for conscious state generation, after de-correlation from all spatial message contents relating to functionally specified cortical topology, is virtually unlimited. The code neither implies an identity link between the spatial patterns described by an activated subset of PRNs, such as those depicted as an example in Figure 1b, and the temporal firing sequence recorded at any such PRN, nor is there any reason why it should. Whether the nine resonant activity patterns shown in Figure 2 b will trigger a given conscious state is not determined by the spatial activity distribution as such, but by the relative probabilistic weight or, expressed in computational jargon, the synaptic weights of the connections of a given subset of PRNs, of a given temporal activity distribution compared with that of concomitantly active PRNs within large populations of such neurons. Thus, any of the nine different resonant states represented in Figure 2 b would only generate a conscious state if the temporal sequence shown produces resonant activity above a statistical probability threshold. The biological plausibility of such a probabilistically driven temporal code relies on the fact that, in the outside world, some physical events are more likely than others. We may therefore assume that brain events are also governed by probabilistic mechanisms.

Such probabilistic mechanisms ensure both the relative unicity and the seriality of conscious brain events in a competitive race of massively distributed temporal resonances, where the winner takes all, except in very special cases, like that of gradual extinction and a temporarily equal probability of temporal signatures in clinical cases of amputation of body members (Ramachandran & Hirstein, 1998), discussed earlier herein. How neuronal circuits learn statistical temporal information embedded in distributed patterns of activity is demonstrated in the TEMPOTRON model by Gutig & Sompolinski (2006).

4.2. From elementary temporal activity patterns to a dynamic resonant code

Like time-bin resonance itself, the selection of the critical temporal firing patterns that constitute the access code for conscious states would use purely statistical criteria, leading to fewer and fewer consolidated patterns for increasingly complex and integrated signal coincidences as our brain learns and develops. When we are born, all brain activity is more or less arbitrary, not necessarily random. During brain development, temporal activity patterns elicited by events in biophysical time (t) ranging from 30 to approximately 500 ms (as explained above) will be linked to particular conscious experiences in a decreasingly arbitrary manner as frequently occurring codes are progressively consolidated through a process called

‘developmental selection’. This is illustrated in Figure 2, which is our adaptation of Figure 6 from Helekar’s (1999) article. Our model thereby resolves a critical problem with Helekar’s theory, which fails to explain how non-arbitrary linkage of codes and contents would be put into place.

Helekar daringly proposed a genetically determined linkage, which flies into the face of a large body of work suggesting that brain processes are highly plastic and experience dependent, and which may explain why his work did not receive much consideration from the neuroscience communities. A linkage of subjective experience and specific temporal brain activities that would be innate and genetically determined leaves the question of a mechanism for consciousness unanswered. Yet again, we find ourselves confronted with theoretical reasoning in terms of some kind of obscure superstructure. Helekar’s “elementary experience-coding temporal activity patterns” are conceived in terms of some designated subset of neural firing patterns belonging to the set of all possible temporal patterns that can be generated by the brain. His original hypothesis stated that only those patterns that are members of the designated subset would give rise to conscious experiences upon their repeated occurrence. The repeated occurrence of ordinary patterns, which he calls non-coding patterns, would not produce conscious experience. The problem with such reasoning is that the contents we may consciously experience are also represented non-consciously in the brain. Helekar’s assumption that the subjective nature of phenomenal consciousness *per se* is genetically determined leads us right back to the question raised at the beginning: “what is phenomenal consciousness”?

Rather than getting trapped in circular reasoning by invoking a genetic programme, we defend the far more likely hypothesis that a non-arbitrary linkage of the contents of a conscious state and its temporal signature happens progressively and on the basis of developmental processes and brain learning. Once a given temporal signature has been arbitrarily linked to a conscious state, it remains potentially available as a ‘brain hypothesis’, which is then either progressively consolidated, or not. Once consolidated, the linkage of code to content becomes non-arbitrary, or deterministic. The progressive consolidation of linkages happens outside consciousness through the repeated matching of ongoing representations to representations in long-term memory (see Figure 3).

4.3. From temporal resonance to biophysical eigenstates

What distinguishes a conscious state from a non-conscious state in our model solely depends on a statistical criterion. A brain mechanism achieving coincidence computation would lead to the activation of a given temporal resonance code at a given time on the basis of a coincidence threshold. A conscious state arises from a temporarily retrieved resonance state, tagged by a specific temporal signature and generated within reverberating neural circuits that extend across long distances and are updated outside consciousness during lifespan brain development. Thus, what is called “experience” in common language is coded in the brain in terms of signal sequences in purely biophysical time. The statistical coincidence of specific temporal sequences activates, maintains, and inactivates conscious states in the brain like a bar code activates, maintains, or inactivates the electronic locks of a safe. Given the almost infinite number of signal sequences that are possible in such a code, there is no reason why there should not be a unique temporal pattern for a unique conscious state. In terms of quantum physics analogy, the time-bin resonance model suggests that non-conscious states are described by temporal wavefunctions which do not have a well-defined period. While a non-conscious state may be a combination of many non-specific *eigenstates*, resonant activity beyond the probabilistic coincidence threshold produces the well-defined temporal activity pattern or wavefunction of a single specific *eigenstate*, the ‘*conscious eigenstate*’.

5. A few fun-questions for the time-bin model

Specific questions that the time-bin model accounts for include the following:

- 1) How does a conscious state arise from statistical supra-threshold activation of its temporal signature?
- 2) How precise would such a signature be?
- 3) How would it account for the generation of different conscious state levels in anatomically different brain structures?
- 4) How does the biophysical time-bin code take into account variations in the subjectively experienced duration of a conscious state or psychological moment?

5.1. *From the first tune to conscious experience in a concert hall*

From the early days of our existence when nothing we see, feel, or do is conscious, visual, auditory, tactile, and other sensory input from multiple sources is steadily processed and progressively integrated into more and more stable memory representations through the extraordinary capacity of non-conscious brain processes. These representations progressively fill the steadily up-dated database that forms our long-term memory, from the first time we see a face or hear a tune to the moment we start recognizing tunes, pieces of music, and faces and names of performers. At some stage in this process, when there is enough resonant circuitry extending across longer and longer distances in the brain, allowing the increasingly non-arbitrary linkage between experience and temporal signatures capable of triggering conscious state access on the basis of coincidence statistics that have become robust enough, some of these non-consciously integrated representations will become available to conscious experience. When we sit in a concert hall and listen to a symphony by Brahms, we will experience successive mental events during which certain aspects of the symphony, the visual scene, or the person sitting next to us are selectively and momentarily made available to a conscious state. What is selected will depend on how many coinciding, non-conscious memory events relating to previous experiences will produce activity above a certain activity threshold in the dedicated resonant circuits that generate the temporal signatures of conscious states. Whether or not a statistical coincidence threshold is attained may be under the influence of top-down attention or volition, causing top-down amplification as suggested by Dehaene *et al* (2006), or it may be determined by non-conscious resonant processes, which is likely to be the case in daydreaming or in lucid dreams during REM sleep phases, which are considered mental states equivalent to conscious states.

When a conscious state is triggered, we become for a short moment able to take stock of past events and to project events into the future. This ability reflects the time-ordering function of consciousness. It allows humans to plan and to read sense into their lives. Sometimes when we are conscious, we may be under the impression that what we experience looks or feels new, although we have seen or felt the same many times before. Conversely, when we find ourselves in a new situation, a conscious experience may leave us with the feeling that we have “been there before”, or that “this has happened before”. Such impressions are readily explained by the statistical nature of the temporal access code for conscious states, as proposed here.

5.2. *Apparent novelty and 'déjà vu'*

Subjective impressions of novelty or 'déjà vu' would result from the fact that the temporal signatures of conscious states represent a code that is based on statistical likelihood, not on the exact replication of an identical signature when two identical contents are experienced. In fact, a brain hypothesis relating to a physical event can never be more than a best guess. This entails that two identical contents of conscious states are never experienced in exactly the same way, in the same way as two entirely different contents may well leave us with an impression of 'déjà vu'. As explained in our model assumptions above, there is no reason why the temporal resonant code of conscious states would have to be perfectly accurate; a code generating a statistically robust signal or pattern coincidence thresholds is sufficient. This idea of an approximate code is consistent with the hypothesis of a multiple realizability of conscious states.

5.3. *'Multiple realizability'*

Rather than assuming that there would be a unique physiological state of the brain for every unique mental state, philosophers such as Lewis (e.g. 1983) have argued that the idea of different physiological or physical life-forms being in a same mental state without being in the same physiological or physical state would be the far more plausible hypothesis. The latter has been termed 'hypothesis of a multiple realizability of mental states'. As mentioned earlier, there are certainly enough possible signal or pattern combinations to ensure the generation of a unique temporal signature for a unique conscious state. We do believe, however, that a brain code working with such a degree of precision is, indeed, unlikely. Our own view consists of thinking that brains with a different level of physiological development, different overall number of neurons, spatial functional topology, and inter-connectivity should be able to generate temporal signatures that trigger equivalent, not necessarily identical, conscious states in different species. This should be possible on the basis of resonant circuitry with various different intrinsic topologies and statistical activation thresholds far less robust than those established on the grounds of a body of brain data as large as that which reflects a human lifelong experience. Whether such conscious states would give rise to equivalent qualitative experience or *qualia* is, however, uncertain. What is relatively certain, in our view, is that conscious brains become connected with the physical world in the course of their development, and that the latter is to be conceived in terms of an continuous process.

5.4. The conscious brain and psychological time

In a way similar to that of sonar systems which connect to the outside by acquiring some form of knowledge of a physical environment, conscious states appear to be encoded in our brains in terms of critical temporal base frequencies as through scanning or pulsing. Although a conscious state may be experienced in any form of psychological space-time, the associated biophysical periods in the brain ‘scale’ this experience through a completely self-sufficient code. This explains how the inner clocks of consciousness can operate independently from spatial, verbal or any other form of cognitive or emotional experience. The brain would thus be able to detach itself from the subjective nature of conscious experience, from what may seem “exciting” or “boring” to us, with time “flying by” or “standing still”. While we are in a conscious state, imprisoned by the events we are experiencing, the brain is scaling signals related to these temporarily available events in purely biophysical time (see Figure 5).

6. Conclusions

Dresp-Langley and Durup's (2009; 2012) concept of a biological access code to consciousness directly addresses the mind-body problem by suggesting that a conscious mental state is a dynamic result of the progressive, life-long development of the brain, as previously suggested in Grossberg's earlier theories, and clarified in greater detail in the most recent developments (Grossberg, 2017). Some time ago, Nagel (1974) insisted that, in order to understand the hypothesis that a mental event is a physical event, we require more than the understanding of the word ‘is’. His comment directly relates to identity theory (e.g. Feigl, 1958; Gray, 1971), a class of mind-body theories which reject dualism by considering two possibilities, or hypotheses, of identity between a mental state and a physiological state. The first is type identity, where mental states themselves would be physical states, the second token identity, where mental states would be the direct reflection of a physiological or physical state. Our own model assumptions quite evidently would not sustain the type identity claim. Without even beginning to suggest that the theoretical approach proposed here solves the “hard problem of consciousness”, we claim that it nevertheless successfully addresses a fundamental problem recently discussed by Block (2007). Since phenomenal consciousness exceeds cognitive accessibility, we believe that a first step would be to propose a brain theory that dissociates conscious cognitive performance from conscious experience. Our suggestion of a purely temporal signature for conscious states achieves this by explaining how such states may arise from temporal resonance of memory signals in the absence of any stimulus input or

ongoing cognitive activities related to perception, attention, or conscious report. Also, we believe that in the light of our theory it may become a little clearer how brain mechanisms could explain what the German philosopher Martin Heidegger discussed in his writings on "*Being and Time*" (*Sein und Zeit*, 1927): the fact that the contents of any given conscious experience are grounded in past ones and, in a single moment in time, contribute to shaping those we are to experience in the future.

Thus, as Nagel (1974) pointed out, we are to go beyond the word 'is' when it comes to trying to explain consciousness. We adhere to this point of view, and prefer not to consider the mind-body problem in terms of any kind of identity link. In our own view, the relation between mind and brain is governed by processes that are essentially dynamic, which is difficult to reconcile with any theory that claims an identity link between a mental state and a brain state. The links between a conscious state and a physiological state are most certainly determined by probabilistic mechanisms, they are more of a transient nature than of a sustained one, and they tend to be plastic rather than fixed. This plasticity is biological by nature and the human mind would not be able to function without it. Although social pressure may drive human consciousness in certain directions rather than others at a given moment in time, the claim that the human mind would be an artefact of such pressures is not only unsubstantiated but ignorant of the neurobiology of what Grossberg in some of his finest work referred to as "the adaptive brain".

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