Cogn Neurodyn
DOI 10.1007/s11571-017-9450-4

RESEARCH ARTICLE

# Relationships between short and fast brain timescales

Eva Déli[1] · Arturo Tozzi[2] · James F. Peters[3,4]

Received: 10 April 2017 / Revised: 22 June 2017 / Accepted: 16 August 2017


**Abstract** Brain electric activity exhibits two important features: oscillations with different timescales, characterized by diverse functional and psychological outcomes, and a temporal power law distribution. In order to further investigate the relationships between low- and high- frequency spikes in the brain, we used a variant of the Borsuk–Ulam theorem which states that, when we assess the nervous activity as embedded in a sphere equipped with a fractal dimension, we achieve two antipodal points with similar features (the slow and fast, scale-free oscillations). We demonstrate that slow and fast nervous oscillations mirror each other over time via a sinusoid relationship and provide, through the Bloch theorem from solid-state physics, the possible equation which links the two timescale activities. We show that, based on topological findings, nervous activities occurring in micro-levels are projected to single activities at meso- and macro-levels. This means that brain functions assessed at the higher scale of the whole brain necessarily display a counterpart in the lower ones, and vice versa. Our topological approach makes it possible to assess brain functions both based on entropy, and in the general terms of particle trajectories taking place on donut-like manifolds. Condensed brain activities might give rise to ideas and concepts by combination of different functional and anatomical levels. Furthermore, cognitive phenomena, as well as social activity can be described by the laws of quantum mechanics; memories and decisions exhibit holographic organization. In physics, the term duality refers to a case where two seemingly different systems turn out to be equivalent. This topological duality holds for all the types of spatio-temporal brain activities, independent of their inter- and intra-level relationships, strength, magnitude and boundaries, allowing us to connect the physiological manifestations of consciousness to the electric activities of the brain.

✉ Arturo Tozzi
tozziarturo@libero.it

Eva Déli
eva.kdeli@gmail.com

James F. Peters
James.Peters3@umanitoba.ca

[1] Institute for Consciousness Studies (ICS), Benczurter 9, Nyíregyháza 4400, Hungary

[2] Center for Nonlinear Science, University of North Texas, 1155 Union Circle, #311427, Denton, TX 76203-5017, USA

[3] Department of Electrical and Computer Engineering, University of Manitoba, 75A Chancellor's Circle, Winnipeg, MB R3T 5V6, Canada

[4] Department of Mathematics, Adıyaman University, 02040 Adıyaman, Turkey

**Keywords** Quantum mechanics · Quantum cognition · Consciousness · Brain frequencies · Emotion regulation · Behavioral neuroscience · Borsuc Ulam theorem

## Introduction

Animals enhance their access to information—thus chances of survival—via the sensory system. The sensory organs are information grabbing machines; seeing further, smelling keener enables animals to gather nutrients (i.e., expanding time) and avoid physical dangers (i.e., time compression), an effective time machine that can lead to the relativity of time perception (Fingelkurts and Fingelkurts 2014). Interaction through sensory stimulus corresponds to energy-information exchange. The path, rhythms, extent and other physical qualities of brain frequencies are finely regulated and turn the brain into a complex, yet subtle system. But the central nervous system is much more than a finely-regulated circuit board. Electric flows generate associations, meaning and memory in ways reminiscent of quantum networks. Quantum theory became a mainstream, accepted scientific idea for modeling mental phenomena (Khrennikov 2016) and the mind's quantum-like behavior is exploited in fields as diverse as search-engine optimization, psychology, economy, and sociology—in some cases for nearly a century. More than 70 recent national surveys, which examined the order effect of successive attitude questions, found quantum probability theory an impeccable predictor of human judgement (Wang et al. 2014). In quantum systems, outcome is highly dependent on the context of measurement and likewise, almost all cognitive processes, such as memory, decisions and perception, have contextual nature (Busemeyer and Bruza 2012). Therefore, quantum probability theory, which was invented to explain noncommutativity of measurements in physics, provides simple and surprisingly accurate predictive power in studying order effects in social and behavioral science (Brembs 2011; Nikolov et al. 2015; Pothos and Busemeyer 2013; Wang et al. 2014). In the brain, the appropriate temporal order of the cortex neuronal activation pattern triggers corresponding memories or experience, and forms a "temporal horizon". Reminiscent of the observer effect in quantum mechanics, the quantum-like evolution of the brain maintains the unity and permanence of the mind. Measurement (interaction) actively modifies the particle being measured, and in the brain it corresponds to cognitive change. The mental world is sectioned into a stable, stepwise progression of perception or learning, such as the empowering moment of riding a bike for the first time. This is the same for recognition, getting a joke, or meeting a friend. There is a moment of inspiration (loss, shame or fear), when a new balance is formed and understanding clicks. In line with this observation, it has been suggested that conscious awareness necessarily demands mental content being held "fixed", "frozen" within a discrete but continuous progressive present moment that stands for a phenomenal unity (Fingelkurts and Fingelkurts 2014). This occurs because spatial relationships, encoded in sensory stimulus, are translated into temporal rhythms, an orthogonal organization, by the place cells of the hippocampus (Ventriglia 2014). The brain's gradually improving responses to stimuli molded brain organization into the structural, organizational mirror of physical systems. Therefore, social interaction engenders particle-like features, such as uncertainty, hysteresis and territorial needs by the Pauli exclusion principle, which states that two fermions (pieces of matter) cannot be located in the same place.

The principle of static time shows that, by the standpoint of a hypothetical observer external to our Universe, the global cosmic structure is static and lacks temporal evolution (Moreva et al. 2013), hence changes remain local. In the brain, activation by stimulus is transient, because the global charge neutrality (i.e., the default mode network, DMN; we will discuss later about it) is automatically recovered via self-regulation (Deli 2016). Thus, the brain's global structure ensures stable personality throughout life, in spite of constant interaction with the environment. The brain transfers sensory stimulus via complex electromagnetic flows to the cortex, where a meaningful response is formulated and carried back by the same electromagnetic means. A constant flux of local electromagnetic potential differences in the complex neural landscape of the brain vary according to the principle of least action, but the resting brain's recurring electromagnetic activities form a highly reproducible harmonic function (Atasoy et al. 2016) that takes the form of a four dimensional hypersphere, in which toroidal oscillations (where two antipodal particles cannot never meet or become closer, due to their recurrent rotations) give rise to repetitive patterns of movements, thoughts, or memories (Tozzi and Peters 2016a). The coherent fluctuations in the spontaneous activity of the DMN show high metabolic rates and blood flow at rest, but deactivate when specific goal-directed behaviour or cognition is needed (Damoiseaux et al. 2006). Even in the absence of synaptic or anatomical connectivity, the DMN displays great autonomy and complexity, indicating its essential role as the ground state of the brain (Tozzi et al. 2016). Spontaneous fluctuations have been observed not only in electric activity, but also in various haemodynamic and metabolic parameters, as well as spontaneous fluctuations in the membrane potential, spontaneous spikes and neurotransmitter release (Kavalali et al. 2011; O'Donnell and Van Rossum 2014). In contrast, highly organized oscillation patterns, which reduce the degrees of freedom, are closely tied to specific mental activities, such as sensory processing (synfire chains, Abeles 1991).

The entropic consequence of energy-information exchange has been recognized by Landauer's famous principle. Hence, information accumulation in the brain, which is typical of sensory activation, corresponds to high entropy (Tozzi and Peters 2017). Sensory processing requires energy, which is satisfied by enhancing the oscillation frequencies in the brain. This information-energy relationship permits the consideration of cognitive processes based on thermodynamics, and ties mental operation into the general energy cycle of the physical environment—independent volition. Sensory information flow toward the cortex is an inextinguishable, pressing barrage of enhanced frequencies which activates the sensory cortex, which turns sensory information processing instinctive and involuntary. For example, reading and comprehending signs or deciphering stimuli occurs automatically, without conscious intent and the musicality of a familiar tongue cannot be perceived. However, the brain's access to information by sensory perception is imperfect and limited (Pakhomov and Sudin 2013). Sensory flow is also inversed from left to right and upside down in the brain stem, which projects a small, upside-down image onto the back wall of the cortex. Sensory operation therefore is analogue to a camera obscura. The camera obscura (from Latin *vaulted darkened chamber*) is a box with a small opening or pinhole, which reflects a small, reversed image projected onto its back wall (Deli 2016; Peters 2017). Thus the brainstem effectively isolates the brain from its environment, and formulates an independent, inner world of the mind with its highly personal and subjective nature of experience, memories and ideas. The momentary projection of the temporal manifold depends on both the viewer and the self. The constantly changing, complex and elaborate mental world can only be accessed from the inside; for outside observers it is a holographic projection, which however appears strangely constant from childhood to old age.

In sum, we investigate the relations among nervous activities occurring in micro-, meso- and macro-levels of observation, in order to build a new hypothesis of consciousness and mental operation based on topological and quantum-like formalism. The electrical activity in the brain generates brainwaves, in which the low- and high-frequency bands determine opposite energy-information flows (Atmanspacher and Rotter 2008) that stand for the antipodal energetic poles of the brain's operational regulation by the Borsuk–Ulam theorem. Then we demonstrate that slow and fast nervous oscillations mirror each other over time via a sinusoid relationship, providing the possibility to link the two timescale activities through the Bloch theorem. Hence, cognitive phenomena, as well as social activity can be described by the laws of quantum mechanics, while memories and decisions exhibit holographic organization. The goal of this paper is to build a comprehensive theory that describes the operation of the mind, allowing us to connect the physiological manifestations of consciousness to the electric activities of the brain.

## Materials and methods

### Physical foundations

The classical view of a particle is point-like; however, in string theory it is a 1-dimensional object, which is considered the basis for consistently describing all of nature. In string theory, particle vibrations are motions of loops within a Calabi–Yau manifold, where field curvature changes are recorded by a holographic organization of a multidimensional waveform. This is also true in the mind. In the brain electromagnetic activity is often appears multidimensional. For example, resting state activity circumscribes a four dimensional hypersphere (Peters et al. 2017), in contrast to the three spatial dimensions of the physical world. Since the constantly changing cortical projection can be replayed repeatedly, past experiences inform present behavior and lead to far superior response. The mind also shows essential unity, which was recognized in philosophy well before science has investigated this question. A feeling of oneness with the body emerges from detailed representation of the body, via multiple sensory organs, in the brain (Guterstam et al. 2015), which gives rise to a single, unified experience. Conscious perception is never fractured: ambiguity forces a non-deterministic, quantum-like fluctuation between two possibilities (images, ideas, or concepts); for example, only one view of the Necker cube can be perceived at any one time. Indeed, although we can contemplate many possibilities, once we decide on a problem all other options cease to exist.

The non-intuitive and multifarious nature of mental operation, first proposed by philosophers and sages over the millennia of human civilization, can be successfully modeled by quantum probability (Brembs 2011; Pothos and Busemeyer 2009). The label "quantum" comes from that, in contrast with classical mechanics, certain quantities take on only discrete values. In quantum mechanics, particles have wavelike properties, and the Schrodinger equation governs their behavior. But quantum mechanics cannot predict with certainty the outcome of a simple experiment; it can only offer statistical information about the possible results. In contrast to classical systems, where measurement merely observes a preexisting quality, quantum measurement entails decoherence, which actively changes some property of the system being measured. Probabilistic assessment is often strongly context and order dependent, and individual states can form entangled, composite systems. Remarkably the same principles, that measurement corresponds to cognitive change (i.e., decoherence), appear to apply to the mind as well. Since human behavior is notoriously unpredictable, only statistical information can be gained about political views, shopping, or any other decision making activity. In the brain stimulus sparks oscillations that cross successive regulatory layers in their way to the neocortex and generate a response that restores the resting state of the brain and leads to discrete energy processing, which endows the mind with quantum characteristics.

The brain's identification with the body forms the basis of a homeostatic self-regulation (Guterstam et al. 2015). The mind is a cacophonous sensory kaleidoscope, peppered with transient ideas and possibilities that distill into a single decision or understanding. Even divergent sensory perception and confusing, chaotic information load coalescence into a unified experience, decision or memory. Festinger's cognitive dissonance theory (1957) shows that cognitive or emotional discrepancy can force mental change, potentially even sacrificing core beliefs, in order to restore mental congruency. The constancy of self becomes particularly apparent when changes, even dramatic ones, affect the body or the brain. Such constancy turns the mind surprisingly particle-like, where ideas and thoughts form a highly fluid, malleable mental background, which is founded in electric activities of the brain and over which sensory interaction with the outside world becomes possible. Hence, we investigated the relationship between the background, resting activities to sensory activation in the brain.

## Brainwaves: stimulus builds on the DMN

The prescient experiments of Libet (1985) have shown that volition show close correlation to the brain's background electrical fluctuations. However, cortical areas are universal processors tuned not so much for particular sensory modality, but rather for particular algorithms of incoming information processing (Pigarev and Pigareva 2015). During stimuli-evoked activity or cognitive demands, the brain transitorily exhibits functional conformations—other than the spontaneous ones—,which are linked with specific psychological correlates (Cole et al. 2014). The high frequency activity has been correlated, i.e., with perceptual binding and feedback/feedforward waves which improve the perception of external inputs (Buzsaki et al. 2013). The (environmental and internal) inputs cause changes in spike frequency in diverse cortical areas: the brain thus exhibits a high number of possible source configurations, such as gamma oscillations in somatomotor cortex during states of enhanced vigilance, or alpha waves in posterior zones with eyes open, and so on (Bastos et al. 2015). The resting modules form spatiotemporal symmetry vis-à-vis the primary sensory regions of the brain, indicating an organizational relationship between resting and evoked activities. To verify this idea, we have examined the relationship between low and high oscillations in the brain. Brain activity observed at both low and high temporal scales exhibits a $1/f^{\alpha}$-like power spectrum (He et al. 2010), including not just macroscopic electric oscillations, electroencephalography, magnetoencephalography and functional magnetic resonance imaging signals (He 2014), but also microscopic membrane potentials and fluctuations in neurotransmitter release (Milstein et al. 2009; Linkenkaer-Hansen et al. 2001). In particular, the temporal frequency spectrum of cerebral electric activity displays a scale-invariant behaviour $S(f) = 1/f^{\alpha}$, where *S(f)* is the power spectrum, $f$ is the frequency and $\alpha$ is an exponent that equals the negative slope of the line in a log power versus log frequency plot (Bakouie et al. 2017; Van de Ville et al. 2010; Pritchard 1992). Pink noise can be regarded as an intrinsic property of the brain characterizing a large class of neuronal processes (Fraiman and Chialvo 2012; He et al. 2010), suggesting the possibility that power law distributions contain information about how large-scale physiological and pathological outcomes arise from the interactions of many small-scale processes (de Arcangelis and Herrnann 2010). The emergence of power law distributions in the brain has been also correlated with the spontaneous appearance of high frequency neuronal avalanches (Beggs and Timme 2012). Therefore, both slow and fast oscillations are equipped with a power law structure.

The Borsuk–Ulam Theorem (Borsuk 1933) points out that, if a sphere $S^n$ is mapped continuously into a*n*-dimensional Euclidean space $R^n$, there is at least one pair of antipodal points on $S^n$ which map onto the same point of $R^n$. The notation $S^n$ stands for an n-sphere, which is a generalization of the circle (Weeks). An $n$-sphere is a n-dimensional structure of constant curvature, embedded in a convex $n + 1$ space. For example, a 2-sphere ($S^2$) is the 2-dimensional surface of a 3-dimensional ball (a beach ball is a good illustration). Examples of antipodal points are the poles of a sphere (Matoušek 2003). Tozzi and Peters (2016b) provide a mathematical treatment for technical readers.

The concept of antipodal points (also regions) can be used not just for the description of simple topological points or regions, but also of more complicated features, such as shapes of space (spatial patterns, i.e., area and diameter), of shapes of time (temporal patterns), vectors or tensors, functions, signals (Borsuk 1958–1959; Borsuk 1969; Peters 2016). If we simply evaluate systems activity instead of "signals", BUT leads naturally to the possibility of a region-based, not simply point-based, geometry. We are thus allowed to describe systems features as antipodal points on a $n$-sphere. If we map the two points on a $n-1$ sphere, we obtain a single point. This means that signal shapes can be compared (Weeks 2002; Peters 2016): the two antipodal points standing for systems features are assessed at one level of observation, while the single point at a lower level (Tozzi and Peters 2017). The BUT can be used not just for the evaluation of antipodal, but also of non-antipodal points on an $n$-sphere. We can consider regions on an $n$-sphere that are either adjacent or far apart (Tozzi et al. 2017a, b). And this BUT variants applies, provided there is a pair of regions on $n$-sphere with the same feature value. Therefore, the two points (or regions) do not need necessarily to be antipodal, in order to be described together (Peters 2016). This makes it possible to evaluate matching signals, even if they are not "opposite", but "near" each other: the antipodal points restriction from the "standard" BUT is no longer needed. Although BUT was originally described just in case of $n$ being a natural number which expresses a structure embedded in a spatial dimension, nevertheless the value of $n$ can stand for other types of numbers. The $n$ value of $S^n$ can be also cast as an integer, a rational or an irrational number (Tozzi and peters 2016b). For example, we might regard functions or shapes as embedded in a sphere in which $n$ do not stand for a spatial dimension, but for a fractal one. This makes it possible to use the $n$ parameter as a tool for the description of nervous power laws.

Psychological findings greatly support the notion that the mental state and its beliefs play a crucial role in perception, motivation and choosing ones goals. For example, cholinergic modulation alters vigilance, by changing the quenching threshold, which determines the neuronal storage of activity pattern (Palma et al. 2012). Below a certain threshold inputs are suppressed as noise, and neural coding of the features occurs above it. Also, gamma-band activity in the alert monkey is largely an emergent property of cortex from the resting state waves (Bastos et al. 2014). Changes in slow oscillations modify fast oscillations and, inversely, incoming stimulus modifies the energy level of the resting state. Because higher energy base-level activity of the resting state might give rise to focused or stressful response, the brain's resting state determines the response's frequencies to stimulus and mental interaction is founded on the DMN (Tozzi et al. 2016).

## Brainwaves: the role of oscillations in consciousness

Meijer and Geesink (2016) noticed how the particular spectrum of frequency bands point towards nature employing discrete eigenfrequencies or standing waves that match precisely with an acoustic scale, with sharp frequency ratios. Their findings touch upon the science of acoustics also, since they showed that the discrete frequencies could be modeled by music torus geometry. Geesink and Meijer (2016) proposed, based on an extensive literature survey, a hypothesis of a mathematical algorithm for coherent quantum frequencies, that may create stability of biological order. Their data point towards typical, discrete, coherent frequencies of electromagnetic waves able to stabilize or de-stabilize cells. This also stands for the central nervous system: electrical activity in the brain formulates a "wave-like" pattern, the so called brainwave, with a mean action potential rate of 4 Hz (Sengupta and Stemmler 2014). It is also thought that the greater and lower oscillations are associated with unrelated functional activity. Namely, the slow cortical activities correlate with spontaneous brain activity, the DMNs and the unconstrained, conscious cognition (i.e., mind-wandering or day dreaming propensities) (Christoff et al. 2016) or the dreaming state (Fox and Raichle 2007). In turn, during stimuli-evoked activity or cognitive demands, the brain transitorily exhibits functional conformations, which are linked with specific psychological correlates, such as sensory processing, perceptual binding and feedback/feedforward waves which improve the perception of external inputs (Patel et al. 2013) or negative emotional states (Seo et al. 2008; Zeeman 1976). The DMN, i.e., functionally and structurally connected regions show high metabolic activity and blood flow at rest, but deactivate when specific goal-directed behaviour or cognition is needed (Damoiseaux et al. 2006). In the brain, the direction of information (energy) transfer in the limbic structures is highly dependent on frequency; neocortical-limbic transfer occurs during slow theta waves (4–10 Hz), and data transfer reverses during gamma frequencies (30–130 Hz), among others. Low brain frequencies increase the degrees of freedom, forming complexity of higher dimensionality; whereas high brain frequencies are more deterministic and therefore allow fewer degrees of freedom and lower dimensionality (Buzsaki et al. 2013; Mazzucato et al. 2016). Since high frequencies serve sensory processing and other information enriched states, they can be considered high entropy states. In contrast, the increased degrees of freedom of the resting state might correspond to low entropy and permits the consideration of the brain energy-information cycle based on entropic considerations.

The energy need and information carrying capacity of brain waves is proportional to their frequencies. Since low- and high-frequency bands determine opposing energy-information flow, they can be considered as opposite energetic poles of the brain's operational regulation. The relationship between the low and high frequencies in the brain and the energy-information flow or direction (Fig. 1) allow us to represent scale-free brain frequencies as a sinusoid curve (Fig. 2), where the high and low frequencies appear to be energetic mirrors of each other. The Planck–Einstein relation expresses the correlation between energy (information) and the frequency (ν): $E = h\nu$. The high energy need of enhanced brain frequencies curtails the volume of vibrating brain tissue (the biological limit of timely energy supply), limiting the capacity for information transmission (Fig. 2, indicated by #1), whereas the rate of energy transmission approaches zero during the lowest frequencies (Fig. 2, indicated by #3). The inverse relationship of energy-information transmission leads to a power-law distribution between frequency bands (Penttonen and Buzsaki 2003). However, our account uncovers a deeper reason for the regulation and power law of electromagnetic activity in the brain: the principle of least action. Since the energy need, and the ability to transmit

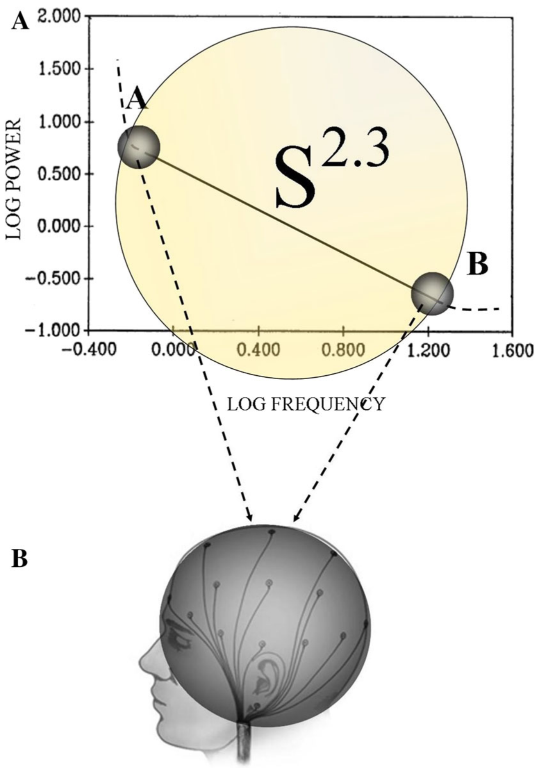


**Fig. 1** **a** Log amplitude versus log frequency scatter plot of brain spikes detected by EEG techniques (modified from Pritchard). The Figure displays on the *x* axis the frequency (in Hz) and on the y axis the power (in $\mu V^2$) of the electric spikes. Note that the scale is logarithmic: it means that on the *x axis*, for example, $-0.400 = 0.39$ Hz, $0 = 1$ Hz, $0.4 = 2.52$ Hz, $1.2 = 16$ Hz and so on. In turn, on the y axis, $-1.000 = 0.1\ \mu V^2$, $-0.5 = 0{,}32\ \mu V^2$, $0.000 = 1\ \mu V^2$, $1.000 = 10\ \mu V^2$, and so on. The figure also depicts a fractal dimension, in this case equipped with the slope $\alpha = 2.3$. The BUT now comes into play: the *black circles* A and B, which respectively depict power laws at low- and high- brain frequency, stand for two antipodal points with matching description, embedded in a n-sphere with fractal exponent α (in this case, 2.3). Note that the Borsuk–Ulam theorem is not valid at the slope's tails, where the α exponent is lost (*dotted lines* on the *right* and *left* of the main slope). **b** The total fractal activity detected by different functional neurotechniques stands for the projection of the two antipodal points on a $n-1$ -manifold. A head mounted EEG is showed for sake of simplicity

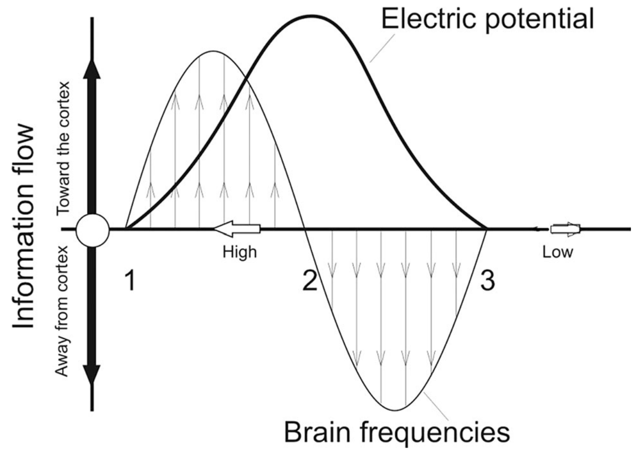


**Fig. 2** The brain's changing energy balance due to stimulus over time (between the frequencies 1, 2 and 3). The brain frequencies change from high, on the *left* (#1), to low, toward the *right* (#3) and determine the direction of information flow in the brain (shown by *thin line*). The potential difference between the cortex and the limbic brain is indicated by *thick line*. The brain is energy neutral before stimulus (#1) and after a response (#3), but stimulus induces a potential difference between the cortex and the limbic brain (indicated by *2*). The high energy need of enhanced brain frequencies curtails the volume of vibrating brain tissue, limiting information transmission capacity (indicated by *#1*), whereas the energy transmission capacity disappears during the lowest frequencies (indicated by *#3*). Cortical activation extinguishes the energy of the stimulus (#2), but it generates apotential difference, which initiates a flow reversal that recovers the DMN (#3)

information are proportional to the frequencies, the occurrence of higher frequencies in the brain dynamics decreases exponentially, but the occurrence of slow waves exponentially enhances. Their combined effect leads to power law of the brain's electromagnetic spectrum (Penttonen and Buzsaki 2003). The high energy need of enhanced brain frequencies curtails the volume of vibrating brain tissue, limiting its information transmission capacity, whereas the rate of energy transmission approaches zero during the lowest frequencies. As a consequence, the frequency-power relationship breaks down at both extremities and the curve develops a tail on both ends, shown by dotted lines on the right and left of the main slope (Fig. 1a).

There is a rough positive correlation between brain size and animal size. However, thecerebrum's modular structure in birds is inefficient for growth, which effectively curtails the size of their brains. Neurons organize in microcolumnar layers in the mammalian cortex; a structure that can easily expand with growing brain size. During mammalian evolution, this organizational flexibility permitted a big expansion of brain, and consequently body size. Although four orders of magnitude separate the brain size of shrews from that of whales, the typical brain frequencies have remained astonishingly constant. Only the theta band, which is lower in humans (1–4 Hz) than in small animals such as rodents (6–10 Hz), shows notable difference (Buzsaki et al. 2013). Although axons with large conduction velocity facilitate information transmission, the remarkable evolutionary stability of brain frequencies across mammalian evolution with enormous differences in body size, brain size, and intellectual abilities is not understood. Even in the absence of stimulus, the connectome excitatory–inhibitory interactions produce harmonic functions. A parallel between brain oscillations and sound waves produced in a musical instrument, vibrations in a metallic plate, or electron wave function of a free particle given by the time-independent Schrödinger equation, have been proposed (Atasoy et al. 2016; Deli

2015, 2016). As harmonic oscillations emerge in physical systems in response to outside stimulus, in the brain seemingly reflecting the varied history of stimuli, wave form in the brain does not appear until 34th week in the fetus. For example, in instruments fitted vibrations, so called standing waves produce sound. The longest wave is called the fundamental, while multiple waves produce overtones. We propose that electromagnetic oscillations form in the brain in a similar vein. Just as a particular instrument can be recognized by its individual sound, brain oscillations (particularly in the lower-frequency range, which are produced by greater brain volume) are presumably fundamental and thus characteristic of the topographical shape and volume of the cortex. Thus, the frequencies can be considered the universal notes for the functioning brain. Just like in wind instruments, the higher notes are produced by reducing the vibrating volume; higher frequencies are produced by activating a smaller region of the brain's modular structures. In a musical instrument a standing wave is the result of the wave reflecting off the end of the tube and interfering with itself. In the brain the oscillations are reflected off the cortical surface. Neuronal activation on the cortical surface absorbs and extinguishes the energy of brain oscillations and forms standing waves between the limbic area (where the brain frequencies are spontaneously generated) and the cortical surface. Keeping the fundamental and overtones frequencies constant requires exact volume (or constant surface-volume ratio). However, brain volume increases as the radius cubed, whereas the cortical surface increases as the radius squared. As with wind instruments, in which the length is changed to modulate the sound, the evolutionary stability and universal regulatory code of brain frequencies is ensured by the increase of the cortical surface (area and/or square root of thickness) as the third power also. (Very small mammals, where the cortex does not fully surround the limbic brain, form exceptions.) The packaging of the disproportionally increasing cortical surface led to convolution, the formation of gyri and sulci, which inadvertently produced a more robust cortex. Indeed, the most convoluted cortices can be found in animals with the biggest brains, such as elephants and cetaceans. The linear relationship between the limbic and cortical region was overlooked in the recent study by Mota and Herculano-Houzel (2015), probably, by failing to account for the thick cortical mass of cetaceans (a substantial addition to limbic mass) in calculations. Because experience can accumulate in the immensely complex neuronal connections of the cortex, the folded cortical structure inadvertently enhances mental abilities, such as information processing, memory, and learning (Deaner et al. 2007). To face new challenges, old associations can be reconnected in a novel way. The complexity, convolution, and overall size of the neocortex of large mammals enable them to form close-knit, stable social groups based on compassion and kinship.

## Interaction

The brain regulates itself by energy and charge conservation laws. Brain frequencies activate cortical assemblies of neurons, which generate a response and restore the brain's resting, equilibrium position (Mantini and Vanduffel 2013; Raichle and Snyder 2007). Thus oscillations can be viewed as a spring that moves energy (or information) in the form of electric current between the cortex and the limbic brain. The innate drive toward low entropy leads to a subtle regulation by the continuous and pervasive electromagnetic flows of the intact brain, giving rise to inexplicable, mysterious and highly involuntary mental processes. Bounding the space of holographic CFTs in string theory with complex systems has been shown recently (Perlmutter 2016). The importance of low entropy, corresponding to complexity, has been recognized in biology, evolution, aging (Lipsitz and Goldberger 1992), technological development (Levy 1994), innovation (Poutanen et al. 2016) and other fields. In the mind the spatial relationships of the physical world is replaced by an orthogonal "temporal horizon" of memories or experience. Temporal crystals have been created in the laboratory (Zhang et al. 2016), which allows us to conclude that such topological duality might holds for spatio-temporal brain activities also, independent of their inter- and intra-level relationships, strength, magnitude and boundaries. The brain frequencies determine the energy direction, neocortical-limbic transfer occurs during slow waves (positive emotions), and data transfer reverses during high frequencies; increasing frequencies are deterministic, generate excessive details and waste energy. High frequencies lead to painful and constricted feeling, which seems to last longer, as time *perception lengthens*, leading to impatience, called stress (Fredrickson and Joiner 2002; Yamada and Kawabe 2011). Amazingly, this is true even for unconscious stimuli (Oei et al. 2012). The detailed, deterministic oscillations narrow focus, reduce the degrees of freedom, illuminate differences, and lead to critical tendencies (Lupien et al. 2007). Such information accumulation therefore increases entropy and corresponds to a lack of confidence, which reduces trust, causing uncertainty, missed opportunities and failures. In contrast, energy accumulation in the brain is characterized by lack of details, allowing associative representations to emerge, producing confidence, trust, and belief. The willingness to work hard for rewards, even in cases of low probability of payout, is typical for a mind with high mental energy (Schultz 2007; Treadway et al. 2012). Trust and belief is the perception of temporal excess that encourages a patient, powerful, happy, and therefore satisfied mental state, which turns ambiguous situations into successful, positive outcomes. The connection of slower oscillations with positive emotions, and enhanced brain frequencies with negative mental states has been corroborated in numerous studies (Bethell et al. 2012; Seo et al. 2008; Rudd et al. 2012). Emotions engender actions that modify the neuronal connections (modulating the mental energy), keeping them in constant flux that changes, modifies their meaning. In this way, the mind forms standing waves that are true to the local field. Such sophisticated homeostatic regulation based on entropy allows mammals and birds to be warm blooded, form the mysterious inner world of consciousness, display impressive learning ability and develop complex social life (McNally et al. 2012).

As the energy requirement of neuronal activation gradually extinguishes the information flow, it gives rise to an electric potential difference between the limbic and cortical areas, which reverses the flow via slow oscillations (Fig. 2, #2). The information flow reversal from the frontal toward occipital direction, and back toward the limbic region recovers the low entropy DMN. The sensory transmission toward the sensory cortex by fast oscillations and response by slow oscillations was confirmed in humans (Buzsaki et al. 2013), but should be typical in all mammals. Liu et al. (2015) examined the effects of high (40–100 Hz) and low frequency stimulation of rat central thalamus relay neurons in vivo. High frequency application caused widespread forebrain activation, whereas low brain frequency stimulation generated a jerking strain, possibly even convolution (Liu et al. 2015). The finding shows that electromagnetic flows in the brain correspond to energy-information exchange and polarity effects in normal brain's operation. Through long-term potentiation (Bliss and Lomo 1973) enhanced brain frequencies decrease the degrees of freedom by accumulating information (i.e., reducing trust) in the brain. Hence, normal social functioning depends on an abstract mental world of the resting state of the brain.

## The unique and holographic nature of experience: the Bloch wave

A recent surge of publications examine the brain as a complex physical system, in which resting potential is characterized by a recurrent, highly reproducible harmonic function between the major modules of the brain (Atasoy et al. 2016; Peters et al. 2017; Tozzi et al. 2017b). Changes in extracellular parameters, regulated by information transmission, can be related to long-range nervous interactions and flows (Touboul 2012). Hence, quasi-neutral state can be described with slow to moderate electromagnetic fields and forces, which give rise to fast and slow brain oscillations. The local changes generate spatial currents which modulate ion flows (Pereira 2017), and in the brain electric potential differences between different modules give rise to oscillations that carry information, as globally coherent, large-scale waves in the delta, theta, alpha and beta bands that propagate with a variety of velocities. Their mean speed at each frequency band is proportional to temporal frequency, giving a range of 0.06–4.0 m/s, from delta to beta. Both ongoing activity and task-relevant intervals instigate large-scale coherent motion of the cortical signal that is measurable at the scalp (Alexander et al. 2016). Regions that are formed by resting state oscillations are located at opposite end of a spatial organization from primary sensory and motor regions; sitting at the top, most abstract representational hierarchy. Thus, the resting state is substantially insulated from direct environmental input, because energy-information exchange is meticulously regulated via the frequency conversion in the limbic system. It is intuitive and generally accepted that individual sensory experience, exemplified by Proust's Madelaine cookies, varies widely between people. Such subjective information-energy conversion turns the brain holographic. To clarify how the brain state might interpret stimulus, we calculated how the stimulus wave is shaped by the resting potential. Our topological approach showed that low- and high-frequency fractal spikes are correlated in the brain, because they display the same features (Fig. 1). This in touch with the claims of Pereira et al. (2017): in search for neural correlates of human brain activity, they suggested that a dynamical signature of conscious processing can be identified by means of a mathematical analysis of how the faster brain rhythms are nested in the slower ones.

Sensory activation zones are arranged evenly between the nodes of resting states, forming microscopic crystal-like symmetry (Margulies et al. 2016). This takes us into the realm of quantum dynamics. The issue of brain function correlated with quantum phenomena has been tackled by different Authors. To make an example, Pereira (2017) and Fernandes de Lima and Pereira (2017) investigated the mechanisms of neuroglial interactions involved in neural plasticity, highlighting the role of nonlinear interactions between glial membranes and synaptic terminals, based on the quantum dynamics of hydroionic waves within the neuropil. In this regard, hydroponic waves within the neuropil are considered to carry both physiological and cognitive functions. This crystal-like symmetry forms antipodal points, allowing calculation from a detected or measured point onto the opposite side of the diameter (corresponding to two points on the fractal slope). Once a matching description between slow and fast brain oscillations was established, we looked for a feasible equation able to link their reciprocal activities. We found a theory from an apparent far-flung branch, solid-state physics. In a periodically repeating environment (such as a lattice), the Bloch wave is a linear oscillation obtained by the product of (Floquet 1883; Traversa et al. 2013; Ahn and Hogan 2015): a periodic function with the same periodicity as the lattice, a plane wave. In such a solid-state physics' system, the wave function $\Psi$ for a particle has the form:

$$\Psi(x) = e^{ikr}u(x),$$

where $\Psi$ is called a Bloch wave, x is its position, $e^{ikr}$ is a plane wave (in which $e$ is the Euler's number, $i$ is the imaginary unit, $k$ is a vector of real numbers called the *crystal wave vector*), and $u(x)$ is a periodic function with the same periodicity as the lattice. A mathematical treatment for technical readers is provided in the "Appendix".

## Results

In a brain framework, we are allowed to look for the nervous correlates of the Bloch wave's equation (Fig. 3a): We may consider just the real part and put aside the imaginary part of the Bloch theorem.

The brain stands for a 2-D lattice. We are indeed allowed to unfold and flatten cerebral hemispheres into a two-dimensional reconstruction by computerized procedures (Van Essen 2005).

The periodic functions u stand for the spontaneous, slow brain oscillations which take place on the 2D brain lattice. We may conventionally state that u has the same periodicity of the brain lattice, because it corresponds to the nervous spontaneous oscillations.

The plane waves (the vectors of real numbers k) stand for the fast, task-evoked brain oscillations.

The Bloch waves stand for an unknown brain parameter able to link together the parameters u and k.

Figure 3b provides a simulation of the Bloch theorem applied to brain function. The picture shows that a change in slow oscillations leads to a change in fast oscillations, and vice versa.

Functional connectivity and the nodes of slow resting oscillations constrain the paths of emerging oscillation flows. Since the connectivity of functional hubs is frequency dependent, the information flow is dynamic and wave-like. Fast sensory oscillations can nest in the slow periodic function of these nodes. The brain's plasma-like operation encourages phase coherence in the collective flows of the extracellular space, in which long range connections modulate oscillation timing and frequencies. The nodes of resting potential in the brain might serve as stable deflection points that interfere with stimulus to create complex activation pattern.

## Conclusions

A new hypothesis of consciousness and mental operation is proposed based on particle and quantum-like formalism. We show how the physiological manifestations of

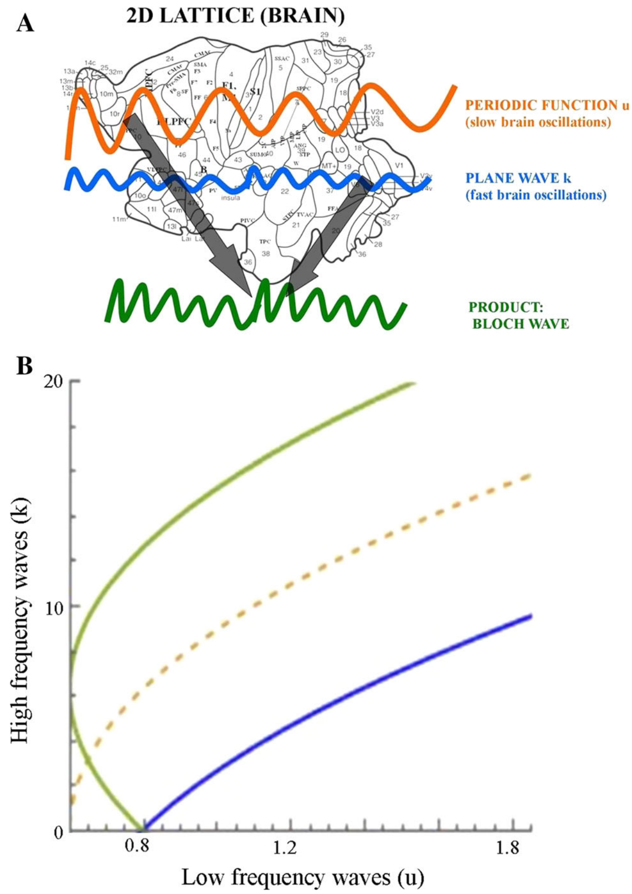


**Fig. 3** **a** A rough sketch depicting the brain correlates of the Bloch theorem. **b**. Relationships between slow and fast brain oscillatory activity, according to the Bloch Theorem. A simulated plot of Bloch wave forms, for $k$ (high frequency waves) on the $y$-axis, and $u$ (low frequency waves) on the $x$-axis, is displayed. The brain spike frequencies are expressed in Hz (note that this time the scale is non-logarithmic). The *different lines* correspond to diverse values of the Bloch wave. Just the slow frequencies included in the fractal range are displayed, while the non-fractal slope tail on the left of Fig. 1a is excluded

consciousness (such as emotions, memories and qualia) might arise out of the electromagnetic activities of the brain. The correlations between nervous fluctuations with different timescales and functional activity (the low- and the high- frequency spikes) can be represented by the Bloch theorem, because its periodic function can be replaced with the scale-free ultra-slow waves of the default mode networks, and its plane wave can be substituted with the fast brain spikes. In such a way, the increase in frequency of the slow electric oscillations leads to a predictable increase of the fast electric ones. Resting fluctuations of the brain exert a dominant role in regulating the brain's ability and potential to respond to sensory stimulus, leading to a functional inter-correlation between low and high oscillations, in which the momentary mental state reflects the brain's electromagnetic activity. Our simulation showed that spontaneous fluctuations in cortical excitability might have a remarkable effect on the field potentials activity frequency spectrum as well as the spiking activity of neurons. Fluctuations in electromagnetic activity in the brain are intertwined with all other functions of the field potential, and the spiking activity of neurons. This "coupling" or nesting of many spikes subserves an important coordinating role and provides a logical structure for the integration of functional activity (Buzsáki and Watson 2012; Fox and Raichle 2007) via energy conservation and the principle of least action. In building the electromagnetic signal of stimulus on top of the resting brain's energy level, the brain operates according to the principle of least action, thereby forming a unique electric brain pattern, which is a holographic, highly subjective experience and mental world, characteristic of the individual, her past experiences and her current brain state. Such relativity of information content is linked to time perception and indeed reflection of relativity of time in general relativity. Moreover, the temporal expanse of mental concepts and feelings entails an orthogonal orientation against the field of gravity. In analogue to gravitational interaction of elementary fermions, mental interaction formulates a social field that plays crucial role in regulating thinking and behavior.

This hypothesis is supported by the observation that many types of behavioral variability follow a $1/f$ frequency distribution similar to that of spontaneous BOLD. Because higher frequencies have greater energy need and greater information carrying capacity, the regulation of the brain's electromagnetic activities show a power law relationship (Fox and Raichle 2007). The Bloch theorem might shed new light on the interpretation of the data from functional neuroimaging. If we were able to calculate the Bloch wave from the experimental records, we could obtain a simple factor which summarizes the behaviour of the brain's dynamical system—and which could also be compared with the real data from pairwise entropy studies (Watanabe et al. 2014). The "order parameter" might allow a better comprehension of cortical dynamics. This method could be used in the study of EEGs as well as fMRI neuroimaging. We also suggest other feasible applications of the Bloch theorem in different fields of neuroscience: for example, if we replace the brain with a lattice, we might evaluate the first Brillouin zone and quantify the Bloch waves in different functional states (for further details, see "Appendix"). The fact that the same Bloch wave may be obtained from different types of oscillations could explain the apparently chaotic behaviour of cortical fluctuations. If the Bloch waves change in different functional states (i.e., sensations, perceptions, emotions, mind wandering and so on), we might be able detect the underlying activity, starting just from the knowledge of the Bloch wave. Furthermore, the well-known relationships between Bloch waves, Floquet multipliers, Lyapunov exponents and limit-cycle attractors (see "Appendix") allow us to evaluate the brain oscillations' spatial fractals/temporal power laws in the context of dynamical system theories. To make an example, starting from the Lyapunov exponents endowed in the metastable brain at the edge of chaos (Beggs and Timme 2012), we might achieve a more manageable linear system, which depends just on the various brain timescales.

The brain communicates with the environment via the sensory system, which transform stimuli into the language of oscillations that propagate to the cortex. Therefore, stimulus triggers oscillations that are dependent both on the external input and the brain state. Hence, brain frequencies reflect the brain's integration into the environment via physical principles (which clearly governs the dynamics of the oscillations). Because the resting state of the brain is insulated from the environment by the sensory system, it can maintain low entropy. In the cortical brain sensory stimulus accumulates information and increases entropy. In the brain interaction (i.e., decoherence) changes mental energy (trust, confidence, etc.) by reorganizing the neuronal organization (the synaptic connections or their strength), while restoring the low entropy, i.e., resting state of the brain, which is insulated from the environment by the sensory system. This way the brain is a self-regulating system based on entropy. Since high entropy states correspond to information accumulation and high frequencies, the resting state of the brain forms low entropy that is automatically recovered via the energy state and stability of neuronal connections and their support cells. The highly debated role of sleep might very well play an important role in recovering the brain's low entropy state (Claussen and Hofmann 2012).

Electromagnetic activity in the brain is not arbitrary or accidental; it is directed by charge conservation laws. Shifting energy balances in the brain change the strength and orientation of synapses, which modifies the mental energy. This way the mind is a temporal gyrocompass, which, by restoring the resting state remains true to the local field. However, in the process, low brain frequencies accumulate energy (trust and confidence see, Neupert and Allaire 2012), whereas high brain frequencies accumulate information (leading to insecurity and fear). Therefore, over time, emotional interactions form a mental landscape (temporal field), which regulates the sensitivity of the brainstem, thus its reaction to the environment. In its constant interaction with the environment, the mind constantly changes and adapts! These way electromagnetic activities, which are wave-like, can manifest as point-like and irreversible moment-to-moment qualia of a quantum system. Hence, mental change and brain evolution is a stepwise progression, where interaction gradually enhanced the brain's organizational symmetry vis-à-vis material systems. Thus energy-information equilibrium is low entropy, resting state, which ensures mental stability and it might be called low entropy principle. *The mind is an insulated, self-regulating system, which carefully controls energy-information exchange with the environment based on its entropy.* Low entropy principle might be present in other self-regulating systems in nature as well.

Studying particles of matter is very difficult due to their size and energy levels; examining the brain poses the opposite problem: the myriad possible ways to study it produce divergent, often confusing conclusions. However, the analog structure and operation of mind and matter holds great promise. With suitable corrections, understanding can be transferred between the fields of neurology and theoretical physics for the mutual benefit of both. This paper is intended as a first step toward building a comprehensive theory that describes the operation of the mind.

## Appendix: Bloch waves and Floquet theorem

The Bloch theorem states that, if you multiply a plane wave by a periodic function, you obtain a Bloch wave, which expresses the energy eigenstates for a particle in a lattice, written as $\psi n_k$, where $n$ is a discrete index.

There are different Bloch waves with the same $k$, each one with a different periodic component $u$. Further, the same Bloch wave can be built in different ways, involving different vectors $k$ and different periodic functions $u$. However, if we take into account just the first Brillouin zone of our lattice, we obtain that every Bloch state has a unique $k$.

The concept of Bloch theorem from solid-state physics—a second order differential equation-is about crystals in any number of spatial dimensions and deals in particular with the Schrödinger equation. However, it can be also applied in theory of ordinary differential equations, through the Floquet theorem (Floquet 1883). Indeed, the two theorems are almost equivalent (Floquet). The Floquet theorem, through a coordinate change in the lattice, transforms the original periodic system into a more manageable traditional linear system with constant, real coefficients. In other words, we map a fundamental matrix solution into a matrix function depending on the time, giving rise to a time-dependent change of coordinates. The Floquet theorem holds for any homogeneous, linear system of first order differential equations with a periodic coefficient matrix. Through a coordinate change in the lattice, the Floquet's theorem transforms the periodic system into a traditional linear system with constant, real coefficients.

We start from a linear first order differential equation:

$$\frac{d(x(t))}{dt} = A(t)x,$$

where $x(t)$ is a column vector of length n, and $A(t)$ is an $n \times n$ periodic matrix with period $T$.Then, for all $t \in R$:

$$\Phi(t+T) = \Phi(t)\Phi^{-1}(0)\Phi(T),$$

where $\Phi(t)$ is a fundamental matrix solution of the above differential equation $d(x(t)) \div dt = A(t)x$, and $\Phi^{-1}(0)$ $\Phi(T)$ is the monodromy matrix. Now consider the $n \times n$ matrices: $B, P, Q, R$: For each matrix B such that:

$$E^{TB} = \Phi^{-1}(0)\Phi(T),$$

there is a periodic (period $T$) matrix function $t \to P(t)$ such that:$\Phi(t) = P(t)E^{tB}$ for all $t \in R$. This representation is the Floquet normal form for the fundamental matrix $\Phi(t)$.

There is also a real matrix R and a real periodic function (period $-2T$) matrix function $t \to Q(t)$, which is continuous and periodic—such that:

$$\Phi(t) = Q(t)E^{tR} \quad \text{for all } t \in R.$$

The latter mapping gives rise to a time-dependent change of coordinates:

$$y = Q^{-1}(t)x,$$

under which the original system becomes a linear system with real constant coefficients $y = Ry$. The mapping of a fundamental matrix solution for such a differential equation into a (time-dependent) matrix function gives rise to a time-dependent change of coordinates, under which the original periodic system becomes a linear system with real constant coefficients $y = Ry$.

The eigenvalues of $e^{TB}$ are called the characteristic multipliers of the system, while the characteristic exponent, called the Floquet exponent, is a complex $\mu$ such that $e^{\mu T}$ is a characteristic multiplier of the system. Floquet exponents are not unique and their real parts correspond to the Lyapunov exponents.

The linear differential equations with periodic coefficients have been widely used in many scientific fields. In particular, they provide a versatile tool for the stability analysis of physical systems equipped with a periodic steady-state and infinite memory, such as Brownian particles and circuit resonators (Traversa et al. 2013). The Floquet multipliers have been also used to assess the stability of periodic motion in natural rhythmic - movements in humans and machines-, not just in linear systems, but also in stochastic noise and in limit-cycle, nonlinear oscillators (Ahn and Hogan 2015).

## References


Abeles M (1991) Corticonics: neural circuits of the cerebral cortex. Cambridge UniversityPress, New York

Ahn J, Hogan N (2015) Improved assessment of orbital stability of rhythmic motion with noise. PLoS ONE 10(3):e0119596. doi:10.1371/journal.pone.0119596

Alexander DM, Nikolaev AR, Jurica P, van Leeuwen C (2016) Global neuromagnetic cortical fields have non-zero velocity. PLoS ONE 11(3):E0148413. doi:10.1371/journal.pone.0148413

Atasoy S, Donnelly I, Pearson J (2016) Human brain networks function in connectome-specific harmonic waves. Nat Commun. doi:10.1038/ncomms10340

Atmanspacher H, Rotter S (2008) Interpreting neurodynamics: concepts and facts. Cogn Neurodyn 2(4):297–318

Bakouie F, Pishnamazi M, Zeraati R, Gharibzadeh S (2017) Scale-freeness of dominant and piecemeal perceptions during binocular rivalry. Cogn Neurodyn 11(4):319–326

Barbey AK, Colom R, Grafman J (2014) Distributed neural system for emotionalintelligence revealed by lesion mapping. Soc Cogn Affect Neurosci 9(3):265–272

Bastos AM, Briggs F, Alitto HJ, Mangun GR, Usrey WM (2014) Simultaneous recordings from the primary visual cortex and lateral geniculate nucleus reveal rhythmic interactions and a cortical source for gamma-band oscillations. J Neurosci 34(22):7639–7644. doi:10.1523/JNEUROSCI.4216-13.2014

Bastos AM, Litvak V, Moran R, Bosman CA, Fries P, Friston KJ (2015) A DCM study of spectral asymmetries in feedforward and feedback connections between visual areas V1 and V4 in the monkey. Neuroimage 108:460–475. doi:10.1016/j.neuroimage.2014.12.081 **(Epub 2015 Jan 10)**

Beggs JM, Timme N (2012) Being critical of criticality in the brain. Front Physiol 3:163

Bethell EJ, Holmes A, MacLarnon A, Semple S (2012) Evidence that emotion mediatessocial attention in rhesus macaques. PLoS ONE 7(8):e44387

Bliss T, Lomo T (1973) Long-lasting potentiation of synaptic transmission in the dentate areaof the anaesthetized rabbit following stimulation of the perforant path. J Physiol 232:331–356

Borsuk M (1933) Drei sätze über die n-dimensional euklidische sphäre. Fundam Math 1:177–190

Borsuk M (1958–1959) Concerning the classification of topological spaces from the standpoint of the theory of retracts. Fundam Math XLVI:177–190

Borsuk M (1969) Fundamental retracts and extensions of fundamental sequences. Fundam Math 1:55–85

Brembs B (2011) Towards a scientific concept of free will as a biological trait: spontaneous actionsand decision-making in invertebrates. Proc Biol sci R Soc 278(1707):930–939. doi:10.1098/rspb.2010.2325

Busemeyer JR, Bruza PD (2012) Quantum Models of cognition and decision. CambridgeUniversity Press, New York

Buzsáki G, Watson BO (2012) Brain rhythms and neural syntax: implications for efficient coding of cognitive content and neuropsychiatric disease. Dialog Clin Neurosci 4:345–367

Buzsaki G, Logothetis N, Singer W (2013) Scaling brain size, keeping timing: evolutionarypreservation of brain rhythms. Neuron 80(4):751–764

Christoff K, Irving Z, Fox KC, Spreng RN, Andrews-Hanna JR (2016) Mind-wandering as spontaneous thought: a dynamic framework. Nat Neurosci Rev. doi:10.1038/nrn.2016.113

Claussen JC, Hofmann UG (2012) Sleep, neuroengineering and dynamics. Cogn Neurodyn 6(3):211–214

Cole MW, Bassett DS, Power JD, Braver TS, Petersen SE (2014) Intrinsic and task-evoked network architectures of the human brain. Neuron 83(1):238–251. doi:10.1016/j.neuron.2014.05.014

Damoiseaux JS, Rombouts SA, Barkhof F, Scheltens P, Stam CJ et al (2006) Consistent resting-state networks across healthy subjects. Proc Natl Acad Sci USA 103(37):13848–13853 **(Epub 2006 Aug 31)**

de Arcangelis L, Herrmann HJ (2010) Learning as a phenomenon occurring in a critical state. Proc Natl Acad Sci 107:3977–3981

Deaner RO, Isler K, Burkart J, Van Schaik C (2007) Overall brain size, and notencephalization quotient, best predicts cognitive ability across non-human primates. Brain Behav Evol 70(2):115–124

Deli E (2015) The science of consciousness how a new understanding of space and time infers the evolution of the mind. Self-Published Hungary, Hungary

Deli E (2016) Consciousness, a cosmic phenomenon—a hypothesis. J Conscious Explor Res 7(11):910–930

Fernandes de Lima VM, Pereira Junior A (2016) The plastic glial-synaptic dynamics within the neuropil: a self-organizing system composed of polyelectrolytes in phase transition. Neural Plast. doi:10.1155/2016/7192427

Festinger L (1957) The theory of cognitive dissonance. Stanford University Press, Stanford

Fingelkurts AA, Fingelkurts AA (2014) Present moment, past, and future: mental kaleidoscope. Front Psychol 5:395. doi:10.3389/fpsyeg.2014.00395

Floquet G (1883) Sur les quations différentielles linéaires à coefficients périodiques. Ann Sci l'É.N.S. 2e série, tom 12:47–88

Fox MD, Raichle ME (2007) Spontaneous fluctuations in brain activity observed with functional magnetic resonance imaging. Nat Rev Neurosci 8:700–711

Fraiman D, Chialvo DR (2012) What kind of noise is brain noise: anomalous scaling behavior of the resting brain activity fluctuations. Front Physiol 3:307. doi:10.3389/fphys.2012.00307

Fredrickson BL, Joiner T (2002) Positive emotions trigger upward spirals toward emotional well-being. J Am Psychol Soc 13(2):172–175

Geesink HJH, Meijer DKF (2016) Quantum wave information of life revealed: an algorithm for electromagnetic frequencies that create stability of biological order, with implications for brain function and consciousness. NeuroQuantology. doi:10.14704/nq.2016.14.1.911

Guterstam A, Abdulkarim Z, Ehrsson HH (2015) Illusory ownership of an invisible bodyreduces autonomic and subjective social anxiety responses. Sci Rep 5:9831. doi:10.1038/srep09831

He BJ (2014) Scale-free brain activity: past, present, and future. Trends Cogn Sci 18(9):480–487

He BJ, Zempel JM, Snyder AZ, Raichle ME (2010) The temporal structures and functional significance of scale-free brain activity. Neuron 66(3):353–369. doi:10.1016/j.neuron.2010.04.020

Kavalali ET, Chung C, Khvotchev M, Leitz J, Nosyreva E, Raingo J, Ramirez DM (2011) Spontaneous neurotransmission: an independent pathway for neuronal signaling? Physiol (Bethesda) 26(1):45–53

Khrennikov A (2016) 'Social Laser': action amplification by stimulated emission of socialenergy. Philos Trans R Soc A 374(2058):20150094

Bliss CA, Kloumann, IM, Harris KD, Danforth CM, Dodds, PS (2012) Twitter reciprocalreply networks exhibit assortativity with respect to happiness pp 1–10 arXiv:1112.1010

Levy D (1994) Chaos theory and strategy: theory, applications, and managerial implications. Strateg Manag J 15:167–178

Libet B (1985) Unconscious cerebral initiative and the role of conscious will in voluntaryaction. Behav Brain Sci 8:529–566

Linkenkaer-Hansen K, Nikouline VV, Palva JM, Ilmoniemi RJ (2001) Long-range temporal correlations and scaling behavior in human brain oscillations. J Neurosci 21(4):1370–1377

Lipsitz LA, Goldberger AL (1992) Loss of “complexity” and aging: potential applications of fractals and chaos theory to senescence. JAMA 267:1806–1809

Liu J, Lee HJ, Weitz AJ, Fang Z, Lin P, Choy M, Lee JH (2015) Frequency selective control of cortical and subcortical networks by central thalamus. eLife 4:e09215

Lupien SJ, Maheu F, Tu M, Fiocco A, Schramek TE (2007) The effects of stress and stresshormones on human cognition. Implications for the field of brain and cognition. Brain Cogn 65(3):209–237

Mantini D, Vanduffel W (2013) Emerging roles of the brain’s default mode network. The Neuroscientist. 19(1):76–87

Margulies DS, Ghosh SS, Goulas A, Falkiewicz M, Huntenburg JM, Langs G et al (2016) Situating the default-mode network along a principal gradient of macroscale cortical organization. Proc Natl Acad Sci. doi:10.1073/pnas.1608282113

Matoušek J (2003) Using the Borsuk–Ulam theorem. lectures on topological methods in combinatorics and geometry. Springer, Berlin

Mazzucato L, Fontanini A, La Camera G (2016) Stimuli reduce the dimensionality of cortical activity. Front Syst Neurosci. doi:10.3389/fnsys.2016.00011

McNally L, Brown SP, Jackson AL (2012) Cooperation and the evolution of intelligence. Proc R Soc B Biol Sci (April). doi:10.1098/rspb.2012.0206

Meijer DKF, Geesink HJH (2016) Phonon guided biology: architecture of life and conscious perception are mediated by toroidal coupling of phonon, photon and electron information fluxes at discrete eigenfrequencies. NeuroQuantology 14(4):718–755

Milstein J, Mormann F, Fried I, Koch C (2009) Neuronal shot noise and Brownian 1/f2 behavior in the local field potential. PLoS ONE 4(2):e4338. doi:10.1371/journal.pone.0004338

Moreva EV, Brida G, Gramegna M, Giovannetti V, Maccone L, Genovese M (2013) Time from quantum entanglement: an experimental illustration. Phys Rev A 89:052122

Mota B, Herculano-Houzel S (2015) Cortical folding scales universally with surface area andthickness, not number of neurons. Science 3(6243):74–77

Neupert SD, Allaire JC (2012) I think I can, I think I can: examining the within-personcoupling of control beliefs and cognition in older adults. Psychol Aging 2(2):145–152

Nikolov D, Oliveira DFM, Flammini A, Menczer F, Feb SI (2015) Measuring online social bubbles. Peer J Comput Sci. doi:10.7717/peerj-cs.38

O‘Donnell C, Van Rossum MC (2014) Systematic analysis of the contributions of stochastic voltage gated channels to neuronal noise. Front Comput Neurosci 8:105. doi:10.3389/fncom.2014.00105

Oei NYL, Rombouts SARB, Soeter RP, van Gerven JM, Both S (2012) Dopamine modulates reward system activity during subconscious processing of sexual stimuli. Neuropsychopharmacology 37:1729–1737

Pakhomov A, Sudin N (2013) Thermodynamic view on decision-making process: emotions as a potential power vector of realization of the choice. Cogn Neurodyn 7(6):449–463

Palma J, Grossberg S, Versace M (2012) Persistence and storage of activity patterns in spiking recurrent cortical networks: modulation of sigmoid signals by after-hyperpolarization currents and acetylcholine. Front Comput Neurosci 6:42. doi:10.3389/fncom.2012.00042

Patel J, Schomburg EW, Berényi A, Fujisawa S, Buzsáki G (2013) Local generation and propagation of ripples along the septotemporal axis of the hippocampus. J Neurosci 33(43):17029–17041

Penttonen M, Buzsaki Gy (2003) Natural logarithmic relationship between brain oscillators. Thalamus Relat Syst 2(2):145–152

Pereira A (2017) Astroglial hydro-ionic waves guided by the extracellular matrix: an exploratory model. J Integr Neurosci 16(1):57–72

Pereira A Jr, Foz FB, Rocha AF (2017) The dynamical signature of conscious processing: from modality-specific percepts to complex episodes. Psychol Conscious Theory Res Pract. doi:10.1037/cns0000115

Perlmutter E (2016) Bounding the space of holographic CFTs with chaos. J High Energy Phys 2016:69

Peters JF (2016) Computational proximity. excursions in the topology of digital images, In: Peters JF (ed) pp 169–171. doi:10.1007/978-3-319-30262-1

Peters JF (2017) Foundations of computer vision. Computational geometry, visual image structures and object shape detection, intelligent systems reference library, vol 124. Springer, Berlin. doi:10.1007/978-3-319-52483-2

Peters JF, Ramanna S, Tozzi A, İnan E (2017) Bold-independent computational entropy assesses functional donut-like structures in brain fMRI images. Front Hum Neurosci 11:38

Pigarev IN, Pigareva ML (2015) The state of sleep and the current brain paradigm. Front Syst Neurosci 9:139. doi:10.3389/fnsys.2015.00139

Pothos EM, Busemeyer JR (2009) A quantum probability model explanation for violationsof ‘l’ derationacision theory. Proc R Soc B 276(1665):2171–2178

Pothos EM, Busemeyer JR (2013) Can quantum probability provide a new direction forcognitive modeling? Behav Brain Sci 36(03):255–274

Poutanen P, Soliman W, Ståhle P (2016) The complexity of innovation: an assessment and review of the complexity perspective. Eur J Innov Manag 19(2):189–213

Pritchard WS (1992) The brain in fractal time: 1/f-like power spectrum scaling of the human electroencephalogram. Int J Neurosci 66:119–129

Raichle ME, Snyder AZ (2007) A default mode of brain function: a brief history of anevolving idea. NeuroImage 37(4):1083–1090

Rudd M, Aaker J, Vohs K (2012) Awe expands people’s perception of time, alters decisionmaking, and enhances well-being. Psychol Sci 23(10):1130–1136

Schultz W (2007) Reward signals. Scholarpedia 2(6):2184

Sengupta B, Stemmler MB (2014) Power consumption during neuronal computation. Proc IEEE 102:738–750

Seo D, Patrick CJ, Kennealy PJ (2008) Role of serotonin and dopamine systeminteractions in the neurobiology of impulsive aggression and its comorbidity with other clinical disorders. Aggress Violent Behav 13(5):383–395

Touboul J (2012) Mean-field equations for stochastic firing-rate neural fields with delays: derivation and noise-induced transitions. Phys D Nonlinear Phenom 241(15):1223–1244

Touroutoglou A, Lindquist KA, Dickerson BC, Barrett LF (2015) Intrinsicconnectivity in the human brain does not reveal networks for “basic” emotions. Soc Cogn Affect Neurosci 10(9):1257–1265

Tozzi A, Peters JF (2016a) Towards a fourth spatial dimension of brain activity. Cogn Neurodyn 10(3):189–199

Tozzi A, Peters JF (2016b) A topological approach unveils system invariances and broken symmetries in the brain. J Neurosci Res 94(5):351–365

Tozzi A, Peters JF (2017) The multidimensional world. Lambert Academic Publishing, Saarbrücken. ISBN-13: 978-3-330-03530-0

Tozzi A, Zare M, Benasich AA (2016) New perspectives on spontaneous brain activity: dynamic networks and energy matter. Front Hum Neurosci 10:247. doi:10.3389/fnhum.2016.00247

Tozzi A, Peters JF, Fingelkurts AA, Fingelkurts AA, Marijuán PC (2017a) Topodynamics of metastable brains. Phys Life Rev. doi:10.1016/j.plrev.2017.03.001

Tozzi A, Peters JF, Jausovec N (2017b) A repetitive modular oscillation underlies human brain electric activity. Neurosci Lett. doi:10.1016/j.neulet.2017.05.051

Traversa FL, Di Ventra M, Bonani F (2013) Generalized Floquet theory: application to dynamical systems with memory and Bloch's theorem for nonlocal potentials. Phys Rev Lett 110(17):170602

Treadway MT, Buckholtz JW, Cowan RL, Woodward ND, Li R, Ansari MS, Zald DH (2012) Dopaminergic mechanisms of individual differences in human effort -based decisionmaking. J Neurosci 32(18):6170–6176

Van de Ville D, Britz J, Michel CM (2010) EEG microstate sequences in healthy humans at rest reveal scale-free dynamics. PNAS 107(42):18179–18184. doi:10.1073/pnas.1007841107

Van Essen DC (2005) A population-average, landmark- and surface-based (PALS) atlas of human cerebral cortex. Neuroimage 28:635–666

Ventriglia F (2014) Random dispersion in excitatory synapse response. Cogn Neurodyn 8(4):327–334

Wang Z, Solloway T, Shiffrin RM, Busemeyer JR (2014) Context effects produced by question orders reveal quantum nature of human judgments. PNAS 111(26):9431–9436

Watanabe T, Hirose S, Wada H, Imai Y, Machida T, Shirouzu I, Konishi S, Miyashita Y, Masuda N (2014) Energy landscapes of resting-state brain networks. Front Neuroinform 25(8):12

Weeks JR (2002) The shape of space, 2nd edn. Marcel Dekker inc, New York-Basel

Yamada Y, Kawabe T (2011) Emotion colors time perception unconsciously. Conscious Cogn 20(4):1–7

Zeeman EC (1976) Catastrophe theory. Sci Am, 234(4):65–70, 75–83

Zhang J, Hess PW, Kyprianidis A, Becker P et al (2016) Observation of a discrete time crystal. arXiv:1609.08684