NEURODYNAMICS AND ARTIFICIAL INTELLIGENCE

Biologically Plausible Models of Rhythm Generating Circuits

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Biological systems are in dynamic equilibrium. They maintain stability by self-adjusting to a variable environment through feedback. Furthermore, the systems maintain stability even as the animal itself changes during growth and aging. We have found that some neural circuits themselves can exhibit a resilience that is independent of sensory feedback. Understanding the mathematical basis for such resilience has general applications for any network of interacting units. It is hardly a surprise that better understanding of various mechanisms of rhythmogenesis have stemmed from experimental and computational studies of CPGs in invertebrate animals, as their circuit wiring can be utterly mapped and easily manipulated. Nevertheless, the use of feasible simplifications in neuronal structures and biophysics may cause minor and major discrepancies between behaviors of a model and the biological neural circuit. In most modeling studies, it remains the methodology for determining which details of a model can be omitted for simplicity and which are important variables. Therefore, it is imperative to devise and showcase experimental systems that are can be reliably replicated and engineered in computational models, analyzed in detail and verified.
Using dynamical system and stability theory we develop a new computational apparatus to elucidate stability, resilience and adaptability of neural circuits to evaluate and quantify the existence range of emergent network-bursting in mathematical circuits against various short-term and graduate perturbations. Models will be based on electrophysiological recordings made from neurons in the swim central pattern generators of sea slugs: Melibe and Dendronotus. The goal here is to transform the assimilated detailed knowledge about complex nonlinear interactions of coupled neurons and synapses into causal, predictive relationships between the properties of mathematical and biological circuits.

Brain-Computer Interface for Evaluating Psychophysiological State

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Brain-computer interface (BCI) is a modern technology which is based on tracking the characteristic forms of brain electrical activity in real time and converting the received information into commands to control the device (PC). This technology is highly demanded in various fields of science and technology, including medicine and manufacturing [1-5].

This study is focused on the development of the BCI to measure changes in brain activity caused by the presentation of the ambiguous visual stimuli. As a visual stimulus the Necker cube was chosen [6], which is a cube with transparent faces and visible edges, perceived as a 3-D object due to the specific arrangement of the edges. The ambiguity of the Necker cube lies in the possibility of interpreting this 3-D object both inverted to the left and to the right one, depending on the different contrasts $I\epsilon[1,0]$ [7] of the inner edges of the cube.

During the research, we conducted a series of experiments aimed at compiling an array of EEG data. All participants in the experiments were instructed to press the left or right button on the remote control, depending on their first impression of the orientation of the cube. During the experimental sessions, the cubes with different contrast edges were randomly displayed, a parallel recording of the brain EEG was performed using the Encephalan-EEGR-19/26 electroencephalograph (Medikom MTD, Russia).

The EEG signal obtained from five electrodes (O1, O2, P3, P4, Pz) was analyzed, which were located in accordance with the extended international system 10-20 [8]. As the analyzing method, a continuous wavelet transform was chosen [9].

The wavelet spectrum of the EEG signal was calculated using a floating window with a length of 2 seconds between 4 and 30 Hz. Each event associated with the presentation of a visual stimulus was analyzed separately in the alpha and beta range, starting 1 second before the stimulus was presented, and ending with the moment of the stimulus appearance. As a result, the set of AI, AII, BI, BII values was calculated for each presentation as follows:

$$A_{I,II} = \sum_{n=1}^{N} \int_{t \in \Delta t_{I,II}} \xi^n(t')dt'', \quad \textbf{where} \qquad \xi^n = \begin{cases} 1, & if \quad f_{\max}^n \in \Delta f_\alpha \\ 0, & if \quad f_{\max}^n \notin \Delta f_\alpha \end{cases}$$

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where N = 5 is the number of EEG channels, and   is the position of the maximum spectral component.
The obtained results were averaged over six presentations, the control characteristic was calculated as:

$$G(t) = \frac{(< A_I > - < A_{II} >) + (< B_I > - < B_{II} >)}{2},$$

where <...> means an averaged value.

The value of   was calculated in accordance with equations 1-3 in real time. It reflects the intensity of the response in brain activity in response to a visual stimulus. High value of   is associated with an intensive response, which is associated with concentrated image processing of the subjects. On the other hand, a low value of   is associated with an abstract state of the subject, when he is not sufficiently focused on the visual stimulus.

The developed BCI was experimentally tested on three subjects, each of which took part in a 4-minute experimental session. The experiment was divided into three sections. During the first section, the subject performed the task in the absence of external influence. It is noticeable that   fluctuates near a certain average value, individual for each subject. After switching on the external influence, the value of   falls sharply and begins to oscillate near the middle, much lower than the average in the previous section. After turning off the external influence,   increases significantly for all subjects.

The use of BCI control of the response of brain activity in response to the presentation of visual stimuli has revealed the possibility of tracking the decrease in attention and focus, based on the corresponding EEG signal, which is important for the development of training and training systems based on real-time brain activity analysis.

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Coherent Resonance in the Brain Under Visual Perception

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Currently, the perception of ambiguous images attracted great attention of many scientists. In a sense, such images are good objects for studying visual perception in general, as well as decision-making mechanisms. Images of this type have been the subject of research for psychologists for a long time [1,2]. Recently, ambiguous images have aroused the interest of physicists and mathematicians [3,4].

Interest in mathematical modeling of neural synchronization has increased significantly after neurobiological experiments with two electrically connected neurons [10], where different synchronous states were found. In order to reflect cooperative neural dynamics, numerical models based on iterated images or differential equations with different coupling configurations were developed [10].

In this paper, we study the dynamics of a network of globally coupled neural oscillators with randomly distributed coupling forces in the presence of noise in each of them. As a model neuron, we chose the Rulkov map [13]. It should be noted that models of map-based neurons are very effective for numerical modeling of neural dynamics and functionality in neurobiological networks, since they allow studying the interaction between individual neurons and mean-field oscillations formed in large-scale networks. They can also be used to implement the biological neural mechanisms responsible for processing sensory information, such as visual, auditory and tactile, as well as for creating synthetic real-time neurobiological controllers for biometric robots and neural prostheses.

To study the dynamics of the system, the time series of the fast variable x and the macroscopic signal averaged over all neurons are taken from the network. To analyze the influence of system parameters, we calculate the dependencies of the signal-to-noise ratio (SNR) on the network size, the number of stimulated neurons, the stimulus amplitude A, and the noise $A\xi$ were calculated. SNR is calculated from the power spectrum of the averaged signal as the difference between the amplitude of the fundamental frequency and the amplitude of the background noise [20].

A coherent resonance effect was found, when for certain values of the amplitude of the external stimulus and number of stimulated neurons the signal-to-noise ratio assumes a maximum value.

To analyze the stochastic resonance, such a characteristic was calculated as the characteristic correlation time, which is defined as [17]:

$$\tau_c = \sum_{n_0}^{N} C(\tau)^2, \tag{1}$$

where x is the signal averaged over all neurons, is averaging over time.

The two-parameter dependence of the characteristic correlation time on the amplitude of the external action and internal noise was calculated. It was found that as the amplitude of the stimulus increases, the amplitude of the noise should decrease so that τc remains maximum. This provides the effect of controlling internal noise by an external stimulus.

A similar effect was observed during the next experiment on measuring the internal noise of the human brain. The subject was shown a Necker cube, an optical illusion, first published in 1832 by the Swiss crystallographer Louis Necker [22]. It is a pattern of lines that the brain interprets as a three-dimensional cube. But there are two possible orientations of this mental cube, and both are equally compatible with a two-dimensional image on paper.

In the course of the experiment, the subject is presented Necker cubes, smoothly changing from "left" to "right" or vice versa, which is chosen randomly, while the background color is selected randomly from the range of colors from white to 90% black in 7.5%. During the display of the changing cube, the subject pushes the button at the moment when he sees the very first switch. After that, the color of the background changes, and the changing cube is again shown, etc. Each background was demonstrated 10 times. As a result of the experiment, the dependences of the relative noise parameter $\xi = T/\tau$ on the intensity of the background I were obtained.

From the experimental data we found coherent resonance phenomenon: there is a resonant value of background intensity, for which brain noise takes its minimum value. We should notice that these resonant values of background intensity are different for each person, and there are a few people without that value.

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Chimera States in a Nonlinearly Coupled Oscillatory Network

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Chimera is, according to Greek mythology, a monstrous creature combining the parts of different animals (a lion with a head of a goat and a tail of a snake). Physicists recently adopted this name for complex states in nonlinear dynamical systems, where instead of an expected symmetric synchronous state one observes coexistence of synchronous and asynchronous elements. Since the discovery of chimeras by Kuramoto and Battogtokh in 2002 [1], these states have been reported in numerous theoretical studies and experiments [2].
We have studied different chimera states in a network of nonlinearly coupled nodes. Our setup is almost identical to that of Kuramoto and Battogtokh, except for nonlinearity in coupling. This nonlinearity leads to novel effects. First, it allows for a homogeneous partially coherent state, which, however, becomes unstable in a long network. In the class of stationary (uniformly rotating) spatially inhomogeneous regimes, together with the classical Kuramoto-Battogtokh chimera, we have observed an inhomogeneous partially coherent state, and a "hybrid" chimera consisting of two domains of enhanced synchrony - one fully and another partially coherent. Furthermore, we observed how the oscillatory instability of stationary chimeras leads to the breathing, periodically time modulated chimeras. In this regime, the synchronous domain breaks into subdomains having different oscillator frequencies. The frequency profile consists of steps, the step height is the modulation frequency. In large spatial domains, regular regimes are typically unstable and one observes either a weakly chaotic state (nonperiodically breathing chimera), or strong turbulence [3, 4].

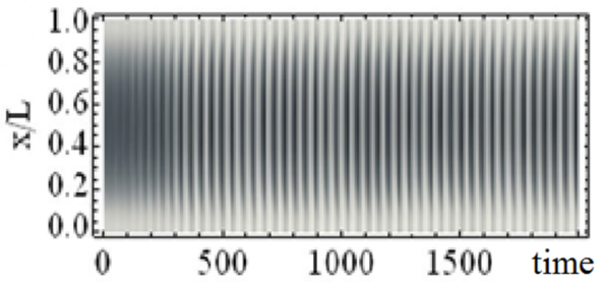

Fig.1. Breathing chimera. Spatio-temporal plot of absolute value of the order parameter.

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Feature Detection in Visual Cortex during Different Functional States

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Cortical activity exhibits distinct characteristics in different functional states. In awake behaving animals it shows less synchrony, while in rest or sleeping state cortical activity is most synchronous. Previous studies showed that switching between functional states can change the efficiency of flowing sensory information. Switching between functional states can be triggered by releasing neuromodulators which affect neurotransmitter release probability and depolarization of cortical neurons. In this work we focus on studying primary visual area V1, by using firing rate ring model with short-term synaptic depression (STD). We show that reconstruction of visual features from V1 activity depends on the functional state, with best precision achieved at the state with intermediate release probability. We suggest that this regime corresponds to the state of maximal visual attention.

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Modeling Rhythm Generation in Swim Central Pattern Generator of Melibe Leonina

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Central pattern generators(CPGs) are neural networks which can produce rhythmic activity in isolation and responsible for behaviors like walking, breathing, and swimming. The underlying mechanism of rhythm generation in CPGs is poorly understood. Understanding simple structured invertebrate CPGs provide insight to more complex structures in the vertebrate central nervous system. We have developed a Hodgkin-Huxley type highly detailed and biologically plausible mathematical model using the extensive data recorded from swim CPG of the sea slug Melibe leonine and study the rhythmogenesis of oscillatory patterns emerging in network motifs composed of half-center oscillators. Half-center oscillators are the building blocks of larger neural networks including CPGs controlling swim locomotion of the sea slug Melibe leonine. To couple four interneurons forming Melibe swim CPG which are endogenous tonic spiking and quiescent cells in isolation, the alpha, and dynamic synapses are used.

Extreme Events in Delay-Coupled Fitzhugh-Nagumo Oscillators

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The study of extreme events has gained increasing attention in recent years due to its ubiquitous appearance in a wide variety of important physical situations ranging from natural disasters to financial crises. Previous studies have indicated many factors and mechanisms which may cause such rare, recurrent, aperiodic events which have a large impact on dynamical systems. Some of these include progressive spatial synchronization and an interior crisis in networks of non-identical relaxation oscillators.

An important factor which often shapes the dynamics of systems in which such extreme events are observed is time delayed coupling. For instance, neural activities across different regions of the brain – whose synchrony may lead to epileptic seizures – are coupled by time delayed coupling. Moreover, as the flow of information in these networks might take different routes to travel from the source to the destination, more than one delay could be associated with a single pair of nodes. The impact of these time-delayed couplings on the emergence of extreme events has not yet been analyzed. In this talk, we investigate if delay couplings alone can induce extreme events in excitable systems.

To study the impact of such delay-couplings, we investigate a system of two identical FitzHugh-Nagumo oscillators diffusively coupled by single or multiple delays. We show that such a system shows rich dynamics which comprises of in-phase and out-of-phase extreme events. The stability of the synchronization manifold and its invariant subsets plays a crucial role in determining the qualitative nature of the dynamics. We also identify that the region in parameter space where extreme events are observed; is sandwiched by two particular bifurcations: a bubbling transition and a blowout bifurcation. Another striking feature of the events of the second category is the loss of synchrony significantly prior to the actual event. This allows us to use the phase difference between the oscillators as a precursor to such an extreme event.

Additionally, from a dynamical systems point of view, the delay-coupled FitzHugh-Nagumo system is interesting because it presents an example of amplitude death in coupled identical oscillators. Our analysis shows that the intricate interplay of the invariant subsets and their manifolds leads to the system showing extremely long transience before convergence to fixed point or chaotic attractors. This interplay also leads to the formation of riddled basins of attraction with tongue-like structures embedded in them.

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Macroscopic Phase Response Curves and Coherence States of Inter-Communicating Gamma Oscillatory Neural Circuits

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Macroscopic oscillations of different brain regions show multiple phase relations that are persistent across time [5]. Such phase locking is believed to be implicated in a number of cognitive functions and is key to the so-called Communication Through Coherence (CTC) theory for neural information transfer [7]. There are a number of mechanisms at the cellular level that influence the network's dynamic and structure macroscopic firing patterns. The question is then to identify the biophysical neuronal and synaptic properties that permit such motifs to arise.

To address this issue, we use a semi-analytic modeling approach. We investigate the dynamical emergence of phase locking within two bidirectionally delayed-coupled spiking circuits with emergent gamma band oscillations.

Internally the circuits consist of excitatory and inhibitory cells coupled synaptically in an all-to-all fashion. Each cell is described by a well-established conductance-based model – the quadratic integrate-and-fire – which is known to replicate the dynamical features of neural voltage [6]. The circuits can be parameterized to show either the pyramidal-interneuron (PING) or interneuron gamma (ING) rhythm activity to emerge. Multiple circuits can also be intercoupled together with reciprocal synaptic connections with variable delays and targeting excitatory and/or inhibitory neurons.

While not explicitly a model of any specific brain area, the design essentially captures many communicating cortical and sub-cortical regions where macroscopic locking takes place. Taking advantage of a mean-field approach combined with an exact reduction method [3,8], we break down the description of each spiking network into a low dimensional nonlinear system. Bifurcation analysis of the reduced system enables us to reveal how synaptic interactions and inhibitory feedback permit the emergence of macroscopic rhythms. We then show how the adjoint method can be applied to derive semi-analytical expressions for the macroscopic infinitesimal phase resetting-curves [2,4]. These mPRCs can in turn be used to determine how the phase of the global oscillation responds to incoming perturbations. In fact, we find that depending on wether PING or ING is expressed and wether the excitatory of inhibitory neurons are perturbed, the PRC can be either class I (purely positive) or class II (by-phasic). Hence we show analytically how incoming excitation can either promote spiking (advancing the phase) or retard the oscillation.

From there, we study the dynamical emergence of macroscopic phase locking of two bidirectionally delayed-coupled spiking networks within the framework of weakly coupled oscillators [1,9]. The fundamental assumption at the core of this theoretical setting is that synaptic projections from one circuit to another are sufficiently weak. The weak coupling condition allows us to abbreviate the bidirectionally coupled circuits description into a phase equation [1,9]. This simplification significantly reduces the complexity of the interacting macroscopic oscillations, making them mathematically tractable, while at the same time capturing crucial principles of phase locking. An analysis of the phase equation sheds new lights on the synaptic mechanism enabling circuits to bound together, and it uncovers the determinant part played by delay and coupling strength upon the dynamical rise of a variety synchronization modes. We show that the delay is a necessary condition to get a symmetry breaking, i.e. a non-symmetric phase lag between the macroscopic oscillations. We also find that this effect can easily be controlled by the synaptic weights of the pyramidal neurons. Using this analysis we find that a whole host of phase-locking relationships can exist, depending on the coupling strength and delay, potentially giving an explanation to the experimentally observed variety of phase locking modes. Our analysis further may allow us to track how the perturbation of one of the interacting circuits is transferred to its coupled partner.

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Synchronization of Systems with Multistable Visual Perception by Deterministic and Stochastic Brownian Noise

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In this work a comparation between systems emulating multistable visual perception by means of synchronization is reported. By the use of the synergetic model of perception [1], a series of simulations are carried on in order to understand its normal behavior, and by changing a control parameter bifurcation diagrams are constructed. Stochastic (S) noise generated by the method of Box-Müller [2], is added to the system for each iteration of the numerical simulation and the system behavior is modified as the noise intensity is increased. In a similar way, Deterministic Brownian (D) noise [3], is added to the system. Error and time of synchronization is characterized from the systems by dissipative coupling in a scheme Master-Slave by different combinations; D-D, S-S, D-S, and S-D. Results shows that synchronization between systems having noise are better when noise in the slave system is deterministic.

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Long-Range Temporal Correlations in Resting-State Brain Oscillations are Correlated with Behavioral Parameters in a Self-Initiated Movement Task

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Introduction

Human neuronal oscillations exhibit long-range temporal correlations (LRTCs) in different frequency bands [1]. Recently, it has been shown that LRTCs are closely related with behavioral outcome measures like perceptual hit rate [2], timing error dynamics [3], classification accuracy [4], and reaction time [5]. In the classical Libet task [6], subjects perform a single abrupt movement, spontaneously, at a time of their own choosing. They then report the time of their conscious intention to act (W–time) using a rotating clock dial. Although many studies have used W-time as a measure, there is a high inter-subject and intra-subject variability in the reported values. To the best of our knowledge, no study has focused on the source of individual variability in W-time. In this study, we hypothesized that, with its close relationship with behavior, LRTCs could explain the inter-subject variability in response time (RT) and W-time.

Methods

We recorded Magnetoencephalogram (MEG) and Electroencephalogram (EEG) data from 19 subjects using a 306-channel Elekta Neuromag MEG system combined with a 60-channel EasyCap EEG system. Subjects were performing a self-initiated movement task using a response pad and reporting their W-time in five different time-limit conditions. In the infinity (Libet task) condition, they were free to make their movement whenever they wanted. In the other conditions, they were free to make their movement at any time within the given time limit (i.e. 2, 3, 5, or 8 s). The time limit conditions were randomized across subjects and across blocks. Each condition was presented to subjects in two blocks (20 trials each). Subjects also had a 5 min. eyes-open resting-state recording at the end of the experiment. We eliminated noisy channels and segments and used independent component analysis to remove eye and electrocardiogram artifacts. We then interpolated data to repair bad channels. In order to estimate the LRTCs, we used detrended fluctuation analysis [7]. Then we calculated a Spearman correlation between four outcome measures (median RT, median W-time, coefficient of quartile variation of W-time, the standard deviation (std) of W-time) and the scaling exponents (α) of neuronal LRTCs in resting state for delta (1-3 Hz), theta (4-7 Hz), low-alpha (8-10 Hz), high-alpha (10-13 Hz), alpha (8-13 Hz), beta (14-30 Hz), and gamma (31-100 Hz) bands using cluster based permutation tests and false discovery rate correction due to different frequency bands and outcome measures.

Results

We found negative correlations between α of resting-state LRTCs in the delta band and median RT when the timelimit was 5 s (p=0.0024), 8 s (p=0.0108) or Inf (p=0.0111). We also found a negative correlation in the low-alpha (p=0.0054) band between α of resting-state LRTCs and std of W-time in the infinity condition. All these results were found only in EEG and we did not find significant correlations for the other conditions.

Conclusions

The results show that people who respond earlier have higher scaling coefficients of LRTCs in their resting-state delta oscillations if they are not tightly limited by time. Moreover, people who report their W-time more precisely have higher scaling coefficients of LRTCs in their resting-state low-alpha oscillations if they are not limited by time constraints. Our experiment partly explains the individual variability of reported W-time.

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Dragon-King-Like Extreme Events in Coupled Bursting Neurons

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We present evidence of extreme events in two Hindmarsh-Rose (HR) bursting neurons mutually interacting via two different coupling configurations, chemical synaptic, repulsive diffusive coupling. A dragon-king-like probability distribution of the extreme events is seen for both the coupling where small to medium size events obey a power law and the extremely large events are outliers. The extreme events originates due to instability in antiphase synchronization (APS) of the coupled systems via two different routes to chaos, intermittency and quasiperiodicity for purely excitatory and inhibitory coupling, respectively. Experimental evidence of the extreme events is found in two repulsively coupled eletronic analog circuits of the Hindmarsh-Rose neuron model, which confirms the dragon-king-like distribution.

Computational Method for Neurophysiological Data Processing Using Nvidia Cuda Technology

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The study of neural networks in the human brain arouses strong interest which is proved by the rise of number of publications in this scientific area during last few years. The significant of those works is the interdisciplinary articles describing the results obtained at the interface between neuroscience and other sciences. Aside from new methods of analysis it is also necessary to develop new hardware and software in order to effectively implement the abovementioned methods. In this case the use of parallel computing technology for big data processing is a rational approach. It can also be used for development of brain-computer interfaces (BCI) [1] which are being rapidly developed and applied for medical purposes [2,3], exoskeletons and robots [4].
In this study we consider the algorithm of real-time stream analysis of multichannel EEG data based on parallel computing methods. We also estimate the algorithmic efficiency in the system based on encephalograph "Encephalan" (Taganrog, Russia) and CUDA C library.
Experimental methods connected with registration and analysis of neural activity signals serve as the main sources of information about human brain functioning. One of the most frequently used methods is electroencephalogram recording which is characterized by complicated time-frequency structure with set of frequency ranges, oscillating patters and high noise component. Continuous wavelet transform (CWT) [5] can be used to research the signals of such complexity. CWT was often used for getting skeletons [6] – lines of local maximums of wavelet-spectrum used for tracking dominant components in EEG signal. Despite CWT allows to carry out detailed time-frequency analysis of EEG signal, it requires large computing power. Thus, to apply this method for real-time analysis of multichannel EEG recording a special approach is needed. One of the possible solutions is parallel computing.
In this study we analyzed EEG signals using CWT and calculating the wavelet-spectrum energy for each of 19 channels in the range from 4 to 30 Hz. Applying CUDA technology allowed to make the calculation process in real-time mode. It is shown in the figure 1. The paralleling process consists of several steps. The first of them is channel parallelization. BCI gets 19 time series, one for each channel. After that we run CUDA module for every channel. At this moment data is transferred from CPU to GPU memory. On the next step we divide the frequency range into N parts. Then CWT is performed for each block on the whole time series. On the last step we divide each block into M threads each of which corresponds with the current time moment of the respective time series. The obtained results are transferred back to CPU memory after the calculation has ended.

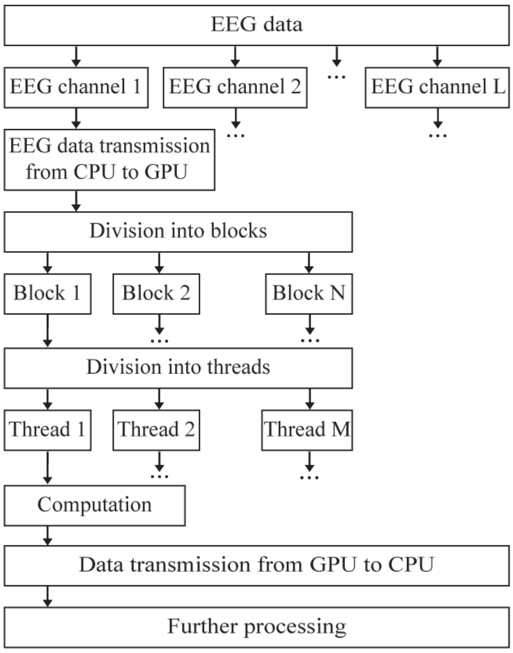

Fig.1. *Parallel CWT algorithm*

Testing BCI based on the algorithm of parallel computing proved efficient at processing neurophysiological data. It emerged that our GPU algorithm based on CUDA is 60 times faster than original algorithm on CPU. This opens up the opportunity for analysis of cognitive processes that are located in different brain areas and require a large number of electrodes.

Acknowledgements

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Chaotic Neuron-Like Activity in the Ensemble of Fitzhugh-Nagumo Elements with Weak Excitatory Couplings

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In this paper we discuss various types of chaotic neuron-like activity which appear in the FitzHugh-Nagumo ensemble with weak excitatory coupling. As was shown in our recent paper [1] this phenomenological model, but with medium coupling, can demonstrate different types of neuron-like activity, such as in-phase, anti-phase, and sequential regimes. In this study we show that all these regimes preserve in the same model with weak coupling. Moreover, we show that weak coupling leads to the emergence of some other types of neuron-like activity. Winner take all, bursting (of both regular and chaotic types) and also chaotic spiking activity can appear in the model with such couplings.

In the paper we show that the boundaries of existence of limit cycles corresponding to in-phase and anti-phase activity are dangerous [2]. On these boundaries asymptotically stable limit cycles lose its stability due to subcritical bifurcations and principally different type of activity (chaotic bursting or chaotic spiking) appears. Strange attractors corresponding to both chaotic bursting and chaotic spiking are not structurally stable. In the parameter space of the system regions with chaotic activity alternates with the so-called stability windows in which asymptotically stable limit cycles appear.

We also show that stability windows inside regions of chaotic bursting activity correspond to the regular bursting activity, while in the stability windows inside chaotic spiking activity regular sequential regimes of various types appear.

Acknowledgements

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Hyperbolic Chaos in Coupled FitzHugh-Nagumo Model Neurons with Alternating Excitation of Relaxation Self-Oscillations

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The aim of the work is to show that in a simple model of two coupled FitzHugh-Nagumo neurons [1], under appropriate control by an external action providing al-ternating self-oscillations in the subsystems it is possible to accomplish the hyperbol-ic chaos corresponding to Smale-Williams solenoids [2].
Consider a model described by the following non-autonomous system of differ-ential equations:

$$\begin{aligned}
\dot{x} &= f\left(t/T+1/4\right)x-\tfrac{1}{3}x^3-u+\varepsilon(y-x),\\
\dot{u} &= ax-bu+I,\\
\dot{y} &= f\left(t/T-1/4\right)y-\tfrac{1}{3}y^3-v+\varepsilon(x-y),\\
\dot{v} &= ay-bv+I,
\end{aligned} \qquad (1)$$

where the variables (x, u) relate to one and (y, v) to another FitzHugh-Nagumo sub-system; parameters a, b, I are assumed to be constant, ε is the coupling coefficient, and T is the modulation period. The modulation is described by a function f, which satisfies $f(\tau+1)=f(\tau)$, and on a single period it is defined by the relations

$$f(\tau)=\left\{A,\ 0<\tau\le\tau_1;\ \frac{(A-C)\tau+C\tau_1-A\tau_2}{\tau_1-\tau_2},\ \tau_1<\tau\le\tau_2;\ \frac{(C-A)\tau+A\tau_2-C}{\tau_2-1},\ \tau_2<\tau\le 1\right.$$

Bearing in mind that with growth of the value f, the frequency of self-oscillations of the FitzHugh-Nagumo oscillator decreases, parameter A can be chosen so that in the oscillation stage of large amplitude the basic frequency to be smaller than the fre-quency of linear oscillations by an integer .
Let us consider operation of the system in the regime with a hyperbolic attractor. We start with situation when one oscillator performs self-oscillation, and the second is inhibited. When the stage of excitation of the second subsystem comes, it begins to oscillate in a resonant manner due to the action of the M-th harmonic component of the oscillations of the first oscillator. Further, the process repeats again and again with a change in the roles of one and the other

subsystem. Each cycle of transmission of excitation is accompanied by transformation of the phase described by the ex-panding circle map . With compression along remaining directions in the state space, this corresponds to occurrence of a Smale-Williams solenoid as at-tractor in the stroboscopic Poincaré map of the system.

In Fig. 1 panels (a), (b), (c) illustrate the transformation of the phases of oscilla-tions in a half-period of modulation, in three distinct modes corresponding to attrac-tors representing different topological types of the Smale-Williams solenoids (respec-tively, with doubling, tripling and quadrupling of the number of turns at each step of the construction). In the first case, the largest Lyapunov exponent of the map for the period of modulation is close to ln2, and in the second – to ln3, and in the third – to ln4, i.e. to the values corresponding to the double, triple, and quadruple expanding circle map. Figure 2 shows a graph of the highest Lyapunov exponent versus the pa-rameter at larger modulation period. There one can observe plateaus corresponding to regions of existence of the attractors with multiplicity of the number of turns, re-spectively, 2, 3, 4, 5.

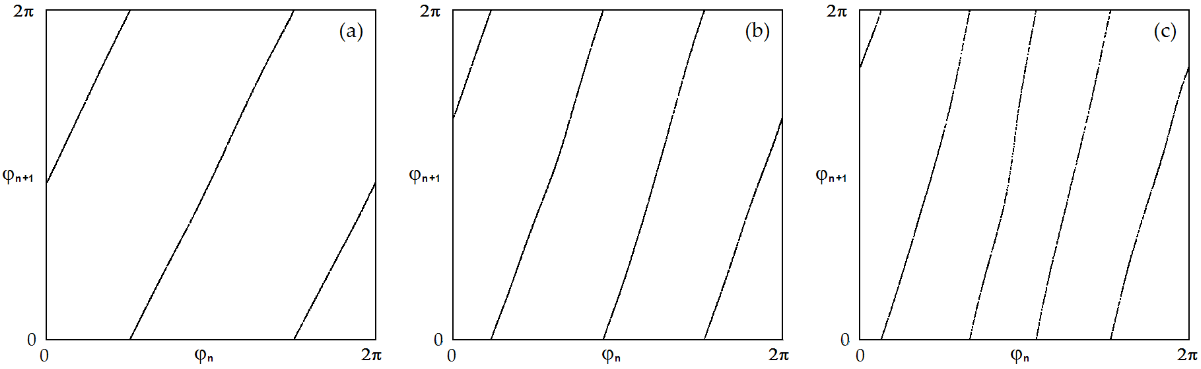

Fig.1. *The maps for the phase in half-period of modulation for A=5.49 (a), A=8 (b), and A=14 (c), where the Lyapunov exponent for the half-period is close, respectively, to ln2, ln3, and ln4, respectively. The remaining parameters are a=1, b=0, I=0.5, ε=0.01, T=400, τ1=0.4, τ2=0.5.*

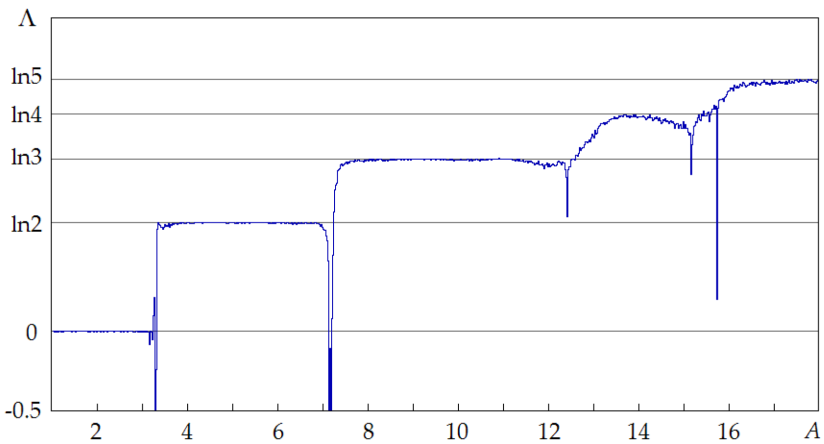

Fig.2. *Parameter dependence of the highest Lyapunov exponent of the mapping for half-period of the modulation at a=1, b=0, K=0.5, C=-2, ε=0.01, I=0.5, T=400, τ1=0.4, τ2=0.5.*

Our results testify to a possibility for systems of alternately excited coupled neurons to manifest hyperbolic chaos, characterized by the property of structural stability. This means a low sensitivity of chaos to variations of parameters, noises, interferences, which can be interesting both for understanding the functional capabilities of systems studied in neurodynamics, and for implementation of their technical counterparts.

Acknowledgements

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The Impact of Electrical Couplings on the Dynamics of Discrete Neuron-Like Elements

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The main goal of this work is to study the influence of electrical couplings to regimes of sequential bursting activity in models of neural ensembles with chemical (synaptic) couplings. For this purpose, a phenomenological model of the minimal ensemble of three non-identical neurons, which demonstrate the specified types of couplings, was considered. Each of the neurons is modeled by corresponding Rulkov discrete neuron [1] with different parameters of individual element. In our previous paper [2] the ensemble of identical Rulkov neurons only with chemical couplings was studied in details. In particular, there were studied various regimes of neuron-like activity occurring in this ensemble when varying the strengths of chemical couplings. Scenarios of appearance and disappearance of these regimes were also investigated. In the papers [3,4] some interesting results were obtained for the role of electrical couplings in the generation of complex regimes of neuron-like activity in the continuous systems. In the present work we investigate the influence both of electrical couplings and the non-identity of the elements on the dynamics of the neuronal ensemble, specially focusing on the evolution of sequential bursting activity, since this regime of neuronal activity is very important from the point of view of neurodynamics [5,6].

We emphasize that results which are presented in the paper are quite similar, by principal qualitative properties, to results of real biological experiments [7]. These results can help to gain a deeper understanding the nature of electrical couplings in the nervous system. The study of their influence on the evolution of neuronal activity is of interest not only from the point of view of nonlinear dynamics, but also contributes to the development of the theoretical basis of bioelectronic medicine and the creation of new methods and approaches for the treatment of diseases of the nervous system that are not amenable to treatment with the help of pharmacological agents.

Acknowledgements

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Unified Neural Network Approach to Cognitive Navigation and Control of Limbs

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Both the effective navigation in time evolving situations, e.g., moving in a crowd, and object manipulation, e.g., catching a ball on the fly, are vital skills for humans and future humanoid robots. The sensory-motor abilities involved in these tasks and ordinarily exhibited by humans may appear simple at first glance. However, the intrinsic complexity of these simple-but-difficult tasks impedes modern robots to mimic smoothly even basic human skills in real-life scenarios.

Navigation and object manipulation require forecasting the future states of different objects in the environment, their matching with feasible body movements, and selecting optimal strategies. The fundamental bases of how our brain solves these tasks remain largely unknown. Here, we discuss a novel approach that addresses both problems at an abstract unified cognitive level, implemented in a lattice of locally coupled neurons.

Earlier we have introduced the concept of generalized cognitive maps (GCMs) that allows representing dynamic situations faced by an agent (human or robot), while moving in a complex environment, as a purely static map [1,2]. Such a representation enables tracing trajectories and navigating to a target in a simple yet robust way [3]. Nevertheless, while dealing with the problem of object manipulation, such an approach is not directly applicable due to spatial extension of limbs. We then exploited the GCM concept in the so-called handspace [4]. Under a transformation from the workspace to the handspace a limb is reduced to a point at an expense of extension of other objects found in the environment. Then, the evolution of the handspace can be modeled by a lattice of neurons whose dimension is defined by the number of degrees of freedom in the limb (the dimension of the handspace). The neural network simulates a wave simultaneously exploring different subject actions, independently on the number of objects in the workspace.

In the talk we will discuss the implementation of GCMs in a neural network and provide representative examples illustrating the network dynamics and robot navigation in complex environment. Then, we will introduce the handspace and show that the approach is scalable to limbs with minimalistic and redundant number of degrees of freedom (DoFs). We will show that method also allows biasing the effort of reaching a target among different DoFs. Such ability is widely used by humans in problems of complex object manipulation. Thus, a unified approach to the problems of cognitive navigation and object handling based on GCMs and neural networks will be introduced and exemplified.

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Brain-Computer Interface for Recognition of Brain Activity in Imagined Movements Using an Artificial Neural Network

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Brain-computer interface (BCI) is an interesting topic of physics, neuroscience and engineering. This technology is already in demand in the applied fields, including medicine, industry and others [1,2,3]. Currently, the developed neural interfaces allow you to control the movement of the cursor [4], partially synthesize speech [5]. BCI can be effectively used for rehabilitation, as well as for exoskeleton control.

In the framework of the current research problem our study is focused on the development BCI for the correct recognition of movements of the right and left hand in real time. For the most effective solution of this problem we have chosen artificial neural networks (ANNs) which is a mathematical tool for the analysis and decoding of brain activity.

During the experiment, we recorded brain activity, when the subject successively squeezed his hand into a fist, and then unclenched back. The person was sitting, so we have excluded the influence of the brain activity associated with maintaining the person in an upright position. The experiment included groups of real and imaginary movements. Before recording imaginary patterns, a person performed a group of real movements. It was image data that was fed to the neural network for training.

To solve the classification problem, we use in our work ANNs of direct propagation. Multilayer perceptron shows good results of recognizing types of movements. Multilayer perceptron is a frequently used tool for solving a wide range of problems in many scientific fields. The effectiveness of solving a problem using multilayer perceptron depends not only on the representativeness of a training set, but also on the successful choice of the structure of the ANN.

The general structure of the used multilayer perceptron is shown in Fig. 1. The number of inputs of the ANN corresponds to the number N of channels of the input set (the maximum number of channels corresponds to the dimension of the EEG data). The number of neurons of the first layer is equal to or more than the number of inputs. Multilayer perceptron contains hidden layers. Classification problem in the case of two classes can be solved by a neural network with one output, which takes one of two values.

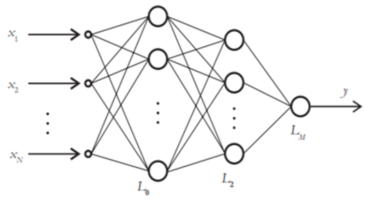

Fig.1. *The structure of the multilayer perceptron*

For neural network correct choice of optimization method determines the electiveness of training. We have used Levenberg-Marquard method, who has a good convergence and accuracy of the solution, for learning of ANN.

The researches on recognition and identification of patterns of various types of human movements using ANNs demonstrate that the use of multilayer perceptron allows to classify confidently (with an accuracy of more than 80%) imaginary movements on rather short time fragments of MEG signals. In addition, preliminary data processing, namely, filtering the signal with a bandpass filter in the frequency range of 0.5-10 Hz, demonstrates an increase in recognition accuracy to acceptable level (88-99%).

The positive results of this study are very useful for creating brain-computer interfaces and control systems for exoskeletons and anthropomorphic devices.

Acknowledgements

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The Dynamics of Ensemble of Neuron-Like Elements with Excitatory Couplings

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We study the phenomenological model of ensemble of two FitzHugh-Nagumo neuron-like elements with symmetric excitatory couplings. The main advantage of proposed model is the new approach to model of coupling which is implemented by smooth function that approximate rectangular function. The proposed coupling depends on three parameters that define the beginning of activation of an element α, the duration of the activation δ and the strength of the coupling g. We observed a rich diversity of different types of neuron-like activity, including regular in-phase, anti-phase and sequential spiking activities. In the phase space of the system, these regular regimes correspond to specific asymptotically stable periodic motions (limit cycles). We also observed in the proposed model a chaotic anti-phase activity, which corresponds to a strange attractor that appears due to the cascade of period doubling bifurcations of limit cycles.

In addition, we investigate in the paper an interesting phenomenon when two different chaotic attractive regimes corresponding for two different types of chaotic anti-phase activity merge in a single strange attractor. As a result, a new type of chaotic anti-phase regime appears from the collision of these two strange attractors by explosion.

We also provide the detailed study of bifurcations which lead to transitions between all these regimes and detect on the (α, δ) parameter plane those regions that correspond to the above-mentioned regimes. We also show numerically the existence of bistability regions when various non-trivial regimes coexist. For example, in some regions, one can observe either anti-phase or in-phase oscillations depending on initial conditions. We also specify regions corresponding to coexisting various types of sequential activity.

In the future, we plan to apply the developed phenomenological model for modeling neural ensembles from a large number of elements.

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Classifying Brain Responses to Motor Imagery by Analyzing MEG Recordings

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Motor imagery is the dynamic simulation of the brain that manifests itself as a result of the rehearsal of a given motor action in the working memory without any overt movement of the corresponding muscles. The understanding of the neurophysiological mechanisms responsible for performing motor imagery is essential for the development of brain-computer interfaces. Motor imagery can be classified into two categories, namely, visual imagination (VI) and kinesthetic imagination (KI).

We carried out the experimental magnetoencephalographic MEG study with 8 untrained subjects, both male (6 persons) and female (2 persons). The subjects were sat in a comfortable reclining chair with their legs straight and arms resting on an armrest in front of them. All subjects were informed about which limb they need to imagine moving next, visually on a screen in front of them. The subjects were then required to commence their imagination on hearing audible beeps as their cue with their eyes closed. Each beep and the following imagination corresponded to a single trial. The number of MEG trials varied between the subjects from 16-28 per limb. The beeps were presented with time gaps varying from 6-8 seconds, randomly distributed. The whole MEG experiment was divided into 4 series with a quarter of the total number of trials in each. There was a 20-sec gap after finishing all the trials of a limb in a particular series. There was a 60-sec gap between each of the 4 series. A background MEG data with closed eyes was recorded at the end of the experiment, the duration of which varied from 40-120 seconds across the subjects. Artifacts in the MEG recordings due to eye-movement, heartbeat, breathing and blinking were removed using the temporal signal-space separation method.

Our experiments confirmed the existence of these two types of motor imagery. While neurophysiological brain activity corresponding to KI is similar to real movement because it implies muscular sensation when performing an imaginary moving action, VI refers to the self-visualization of the corresponding action. KI is usually observed in specially trained subjects or professional sportsmen. The brain activity associated with KI corresponds more closely to real movements in contrast to VI. These two types of motor imagery are distinguished by the activation or inhibition of different brain areas in μ (α and β) frequency region. Motor imagery, especially in subjects with higher tendency for KI over VI, involves the generation of motor signals which are then blocked at some level of the motor system by inhibitory mechanisms. There is evidence that this inhibitory control is exerted by the inferior parietal lobe during motor imagery.

The use of Morlet wavelets allowed us to extract the time-frequency content of the MEG signals from the 102 magnetometer channels. The VI activates primarily the occipital region and the precuneus, whereas KI activates motor-associated structures and the inferior parietal lobe. The difference of the spectral activity between the event and resting, normalized to the mean resting state activity, was used to evaluate the event-related potentials (ERP). The significant changes in ERP of μ-waves are shown in Fig. 1. We suppose that μ-waves act as a carrier to carry information encoded in the γ-region pertaining to the limb motion.

We also applied artificial intelligence to classify MEG trials related to different type of imagery and different kinds of imaginary movement, e.g., lifting either left or right arm, or left or right legs. The classification of the brain states related to different kind of imaginary movement using artificial neural network (ANN) gave better accuracy for the professional sportsman than for untrained volunteers. After evaluating the most informative 72 channels using principal component analysis (PCA), we found that the 30-Hz low-pass filtering provides the best accuracy (up to 83% for professional sportsman) in classification of the brain states related to the imaginary movement of the left and right arms. The results indicate that regular mixing is the most efficient ANN training method.

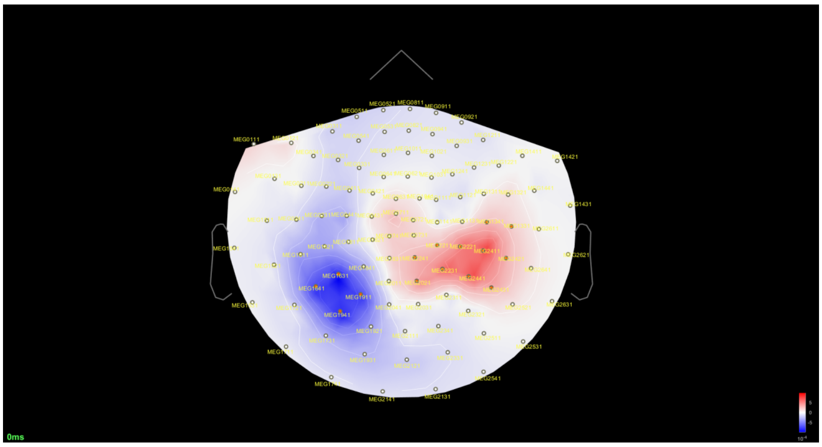

Fig. 1. *Significant changes in ERP in the professional sportsman during motor imagery.*

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Patterns of Periodic and Eventually Periodic Orbits of a Neuron Model with a Periodic Internal Decay Rate

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It is our goal to study the existence of periodic solutions, existence of eventually periodic solutions and the study of boundedness nature of solutions depending on the relationship between the periodic terms of the sequence of our neuron model; in particular, it is our objective to study which particular periodic cycles of various periods will exist, the patterns of these periodic cycles and their stability character as well. Furthermore, we will investigate which particular periodic cycles of our neuron model can be eventually periodic and why only particular ones be eventually periodic; we will analyze this behavior together with a bifurcation diagram as well. Moreover, we study different patterns of the transient terms of eventually periodic solutions to understand the phenomena more precisely.

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Synchronization of Coupled Hindmarsh-Rose Neurons by Time-Delay Using Electronic Circuits

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Study of synchronization of two neuronal electronic circuits based on Hindmarsh-Rose (HR) [1] coupled with delay is performed. Through bifurcation diagram of Inter Spike Intervals of potential action, we study the dynamics behavior of only one neuronal electronic circuit HR, and also identified different regimens dynamics of response of neuronal electronic model to the membrane current I, such as, spiking, bursting and chaotic of the potential action,. We analyzed different regimens of synchronization for two neuronal electronic circuits HR coupled uni- and bi- directional by potential action between of neurons, with different delays and synapsis coupling strength. Based on analyses of the time series between neurons electronic model we have found different types of synchronization; complete synchronization, phase synchronization and lag synchronization which dependent on the gain and time-delay in the coupling.

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Two BZ-oscillators Connected via Both Diffusive and Pulsatile Coupling

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In real nervous systems, in addition to time delayed pulse coupling (chemical synapses) the connection between neurons is realized via gap junctions (electrical synapses), which in some sense are analogous to diffusive coupling. A cooperation of electrical and chemical synapses plays very important role in the functioning of nervous systems. Such type of coupling can be reproduced, for example, in systems of diffusively coupled oscillatory BZ-microdroplets with photochemical reactions. Considering this, two BZ-oscillators coupled via both diffusive and pulsatile coupling were investigated theoretically.

To simulate dynamics of a single isolated oscillator we use 5-variable model of BZ reaction. In order to exclude solutions, which are sensitive to inevitable in real experiments small perturbations, we apply slightly different native frequencies of oscillators. By modifying equations in a certain way different types of coupling were introduced in the following combinations: inhibitory diffusive and inhibitory pulsatile (IDIP), excitatory diffusive and inhibitory pulsatile (EDIP), inhibitory diffusive and excitatory pulsatile (IDEP), excitatory diffusive and excitatory pulsatile (EDEP). We consider each type of coupling to be bidirectional and symmetrical.

Series of numerical simulations with different coupling strengths and time delay revealed that the IDIP coupling is the most interesting since it gives six new dynamical modes, which can't be found neither for the pure diffusive, nor for the pure pulsatile coupling: IP1, IP2, AP2, AP-T, OSI-T, and C. The EDEP coupling has revealed another new mode, the CL (chaos-like) mode. The other two types of coupling (IDEP and EDIP) demonstrate only the threshold transitions from one mode to another one, but no new dynamical modes.

The regions of C and CL modes include many different modes (like C(N1,N2) with different numbers N1 and N2). We suppose that enormous number of C modes can be found in networks of three or four oscillators with mixed coupling.

For two almost identical coupled oscillators, it is not so simple to find a plenty of new modes. We suppose that these modes can be used for information processing. Overall, results of this work might be useful for the development of chemical computer and for more general insight into the functioning of neural networks with both electrical and chemical synapses.

Acknowledgements

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Chimera States in Brain Networks and Application to Epileptic Seizure

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Complex spatiotemporal patterns, called chimera states, consist of coexisting coherent and incoherent domains and can be observed in networks of coupled oscillators. The interplay of synchrony and asynchrony in complex brain networks is an important aspect in studies of both brain function and disease. We analyse the collective dynamics of FitzHugh-Nagumo neurons in complex networks motivated by its potential application to epileptology and epilepsy surgery [1]. We compare two topologies: an empirical structural neural connectivity derived from diffusion-weighted magnetic resonance imaging and a mathematically constructed network with modular fractal connectivity. We analyse the properties of chimeras and partially synchronized states, and obtain regions of their stability in the parameter planes. Furthermore, we qualitatively simulate the dynamics of epileptic seizures and study the influence of the removal of nodes on the network synchronizability, which can be useful for applications to epileptic surgery.

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Stochastic Toroidal Bursting in Hindmarsh-Rose Model

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We study the dynamics of the three-dimensional Hindmarsh-Rose neuron model [1] under the influence of random perturbations. The original deterministic system is characterized by a variety of dynamic regimes and bifurcations. This model can exhibit different types of limit cycles representing tonic spiking and bursting oscillations, period-doubling and period-adding bifurcations, coexistence of several attractors, chaotic regimes. Moreover, recently it was shown that Hindmarsh-Rose model can have peculiar dynamic solutions, torus canards [2].
In this work, we consider parameter zones near the Neimark-Sacker bifurcation related to a transition between the tonic spiking regime modeled by a limit cycle and the bursting regime represented by an invariant torus. We show that in the parametric zone, where the deterministic system exhibits a limit cycle, random disturbances can transform it to a dynamical structure resembling that of a torus, and the spiking oscillating regime changes to the torus bursting one (see Fig.1). In other parameter region, where the deterministic system exhibits the quiescence, noise can lead to the generation of toroidal dynamical structure with the transition to the bursting regime. Moreover, we show that the stochastic emergence of torus is followed by the noise-induced chaotization.
An analysis of these phenomena is carried out using statistical methods of interspike intervals, power spectral density and a new constructive approach based on the stochastic sensitivity function technique and the confidence domains method [3,4].

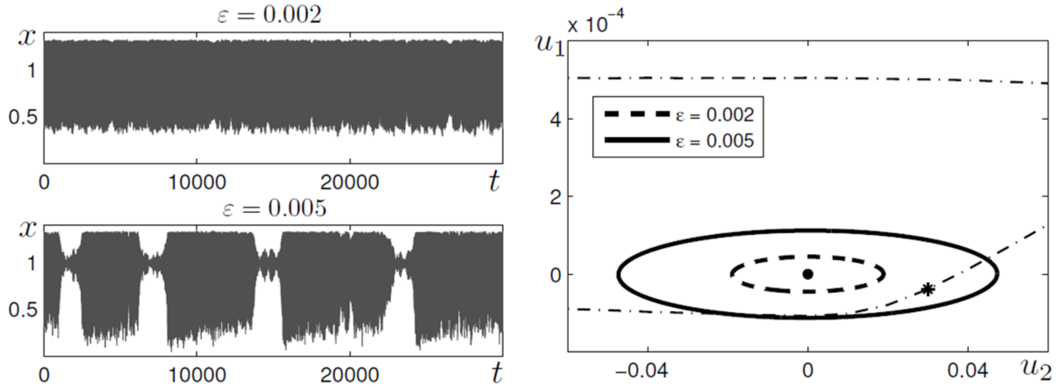

Fig.1. *Stochastic transformation of tonic spiking into toroidal bursting in the three-dimensional Hindmarsh-Rose model: (a) time series of the stochastic system; (b) the method of confidence ellipses in the normal plane.*

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Fast Learning of Complex Behaviors from Demonstration in Neural Networks

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Social or imitation learning through transferring information from an experienced agent to a naive one is widely observed in many species. Yet, the neuronal dynamical mechanisms underlying this paradigm remain largely unknown. While learning, an agent (human or robot) first have to isolate essential motor actions (motifs) from the observed performance, to compose meaningful actions later. Recently we have proposed an approach that allows synthesizing behaviors in a neural network of a learner agent by simply observing the dynamics of a teacher [1]. To tackle the problem, we consider a generalized Lotka-Volterra model with global inhibitory couplings among neurons. Asymmetry of such couplings allows the model to exhibit the so-called winner-less competition (WLC) dynamics [2], according to which a trajectory can wander in the phase space from one saddle to another, thus implementing a particular temporal pattern of neuronal excitation.

Here we propose a learning algorithm capable of copying the behavior of one WLC neural network to another. We further discuss how an autonomous robot equipped with the provided learning model can rewire "on the fly" its synaptic couplings in order to converge to the durations of the teacher's motor motifs, and hence mimic its movements.

To validate the model, we tested the algorithm on two robotic platforms (Pioneer 3DX), one playing the role of a teacher and the other as a learner. Figure 1A shows a flower-like trajectory corresponding to five repetitions of a programmed motor pattern. The neural network of the learner is initialized at random, thus its movements are quite chaotic at the beginning (Figure 1B). However, after few demonstrations the learner learns the teacher's trajectory and finally it successfully copies the teacher's behavior.

The reported mechanism of learning is general and can be used for replicating different functions, including, for example, sound patterns or speech.

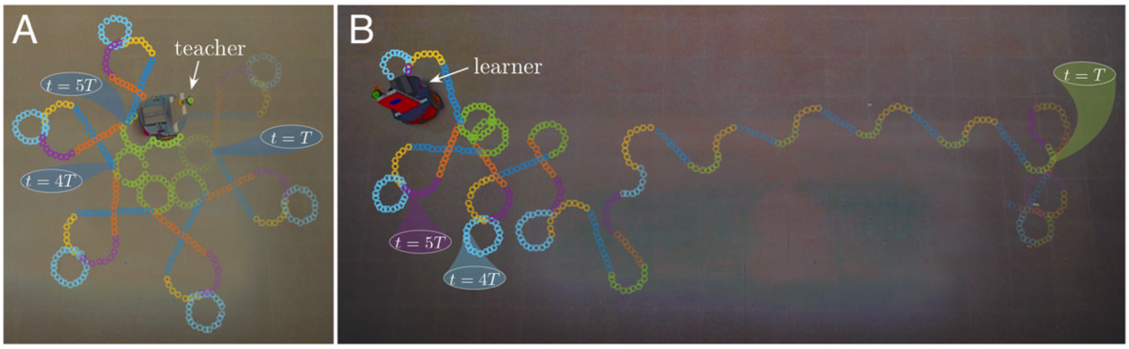

Fig.1. Experimental validation of learning. A) Robot-teacher implements a behavior composed of six motor motifs. The brightness of colors corresponds to time (the brighter, the closer to the present). B) Trajectory of the robot-learner. At the beginning it behaves randomly. However, in a few number of cycles the robot adjusts the coupling strengths and eventually replicates almost exactly the sequence of turns of the teacher.

Acknowledgements

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Experimental Evidences of Time Compaction in Human Cognition

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Animals must interact with time-changing environments in complex and reliable ways for ensuring their survival. For this to successfully happen, the brain must understand what happens around, forming coherent internal representations despite the huge amount of information conveyed by the temporal dimension. This way, cognitive interaction with dynamic environments and/or agents implies processing and storing huge amounts of data that must be quickly retrieved in the form of intelligent behaviours. Recently proposed theory of time compaction has provided a sound explanation to how the brain codifies the vast spatiotemporal information contained in a dynamic situation. According to time compaction, when we perceive a time-changing situation the brain anticipates future relevant events and structure them spatially by solving their possible interactions (including, if pertinent, the subject itself). Therefore, compacting time results in a static purely-spatial internal representation of the perceived dynamic situation containing only the critical information, named Generalized Cognitive Maps (GCM). In consequence, as time is no present, the amount of information the brain processes would be drastically reduced.

In the present work we explore whether time compaction may be a biologically plausible mechanism underlying mammal's cognition. In order to achieve this, 261 human volunteers (135 women and 126 men) participated in an associative learning game in which they were prompted to find the association rule between different visual stimuli and the up and down arrow keys. The game consists in two stages: a first conditioning stage, where the subject learns an associative rule for three static stimuli (scenes showing two static circles), and a second testing stage, where the participant must figure out the association rule for six dynamic stimuli (situations where two circles move following straight lines at constant velocity). The stimuli displayed during the conditioning phase were designed according to the theory of time compaction to interfere with the association rule learning during the testing phase. In particular, one of the static scenes corresponded to the GCM of two of the six dynamic situations displayed during the testing phase, i.e. the scene shows one of the circles in the location where circles in the situation will collide. Thus, according to the time compaction theory, when the arrow key associated to such a scene matches/mismatches with the arrow key linked to those situations, the learning of the association rule during the testing phase was favoured/hampered.

The results reveal that men for whom these matching scene and situations had the same association rule in both phases learned at a faster rate during the testing phase than participants with impaired associations between matching scene and situations, as predicted by the time compaction theory. Actually, it is remarkable that women weren't apparently affected by these conditions, even though they performed on par with control men. This result is coherent with the hypothesized role of time compaction in human cognition as a neural mechanism involved in the optimization of fast and reliable interaction with dynamic complex environments. In addition, regarding verbalization of the association rule figured out during the testing phase, men tend to describe the rule in terms of collision more frequently as they learn faster (regardless the type of conditioning). Finally, we developed a mathematical model describing the learning process during the proposed game simulates the experimental outcome and offers insight into the learning process. These results reveal that dynamic situations are internally structured as static scenes, evidencing the existence of a time compaction cognitive mechanism involved in real-time generation of efficient and complex strategies to interact with our world.

Dynamical Mechanisms of High Frequency Spiking of a Dopamine Neuron

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Dopamine neurons located in the ventral tegmental area (VTA) play a key role in many cognitive tasks. Interactions between the dopamine (DA), VTA γ-aminobutyric acid (GABA) neurons, and prefrontal cortex neurons are critical for regulating DA neuron activity, and thus DA efflux. Here we consider some dynamical mechanisms underlying synchronization properties of DA neurons. The first dynamical mechanisms concern the change of excitability (spike generation) class of the DA neuron depending on its synaptic inputs and synaptic currents. The neuronal excitability determines the neuron's response to stimuli, its synchronization and resonance properties and, ultimately, the computations it performs in the brain. We investigated the dynamical mechanisms underlying the excitability type of DA neurons using both a conductance-based biophysical and a phenomenological models, and its regulation by intrinsic and synaptic currents. Calibrating the model to reproduce low-frequency tonic firing results in N-methyl-D-aspartate (NMDA) excitation balanced by GABA-mediated inhibition and leads to class I excitable behavior characterized by a continuous decrease in firing frequency in response to hyperpolarizing currents. Furthermore, we analyzed how the excitability class of the DA neuron model is influenced by changes in the intrinsic current composition. The key characteristics of synaptic conductances that are often tonically active in vivo also change the class of excitability: Depolarizing GABA receptors reversal potential or co-activating AMPA receptors leads to an abrupt frequency drop to zero, which is typical for type II excitability. Coactivation of NMDARs together with AMPARs and GABARs shifts the class I/II boundary toward more hyperpolarized GABAR reversal potentials. Collectively, these results imply that class I excitability in dopamine neurons might be important for low firing rates and fine-tuning basal dopamine levels, while switching excitability to type II during NMDAR and AMPAR activation may facilitate a transient increase in dopamine concentration, as class II neurons are more amenable to synchronization by mutual excitation.

Another dynamical mechanism allowing to "overclock" the DA neuron relates the action of the synchronized GABA neuron population (which is much faster than the DA neurons). In the framework of a circuit model of the VTA, asynchronous activity of GABA neurons provides a constant level of inhibition to the DA neuron, and, when removed, produces a classical disinhibition burst. In contrast, when GABA neurons are synchronized by a common synaptic input, they are able to produce a moderately strong high frequency pulse train which can provide high frequency forced oscillations of a DA neuron. Such oscillations have the frequency coinciding with the frequency of the external force and amplitude that is larger than the amplitude of the intrinsic oscillations. Distinct from the previous mechanisms, the frequency growth was not based on lowered firing rate of the GABA neurons or weaker hyperpolarization by the GABAR synaptic current. We explain such dynamics in detail using the McKean oscillator (the system, which is a piecewise linear analogue of the FitzHugh-Nagumo model) for which we analytically built a map that gives an explanation of these properties. It was shown that such high frequency forced oscillations exist in the large region of the external force parameters (pulse amplitude and frequency). Interestingly, in application to neuroscience, both excitatory and inhibitory inputs can force the high-frequency oscillations.

This work was partially supported by the Russian Foundation for Basic Research (grants 17-02-00874 and 18-41-520001). Alexey Kuznetsov was supported by NIH NIAAA grant R01AA022821. Boris Gutkin was supported by the LABEX ANR-10-LABX-0087 IEC and IDEX ANR-10-IDEX-0001-02 PSL* and also acknowledges the RF academic excellence Program 5-100.

Cost-efficient Trade-Off in Neural Connectivity and Activity

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We are interested in understanding neural systems as functional, complex dynamical networks. The brain is highly energy consuming, therefore is under strong evolution pressure to achieve cost-efficiency in both cortical connectivity and activity. In our recent works, we emphasized that the formation of the complex network architecture and dynamical activity of neural systems is subject to multiple structural and functional constraints. In the macaque brain connectome, we showed that network connectivity indeed displays a cost-efficiency trade-off, and up to 67% of the existing links can be recovered by the trade-off model. The model also reveals new organization feature of long distance-connectors (LDCs) in the system which are crucial for both functional segregation and integration. In terms of neural activity, we demonstrated using biologically plausible neural circuit model that the co-emergence of salient features of cortical activity, including irregular firing, oscillations and neuronal avalanches as observed in experiments achieves minimal energy cost as well as maximal energy efficiency on information capacity. Indeed, cost-efficient neural network structure and cost-efficient neural dynamics have collaborative interaction to enable neural systems to achieve "less is more" in both structure and dynamics. The perspective of cost-efficiency trade-off could provide a framework to better understand various salient features in neural connectivity and activity, and likely also suggest a novel angle to study the inherent vulnerability in brain networks which could be closely related to various neurodegenerative diseases and brain disorders.

Comparison of Brain Functional Connectivity Estimation on Sensor and Source Levels

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Brain functional connectivity is relatively new but widely used method of studying brain dynamics in rest and task-related activity. However, reliability of EEG measures of connectivity is still discussed due to ambiguous reliability and replication artifacts.

Aims: In our study we aimed at comparison of brain resting state connectivity estimation on sensor space and source space with different mathematical tools.

Methods: 87 participants took part in the study (21.41, SD = 3.56, 25% males). Resting state EEG was recorded for closed and open eyes in sequence CE = OE = CE = OE = CE with 64-electrode BrainProducts ActiChamp amplifier for 10 minutes in dimly lit sound and electric-proof camera.

Connectivity estimation procedures then were performed both in sensor and source spaces. Source space map was obtained after performing sLORETA on reconstructed 3D head model and resulted in 503 brain sources in 513 time windows.

For functional connectivity measures, we firstly calculated the Phase Lag Index of phase synchronization (Stam et al., 2007) for each pair of electrodes in sensor space and 503 sources in source space for six frequency bands (alpha-1 (8-10 Hz), alpha-2 (10-13 Hz), alpha (8-13 Hz), beta-1(13-20 Hz), beta-2(20-30 Hz) and theta (4-8 Hz)). Graph network analysis then was performed for PLI illustration between electrodes and between reconstructed sources from which we calculated the clustering coefficient C (describing local interconnectedness) and average path length L (describing global interconnectedness) for each individual (Stam et al., 2009).

Secondly, Mutual Information were used to obtain brain connectivity matrices in sensor and source spaces (Kraskov, Stögbauer & Grassberger, 2004).

Results

Pairwise connectivity estimates on both sensor and source levels were found to be selectively compatible.
Conclusion: We found that connectivity estimation is compatible when evaluated on different levels of EEG signal sources. However,

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Dynamics of Large-Scale Epileptic Brain Networks

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Epilepsy is one of the most common serious neurological disorders, affecting approximately 65 million people worldwide. Epileptic seizures are the cardinal symptom of this multi-facetted disease and are usually characterized by an overly synchronized firing of neurons. Seizures cannot be controlled by any available therapy in about 25% of individuals, and knowledge about mechanisms underlying generation, spread, an termination of the extreme event "seizure" in humans is still fragmentary. Epilepsy is nowadays conceptualized as a network disease with functionally and/or structurally aberrant connections on virtually all spatial scales. All constituents of large-scale epileptic networks can contribute to the generation, maintenance, spread, and termination of even focal seizures as well as to the many pathophysiologic phenomena seen during the seizure-free interval. I will provide an overview of the progress that has been made in understanding the long-term dynamics of large-scale epileptic networks and will discuss its impact on the development of new therapeutic possibilities as well as on computational models of epileptic phenomena.

Excitability and Synchronization of Phase-Controlled Neuron-Like Generator

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The main object of the study is a neuron-like generator based on a phase-locked loop. The mathematical model of the generator has been introduced and analyzed in [1]. Theoretical study of the model has shown the presence of different self-oscillating modes like regular spiking and bursting and chaotic spiking. The areas of the modes have been found in parameter space.

Theoretical study of the generator in excitable state under pulse stimulation has been conducted. The generator's responses to stimulation have been synchronized with different rational frequency ratios depending on the amplitude of stimulation.

The stimulation of the excitable generator by bursting neuron has been studied. The generation of responses is observed with different ratios: spike generated on each stimulus burst (ratio 1:1), one spike generated on every second burst (ratio 1:2) and some rational ratios (2:3, 3:4, etc) depending on the coupling strength.

Special interest for collective use of the observed generators and for nonlinear dynamics in general is concerned with synchronization of complex multifrequency oscillations (bursts). The neuron is possible to generate oscillations of different complexity, so synchronization of bursts has been studied. For synchronization of unidirectionally coupled bursting generators the increase of synchronization region has also been observed with increasing coupling strength.

Interaction of two unidirectionally coupled neurons has been studied theoretically. Synchronization of regular spiking has been found and synchronization region increase with coupling strength. The coupling function has been adapted from synaptic coupling of two Hodgkin-Huxley neurons [2].

The sharp decrease of coupling strength required to excite spike on slave generator found with low stimulation frequencies. Thus, the probability of response to stimulation increase on low frequency stimulation.

Acknowledgements

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Dynamic Modes in a Network of Five Oscillators with Inhibitory All-to-All Pulse Coupling

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The dynamic modes of five almost identical oscillators with pulsatile inhibitory coupling with time delay have been studied theoretically. The models of the Belousov–Zhabotinsky reaction and phase oscillators with all-to-all coupling have been considered. In the parametric plane Cinh–tau, where Cinh is the coupling strength and tau is the time delay between a spike in one oscillator and pulsed perturbations of all other oscillators, three main regimes have been found: regular modes, when each oscillator gives only one spike during the global period T, C (complex) modes, when the number of pulses of different oscillators is different, and OS (oscillations-suppression) modes, when at least one oscillator is suppressed. The regular modes consist of several cluster modes and are found at relatively small Cinh. The C and OS modes observed at larger Cinh intertwine in the Cinh–tau plane. In a relatively narrow range of Cinh, the dynamics of the C modes are very sensitive to small changes in Cinh and tau, as well as to the initial conditions, which are the characteristic features of the chaos. On the other hand, the dynamics of the C modes are periodic (but with different periods) and well reproducible. The number of different C modes is enormously large. At still larger Cinh, the C modes lose sensitivity to small changes in the parameters and finally vanish, while the OS modes survive.

Oscillator Networks: Collective Dynamics through Generalized Interactions

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Brain function is linked to the dynamics of the underlying network of neural oscillators and the rhythms it generates through synchronization and other collective behavior. The Kuramoto model, which has been widely used to study collective dynamics in oscillator networks in the neurosciences and beyond, assumes that interactions between oscillators is determined by the sine of the differences between pairs of oscillator phases. We show that more general interactions between identical phase oscillators allow for a range of collective effects, ranging from chaotic fluctuations to switching dynamics between states that are locally frequency synchronized.

Interneuronal Heterogeneity in the Cortex Shapes Network Dynamics and Functional States

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This work focuses on the functional roles of the hierarchy of interneuron types observed in the mammalian cortex. In particular, we consider implications of interneuronal heterogeneity for the dynamics of visual and prefrontal cortical areas. We develop a mathematical model of cortical activity, which enables us to study the effects of interneuronal modulation on network activity depending on the interneuron type. Different inhibitory neuron types implement different inhibition mechanisms, both functionally (substractive vs. divisive inhibition) and anatomically (local vs. global inhibition). For the visual cortex activity model, we provide estimates for network stimulus orientation detection error, depending on altered activity levels in specific interneuronal populations. In the prefrontal cortex model, we demonsrate an inhibition-dependent transition from globally synchronized activity to irregular bistable switches of pyramidal neuron subpopulations, an effect observed experimentally.

Complex local circuitry in the cortex comprised of pyramidal cells and three primary types of interneurons [ref] was experimentally shown to modulate the structure of spontaneous cortical activity in a non-trivial manner [ref]. By introducing genetic mutations of specific nicotinic acetylcholine receptors (nAChRs), which are selectively located on interneurons of different types, it was observed that reduced inhibition in the prefrontal cortex (PFC) reduced the synchrony of neuronal firing, eventually leading to irregular chaos-like bistable activity of individual neurons at very low inhibition levels. Increasing inhibition by modulating activity of VIP interneurons also disrupted network synchronicity by introducing timing jitter to global “spike-like” activation events in the network. We demonstrate that this type of activity might be explained in a simple rate-based mathematical model of the PFC, if non-uniformity of synaptic connectivity in the network is taken into account. In our model, strong recurrent connections within subpopulations of neurons (synaptic clusters) induce bistable dynamics within the subpopulation independently from the rest of the network. We show that a set of such interacting bistable clusters might globally synchronize, as seen in the experiments, and the extent of this synchronization depends on the level of activation in specific interneuron types.

We extend the developed framework on the visual cortex primary area (V1) model with specific ring-like connectivity. It is shown that modulation of different interneuron types affects the network’s ability to encode characteristics of stimuli in a different way. In particular, we demonstrate how increased activation of PV+ and SOM interneurons affects orientation detection precision in the V1 area. Optimal connectivity of the multiple-interneuron-type cortical circuitry is found which minimizes orientation detection errors.

Acknowledgements

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Personalized Mathematical Models of Human Cardiomyocytes Electrophysiology

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Over the past few decades, mathematical models of heart electrophysiology came a long way in terms complexity and the area of application. However, despite these advances mathematical models remain strictly deterministic by their nature. While tissue-specific, person-specific and pathology-specific gene expression profiles affect AP propagation; these differences are usually not accounted for. In our study, we use several approaches to determine the personalized set of model parameters: molecular (mRNA) data analysis, i.e. forward problem; and genetic algorithms (GA) to determine the set of parameters using AP recordings, i.e. inverse problem.

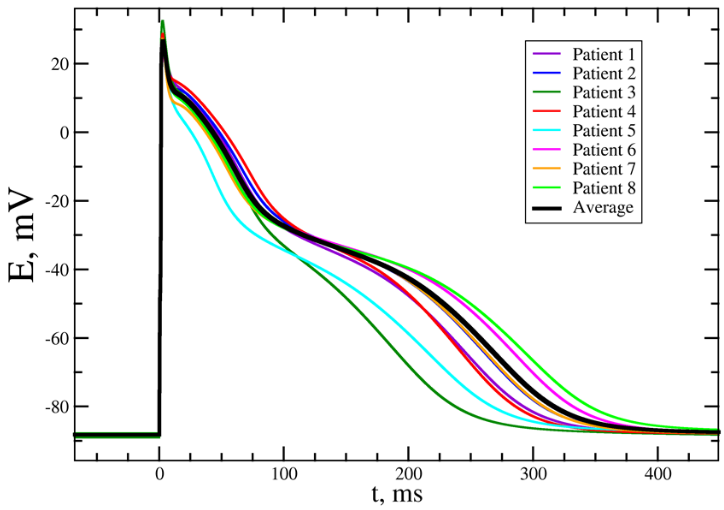

Fig.1. *Person-specific simulated atrial AP waveform.*

Donor hearts (n=8) with no recorded history of cardiovascular diseases were procured for biopsy collection of atrial and ventricular tissue. RNA expression data was measured via Cap Analysis of Gene Expression technique (CAGE) [1]. Personalized mathematical models of human atrial and ventricular cells were developed by modification of O'Hara-Rudy model [2] parameters using RNA data. Inverse problem was solved via GA [3].

Personalized human models were developed by rescaling the ionic channels conductivities of O'Hara-Rudy model. The resulting models retain ventricle-specific action potential morphology and restitution properties. Atrial models were developed in a similar manner with the following modifications. O'Hara-Rudy model was augmented by ultra-rapid potassium current specific for atrial tissue. New formulations were proposed for L-type calcium current and inner-rectifying current because of different profile of corresponding ionic channels subunits expression in atria and ventricles. Resulting models capture atrial-specific AP waveworm (Fig.1) and restitution properties.

Some kind of a "gold standard" is required for personalized models development (i.e. a model with known ionic channels conductivities as well as molecular data). One possible solution is solving an inverse problem to determine ionic channels conductivities using AP measurements. We have developed a modification of GA capable to determine model parameters using AP waveform dependence on cycle length. The error was within 20% for most ionic channels and pumps conductivities (Fig. 2).

The approach for the personalized mathematical models development discussed above is a promising tool for cardiac electrophysiology researcher.

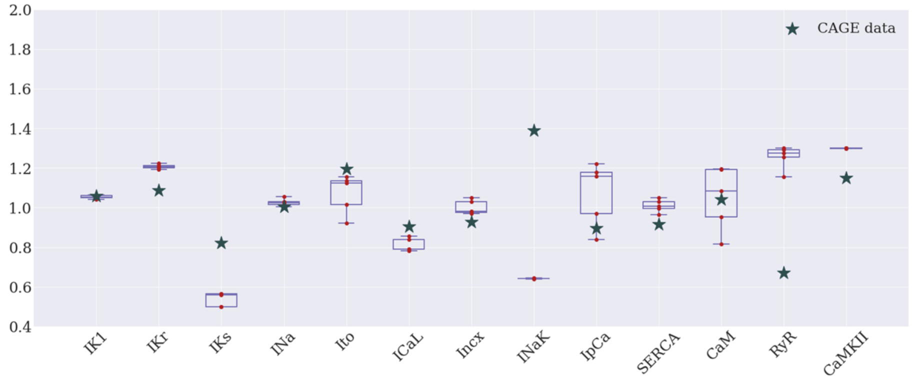

Fig.2. *Comparison of the model parameters determined by GA (box-and-whiskers, different runs of GA are marked by red dots) with molecular data (stars).*

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Chaos and Randomness in Neuronic Systems

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The purpose of this talk is to present several concrete examples of dealing with chaos and random choice/random noise in neuronic systems, i.e. in natural and artificial neuronal circuits.
First, we will present data on chaos in cerebellum and its functional role [1].
Second, we will describe the role of noise in obtaining the effective use of parallel neuronal channels [2].
Third, we will consider roles of random choice of inter-neuronal connections and random initial conditions for synaptic weights in learnable networks in obtaining near deterministic behavior of several synthetic neuronal networks [3-7]. The relationship of these results to the work of biological prototypes will be discussed.

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Axonal Conduction Delays Can Enhance Formation of Up and Down States in Spiking Neural Networks

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Spontaneous transitions between Up and Down states characterized by high and low firing rates in the cortex and striatum is a well known phenomenon [1–2]. Many theoretical models have been developed to explain the dynamics of such kind of transitions [3-5]. Typically, the transitions from Up to Down states cannot be achieved without inhibition. Inhibitory population stabilizes self-sustained Up state to prevent the system from over-excitation. If the inhibition is not present, the continuously growing excitation can be prevented by a short term depression [4]. In these models, noise switches the network between stable attractors.

Apart from the stochastic transitions by influence of noise there is also another mechanism of switching between the Up and Down states. In the Up state slow potassium current deactivates the system and switches it to the Down state. After a while networks restores its activity and switches again to Up state [3]. In addition to these scenarios, in the present work we suggest a new mechanism for the appearance of the Up and Down states. We show that the Up and Down states can emerge without any inhibition, short-term depression, or slow inactivating currents. The key factors in our model, apart from noise, are axonal conduction delays and cellular bistability.

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Nonlinear Dynamics in the Two-Dimensional Mathematical Model of the Extracellular Matrix of the Brain

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The extracellular matrix of the brain (ECM) is a collection of molecules synthesized and secreted by neurons and glial cells. The latest experimental data show a correlation between the processes of changes in the activity of neuronal structural elements (calcium activity of astrocytes and electrical activity of neurons) and the concentration of ECM. Slow changes in ECM over a long period of time (hours, days and months) and the integration of neuronal activity suggest that the ECM takes an important part in learning and memory processes.

In this work, based on the previously proposed model [1], a minimal mathematical model of the interaction of the extracellular matrix of the brain (ECM) and proteases in the presence of a constant neuronal activity of pyramidal neurons was developed. The model is a two-dimensional system of differential equations similar to the previously proposed model [1], where one variable is responsible for changing the concentration of ECM molecules, and the second variable is the change in the concentration of protease molecules. The activity of pyramidal neurons is described by a stationary function. In particular, Dembitskaya et al.,(Dembitskaya et al., FENS abstract) found that a decrease in the activity of ECM leads to the activation of SK2 channels leading to an increase in the threshold of pyramidal neuron excitability, which was inherent in the model.

The presence of various feedbacks in the model, connected both with the change in the concentration of molecules of the extracellular matrix of the brain (through the destruction of ECM molecules by proteases [1] and an increase in the threshold of pyramidal neuron excitability) and the change in the concentration of proteases, forms various dynamic regimes, in particular, the oscillatory regime type predator-prey model [2], and various scenarios for the transition to bistable activity.

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Astrocyte-Induced Synchronization in Neuroglial Networks

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Introduction

Neurons and neural networks are the main cells that generate and transform information in the brain. However, recent researches show that glial cells, namely the most common type of astrocytes, can affect the synaptic transmission of neurons. In this paper, we investigate how astrocytic regulation of the synaptic transmission effects on neural network signaling.

The neural network consisted of eight Hodgkin-Huxley neurons [1] randomly linked together. The membrane potential dynamics of a single neuron evolves according to the following equations:

$$C_m \frac{dV_{m_j}}{dt} = -g_{Na} m_j^3 h_j (V_{m_j} - E_{Na}) - g_K n_j^4 (V_{m_j} - E_K) - g_l (V_{m_j} - E_l) + I_{app} + I_{stim} + I_{syn}$$
$$\frac{dx_j}{dt} = \alpha_x (1 - x_j) - \beta_x x_j, \quad (1)$$

where V_{mj} – membrane potential of the neuron, $j = 1, \ldots, 8$ – neuron number, $x = m,h,n$ – gate variables, I_{stim} – Poisson process. The synaptic current, I_{syn}, simulating interactions between the neurons obeys the following equation:

$$I_{syn} = \frac{g_{syn}(V_m^{(2)} - E_{syn})}{1 + e^{\frac{-(V_m^{(1)} - \theta_{syn})}{k_{syn}}}}, \qquad (2)$$

where $V_m^{(1)}$, $V_m^{(2)}$ – membrane potential of pre- and postsynaptic neurons, respectively.

The astrocytic network was a lattice of eight Ullah astrocytes [2], having a direct connection only with the nearest neighbors. The calcium dynamics of each astrocyte is described by the following system of equation:

$$\begin{aligned} \frac{dCa_{jk}}{dt} &= I_{channel} - I_{pump} + I_{leak} + I_{in} - I_{out} + I_{Cadif} \\ \frac{dIP3_{jk}}{dt} &= \frac{IP3^* - IP3_{jk}}{\tau_{IP3}} + I_{PLC} + I_{IP3dif} + I_{glu} \\ \frac{dz_{jk}}{dt} &= a_2\left(d_2 \frac{IP3_{jk} + d_1}{IP3_{jk} + d_3}(1 - z_{jk}) - Ca_{jk} z_{jk}\right), \end{aligned} \qquad (3)$$

where Ca_{jk} – intracellular calcium concentration, $IP3_{jk}$ – intracellular concentration of inositol triphosphate, z_{jk} – the proportion of non-activated channels on the ER.

The effect of astrocytes on synaptic connections in neural network is determined by the power coefficient of synaptic connection $g_{syneff} = g_{syn}(1 + g_{astro} Ca_{jk})$,

where g_{astro} – regulation coefficient of synaptic connection due to astrocytes, Ca_{jk} – calcium concentration of a nearby astrocyte.

The effect of neurons on astrocytes is described by current I_{glu}:

$$\begin{aligned} I_{glu} &= \frac{\alpha_{glu}}{1 + e^{-\frac{G - 0.4}{0.01}}} \\ \frac{dG}{dt} &= -\alpha_G G + \beta_G H(V_m), H(V_m) = \frac{1}{1 + e^{-\frac{V_m}{0.5}}}, \end{aligned} \qquad (4)$$

where G – extracellular neurotransmitter concentration, V_m – membrane potential of the presynaptic neuron.

Results

First, we examined the activity of a neural network without the astrocyte effect. Each neuron is stimulated by a Poisson process with a certain frequency. In this case neurons were not synchronized. Then we added the effect of astrocytes, which were translated into oscillatory mode. On the duration of calcium signal generation by astrocytes in the neural network synchronization was observed. With the addition of feedback from neurons to astrocytes, neural network synchronization persists.

Conclusions

In this paper, we developed computational model of neuron-astrocytic network and shown that astrocytes influence leads to synchronization of the neural network.

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Dynamical Tools for CPG Modelling Featuring Dendronotus Iris

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We present a conductance based model of the Dendronotus Iris sea slug's swim central pattern generator along with visualizations of its cells' dynamics through a slow-fast decomposition and through scans of several parameter subspaces. We show how these tools, in conjunction with Empirical data, can be used to model robust pattern generating networks. In particular we examine the role of slow synapses in maintaining consistent rhythmic output, and how their dynamical properties relate to the controllability of the circuit.