Complex Systems Modeling Laboratory

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Refereed academic journal

[arkady-107-032-01:2017] Zgonnikov, Arkady and Aleni, Andrea and Piiroinen, Petri T and O'Hora, Denis and di Bernardo, Mario. Decision landscapes: visualizing mouse-tracking data. *Royal Society open science*, 4(11):170482, 2017.

Computerized paradigms have enabled gathering rich data on human behaviour, including information on motor execution of a decision, e.g. by tracking mouse cursor trajectories. These trajectories can reveal novel information about ongoing decision processes. As the number and complexity of mouse-tracking studies increase, more sophisticated methods are needed to analyse the decision trajectories. Here, we present a new computational approach to generating decision landscape visualizations based on mouse-tracking data. A decision landscape is an analogue of an energy potential field mathematically derived from the velocity of mouse movement during a decision. Visualized as a three-dimensional surface, it provides a comprehensive overview of decision dynamics. Employing the dynamical systems theory framework, we develop a new method for generating decision landscapes based on arbitrary number of trajectories. This approach not only generates three-dimensional illustration of decision landscapes, but also describes mouse trajectories by a number of interpretable parameters. These parameters characterize dynamics of decisions in more detail compared with conventional measures, and can be compared across experimental conditions, and even across individuals. The decision landscape visualization approach is a novel tool for analysing mouse trajectories during decision execution, which can provide new insights into individual differences in the dynamics of decision making.

[m-ryzhii-107-032-01:2017] M. Ryzhii, T. Otsuji, V. Ryzhii, V. Mitin, M.S. Shur, G. Fedorov, and V. Leiman. Dynamic conductivity and two-dimensional plasmons in lateral CNT networks. *Int. Journal of High Speed Electronics and Systems*, 26(1-2):1740004, June 2017.

We study theoretically the carrier transport and the plasmonic phenomena in the gated structures with dense lateral carbon nanotube (CNT) networks (CNT "felt") placed between the highly-conducting slot line electrodes. The CNT networks under consideration consist of a mixture of semiconducting and metallic CNTs. We find the dispersion relations for the two-dimensional plasmons, associated with the collective self-consisted motion of electrons in the individual CNTs, propagating along the electrodes as functions of the net electron density (gate voltage), relative fraction of the semiconducting and metallic CNTs, and

the spacing between the electrodes. In a wide range of parameters, the characteristic plasmonic frequencies can fall in the terahertz (THz) range. The structures with lateral CNT networks can used in different THz devices.

[m-ryzhii-107-032-02:2017] V. Ryzhii, M. Ryzhii, D. Svintsov, V. Leiman, V. Mitin, M.S. Shur, and T. Otsuji. Infrared photodetectors based on graphene van der Waals heterostructures. *Infrared Physics and Technology*, 84:72–81, August 2017.

We propose and evaluate the graphene layer (GL) infrared photodetectors (GLIPs) based on the van der Waals (vdW) heterostructures with the radiation absorbing GLs. The operation of the GLIPs is associated with the electron photoexcitation from the GL valence band to the continuum states above the inter-GL barriers (either via tunneling or direct transitions to the continuum states). Using the developed device model, we calculate the photodetector characteristics as functions of the GL-vdW heterostructure parameters. We show that due to a relatively large efficiency of the electron photoexcitation and low capture efficiency of the electrons propagating over the barriers in the inter-GL layers, GLIPs should exhibit the elevated photoelectric gain and detector responsivity as well as relatively high detectivity. The possibility of high-speed operation, high conductivity, transparency of the GLIP contact layers, and the sensitivity to normally incident IR radiation provides additional potential advantages in comparison with other IR photodetectors. In particular, the proposed GLIPs can compete with unitravelling-carrier photodetectors.

[m-ryzhii-107-032-03:2017] V. Ryzhii, M. Ryzhii, V. Leiman, V. Mitin, M.S. Shur, and T. Otsuji. Effect of doping on the characteristics of infrared photodetectors based on van der Waals heterostructures with multiple graphene layers. *Journal of Applied Physics*, 122(5):054505, August 2017.

We study the operation of infrared photodetectors based on van der Waals heterostructures with multiple graphene layers (GLs) and n-type emitter and collector contacts. The operation of such GL infrared photodetectors (GLIPs) is associated with the photoassisted escape of electrons from the GLs into the continuum states in the conduction band of the barrier layers due to the interband photon absorption, the propagation of these electrons, and the electrons injected from the emitter across the heterostructure and their collection by the collector contact. The space charge of the holes trapped in the GLs provides a relatively strong injection and large photoelectric gain. We calculate the GLIP responsivity and dark current detectivity as functions of the energy of incident infrared photons and the structural parameters. It is shown that both the periodic selective

doping of the inter-GL barrier layers and the GL doping lead to a pronounced variation of the GLIP spectral characteristics, particularly near the interband absorption threshold, while the doping of GLs solely results in a substantial increase in the GLIP detectivity. The doping "engineering" opens wide opportunities for the optimization of GLIPs for operation in different parts of the radiation spectrum from near infrared to terahertz.

[m-ryzhii-107-032-04:2017] V. Ryzhii, T. Otsuji, M. Ryzhii, V. Karasik, and M.S. Shur. Infrared detection and photon energy up-conversion in graphene layer infrared photodetectors integrated with LEDs based on van der Waals heterostructures: Concept, device model, and characteristics. *Infrared Physics and Technology*, 85:307–314, September 2017.

We propose the concept of the infrared detection and photon energy up-conversion in the devices using the integration of the graphene layer infrared detectors (GLIPs) and the light emitting diodes (LEDs) based on van der Waals (vdW) heterostructures. Using the developed device model of the GLIP-LEDs, we calculate their characteristics. The GLIP-LED devices can operate as the detectors of far- and mid infrared radiation (FIR and MIR) with an electrical output or with near-infrared radiation (NIR) or visible radiation (VIR) output. In the latter case, GLIP-LED devices function as the photon energy up-converters of FIR and MIR to NIR or VIR. The operation of GLIP-LED devices is associated with the injection of the electron photocurrent produced due to the interband absorption of the FIR/MIR photons in the GLIP part into the LED emitting NIR/VIR photons. We calculate the GLIP-LED responsivity and up-conversion efficiency as functions the structure parameters and the energies of the incident FIR/MIR photons and the output NIR/VIR photons. The advantages of the GLs in the vdW heterostructures (relatively high photoexcitation rate from and low capture efficiency into GLs) combined with the reabsorption of a fraction of the NIR/FIR photon flux in the GLIP (which can enable an effective photonic feedback) result in the elevated GLIP-LED device responsivity and up-conversion efficiency. The positive optical feedback from the LED section of the device lead to increasing current injection enabling the appearance of the S-type current-voltage characteristic with a greatly enhanced responsivity near the switching point and current filamentation.

[m-ryzhii-107-032-05:2017] V. Ryzhii, M.S. Shur, M. Ryzhii, V. Karasik, and T. Otsuji. Device model for pixelless infrared image up-converters based on polycrystalline graphene heterostructures. *Journal of Applied Physics*, 123(1):014503, January 2018.

We developed a device model for pixelless converters of far/mid-infrared radiation (FIR/MIR) images into near-infrared/visible (NIR/VIR) images. These converters use polycrystalline graphene layers (PGLs) immersed in the van der Waals materials integrated with a light emitting diode (LED). The PGL serves as an element of the PGL infrared photodetector (PGLIP) sensitive to the incoming FIR/MIR due to the interband absorption. The spatially non-uniform photocurrent generated in the PGLIP repeats (mimics) the non-uniform distribution (image) created by the incident FIR/MIR. The injection of the nonuniform photocurrent into the LED active layer results in the nonuniform NIR/VIR image reproducing the FIR/MIR image. The PGL and the entire layer structure are not deliberately partitioned into pixels. We analyze the characteristics of such pixelless PGLIP-LED up-converters and show that their image contrast transfer function and the up-conversion efficiency depend on the PGL lateral resistivity. The up-converter exhibits high photoconductive gain and conversion efficiency when the lateral resistivity is sufficiently high. Several teams have successfully demonstrated the large area PGLs with the resistivities varying in a wide range. Such layers can be used in the pixelless PGLIP-LED image up-converters. The PGLIP-LED image up-converters can substantially surpass the image up-converters based on the quantum-well infrared photodetector integrated with the LED. These advantages are due to the use of the interband FIR/NIR absorption and a high photoconductive gain in the GLIPs.

[m-ryzhii-107-032-06:2017] D.S. Ponomarev, D.V. Lavrukhin, A.E. Yachmenev, R.A. Khabibullin, I.E. Semenikhin, V.V. Vyurkov, M. Ryzhii, T. Otsuji, and V. Ryzhii. Lateral terahertz hot-electron bolometer based on an array of Sn nanothreads in GaAs. *Journal of Physics D: Applied Physics*, 51(13):135101, January 2018.

We report on the proposal and the theoretical and experimental studies of the terahertz hot-electron bolometer (THz HEB) based on a gated GaAs structure like the field-effect transistor with the array of parallel Sn nanothreads (Sn-NTs). The operation of the HEB is associated with an increase in the density of the delocalized electrons due to their heating by the incoming THz radiation. The quantum and the classical device models were developed, the quantum one was based on the self-consistent solution of the Poisson and Schroedinger equations, the classical model involved the Poisson equation and density of states omitting quantization. We calculated the electron energy distributions in the channels formed around the Sn-NTs for different gate voltages and found the fraction of the delocalized electrons propagating across the energy barriers between the

NTs. Since the fraction of the delocalized electrons strongly depends on the average electron energy (effective temperature), the proposed THz HEB can exhibit an elevated responsivity compared with the HEBs based on more standard heterostructures. Due to a substantial anisotropy of the device structure, the THz HEB may demonstrate a noticeable polarization selectivity of the response to the in-plane polarized THz radiation. The features of the THz HEB might be useful in their practical applications in biology, medicine and material science.

[m-ryzhii-107-032-07:2017] D. Yadav, G. Tamamushi, T. Watanabe, J. Mitsushio, Y. Tobah, K. Sugawara, A.A Dubinov, A. Satou, M. Ryzhii, V. Ryzhii, and T. Otsuji. Terahertz light-emitting graphene-channel transistor toward single-mode lasing. *Nanophotonics*, 7(4):741–752, March 2018.

A distributed feedback dual-gate graphene-channel field-effect transistor (DFB-DG-GFET) was fabricated as a current-injection terahertz (THz) light-emitting laser transistor. We observed a broadband emission in a 1-7.6-THz range with a maximum radiation power of ˜10 mkW as well as a single-mode emission at 5.2 THz with a radiation power of ˜0.1 mkW both at 100 K when the carrier injection stays between the lower cutoff and upper cutoff threshold levels. The device also exhibited peculiar nonlinear threshold-like behavior with respect to the current-injection level. The LED-like broadband emission is interpreted as an amplified spontaneous THz emission being transcended to a single-mode lasing. Design constraints on waveguide structures for better THz photon field confinement with higher gain overlapping as well as DFB cavity structures with higher Q factors are also addressed towards intense, single-mode continuous wave THz lasing at room temperature.

Refereed proceedings of an academic conference

[arkady-107-032-02:2017] Zgonnikov, Arkady and Lubashevsky, Ihor. Non-equilibrium phase transition in the model of human virtual stick balancing. In *Proceedings of the ISCIE International Symposium on Stochastic Systems Theory and its Applications*, volume 2017, pages 20–24. The ISCIE Symposium on Stochastic Systems Theory and Its Applications, 2017.

Archetypal stick balancing task represents a wide class of unstable processes under human control. The currently dominant theory of human control in stick balancing is based on the concept of discontinuous, or intermittent con-

trol. Traditionally, intermittent control models involve threshold-driven control activation, however, recently it has been demonstrated that, in a simple virtual stick balancing task, some basic properties of human control activation mechanisms can only be reflected by more sophisticated, noise-driven models. The aim of the present paper is to demonstrate that the previously introduced double-well model of noise-driven intermittent control activation can reproduce the experimentally observed human behaviours under various conditions. We show that the model successfully reproduces the experimental distributions of actions points (stick angle values triggering activation of human control) obtained in two previously reported experiments. Moreover, we show that a slight change in the model's noise intensity parameter leads to a sudden shift of model distributions, that is, a non-equilibrium phase transition is observed. Our results extend the current understanding of the concept of noise-driven control activation, suggesting that it is applicable in a variety of experimental setups. The two discovered phases of the double-well model correspond to two different modes of control activation in human operators; physiological basis of these modes has to be investigated in future studies.

[i-lubash-107-032-01:2017] I. Lubashevsky and K. Hijikata. Statistical Properties of Decision-Making Governed by Reinforcement Learning with Status Quo Bias. In *Proceedings of the 48th ISCIE International Symposium on Stochastic Systems Theory and Its Applications, Fukuoka, Nov. 3-4, 2016.*, pages 190–196, May 2017.

Within the paradigm of human intermittent control over unstable systems human behavior admits the interpretation as a sequence of point-like moments when the operator makes decision on activating or deactivating the control. These decision-making events are assumed to be governed by the information about the state of system under control which the operator accumulates continuously. In the present work we propose the concept of reinforcement learning with decision inertia (the status quo bias) that opens a gate to applying the formalism of reinforcement learning to describing human intermittent control. The basic feature of such reinforcement learning is that human behavior in a sequence of selecting available options exhibits quasi-continuous dynamics. Numerical simulation based on a fairly simple model demonstrates that the proposed formalism does possess the required properties of quasi-continuous behavior.

[i-lubash-107-032-02:2017] I. Lubashevsky R. Namae, M. Watanabe. Gray Color Multi-Categorical Perception: Asymptotics of Psychometric Function.

In *Proceedings of the 48th ISCIE International Symposium on Stochastic Systems Theory and Its Applications, Fukuoka, Nov. 3-4, 2016.*, pages 76–80, May 2017.

The results of conducted experiments on categorical perception with respect to gray color categorization into three classes are reported. Namely, the subjects were instructed to categorize shades of gray generated in a random sequence into three classes: light-gray, gray, and dark-gray. The collected data are analyzed employing (i) the asymptotics of the constructed psychometric functions and (ii) the mean decision time in categorizing a given gray brightness. The results obtained in the reported experiments and our previous ones are compared and a plausible macro-level mechanism governing gray color categorization is discussed.

[i-lubash-107-032-03:2017] A. Zgonnikov and I. Lubashevsky. Non-equilibrium phase transition in the model of human virtual stick balancing. In *Proceedings of the 48th ISCIE International Symposium on Stochastic Systems Theory and Its Applications, Fukuoka, Nov. 3-4, 2016*, pages 20–24, May 2017.

Archetypal stick balancing task represents a wide class of unstable processes under human control. The currently dominant theory of human control in stick balancing is based on the concept of discontinuous, or intermittent control. Traditionally, intermittent control models involve threshold-driven control activation, however, recently it has been demonstrated that, in a simple virtual stick balancing task, some basic properties of human control activation mechanisms can only be reflected by more sophisticated, noise-driven models. The aim of the present paper is to demonstrate that the previously introduced double-well model of noise-driven intermittent control activation can reproduce the experimentally observed human behaviour under various conditions. We show that the model successfully reproduces the experimental distributions of actions points (stick angle values triggering activation of human control) obtained in two previously reported experiments. Moreover, we show that a slight change in the model's noise intensity parameter leads to a sudden shift of model distributions, that is, a non-equilibrium phase transition is observed. Our results extend the current understanding of the concept of noise-driven control activation, suggesting that it is applicable in a variety of experimental setups. The two discovered phases of the double-well model correspond to two different modes of control activation in human operators; physiological basis of these modes has to be investigated in future studies.

[i-lubash-107-032-04:2017] S. Kanemoto T. Suzuki, I. Lubashevsky. Cloud Type Interpretation of Statistical Properties of Human Response Delay in Pendulum Balancing. In *Proceedings of the 48th ISCIE International Symposium on Stochastic Systems Theory and Its Applications, Fukuoka, Nov. 3-4, 2016*, pages 203–209, May 2017.

We present the results of our experiments on studying the probabilistic properties of human response delay in balancing virtual pendulum (stick) with over-damped dynamics. The overdamping eliminates the effects of inertia and, thereby, reduces the dimensionality of the system under control. Two types simulators were employed for studying human response in the stick balancing. One of them hides the stick when it is located in some neighborhood of the upward position, the other just makes the stick unaccessible for subject's control. It enabled us to measure directly the delay time as the time lag between the moment when the pendulum becomes visible or accessible and the moment when a subject starts to move the mouse. It is demonstrated that the response delay time is characterized by a wide distribution sensitive to the particular details of stick balancing process and its possible correlations in the sequence of actions are ignorable. Besides, in experiments with the second simulator the subject's anticipation is shown to play a significant role in human control. In particular, the formal delay time can take negative values. It poses a question about the applicability of standard formalism of delayed differential equations to describing human intermittent control.

[i-lubash-107-032-05:2017] K. Hijikata and I. Lubashevsky. Reinforcement Learning with Status Quo Bias. In *Proceeding of the 8 th International Workshop on Biosignal Interpretation (BSI2016), Osaka, Nov. 1-2, 2016*, pages 201–204, 2016/2017.

Characteristic features of human actions in car driving within the car-following setup are studied using TORCS car-driving simulator. Eight subjects participated in these experiments were instructed to drive a virtual car without overtaking and not losing sight of the lead car in any convenient style. The lead car was driven by computer at a fixed speed. As a main result, we draw a conclusion that human behavior in car driving should be categorized as a generalized intermittent control with noise-driven activation. Besides, we hypothesize that the extended phase space required for modeling human actions in car driving has to comprise four phase variables: the headway distance, the velocity of car, its acceleration, and the car jerk.

[i-lubash-107-032-06:2017] I. Lubashevsky and H. Ando. Intermittent Control

Properties of Car Following: Driving Simulator Experiment. In *Proceeding of the 8 th International Workshop on Biosignal Interpretation (BSI2016), Osaka, Nov. 1-2, 2016*, pages 132–135, 2016/2017.

Characteristic features of human actions in car driving within the car-following setup are studied using TORCS car-driving simulator. Eight subjects participated in these experiments were instructed to drive a virtual car without overtaking and not losing sight of the lead car in any convenient style. The lead car was driven by computer at a fixed speed. As a main result, we draw a conclusion that human behavior in car driving should be categorized as a generalized intermittent control with noise-driven activation. Besides, we hypothesize that the extended phase space required for modeling human actions in car driving has to comprise four phase variables: the headway distance, the velocity of car, its acceleration, and the car jerk.

[i-lubash-107-032-07:2017] H. Ando R. Yamauchi, I. Lubashevsky. Mesolevel Intermittency of Human Control: Car-Driving Simulator Experiments. In *Proceeding of the 8 th International Workshop on Biosignal Interpretation (BSI2016), Osaka, Nov. 1-2, 2016*, pages 197–200, 2016/2017.

Based on the open source engine TORCS a rather simple car-driving simulator was created and used to analyze the basic features of human behavior in car-driving within the car-following setup. Eight subjects with different skill in driving real cars participated in these experiments. They were instructed to drive a virtual car without overtaking and losing sight of the lead car driven by computer at a fixed speed. In a series of experiments, the lead car speed was set equal to 60, 80, 100, and 120 km/h. In the present work based on the collected data we single out three characteristic styles of car-driving. Namely, we analyze the statistical properties and time patterns of the car pedal position-the pedal position directly reflects subject actions. The discriminated typical styles of driving can be classified as pulsating, stationary, and the mixture of the previous two. The latter style admits the interpretation as intermittent transitions between the pulsating and stationary styles, we call this feature mesolevel intermittency of human control.

[i-lubash-107-032-08:2017] T. Suzuki and I. Lubashevksy. Human Response Delay as a Random Variable: Experiments on Balancing Overdamped Virtual Pendulum. In *Proceeding of the 8 th International Workshop on Biosignal Interpretation (BSI2016), Osaka, Nov. 1-2, 2016*, 193–196.

We present the results of our experiments on studying the probabilistic proper-

ties of human response delay in balancing virtual pendulum with over-damped dynamics. The overdamping eliminates the effects of inertia and, thereby, reduces the dimensionality of the system under control. The created simulator makes the pendulum (stick) invisible when the angle between it and the upward position is less than 5 o . It enables us to measure directly the delay time as the time lag between the moment when the pendulum becomes visible and the moment when a subject starts to move the mouse. It is demonstrated that the response delay time is characterized by a wide distribution sensitive to the particular details of stick balancing process and its possible correlations in the sequence of actions are ignorable. It poses a question about the applicability of standard formalism of delayed differential equations to describing human intermittent control.

[i-lubash-107-032-09:2017] Ihor Lubashevsky and Kosuke Hijikata. A new probabilistic approach to describing the stream of decision-making events near perception threshold. In *Fechner Day 2017 Conference Proceedings, The 33rd Annual Meeting of the International Socieity for Psychophysics, 22-26 October 2017, Fukuoka, Japan*, pages 347–351, 2017.

Within the paradigm of human intermittent control over unstable systems human behavior admits the interpretation as a sequence of point-like moments when the operator makes decision on activating or halting the control. These decision-making events are assumed to be governed by the information about the state of system under control which the operator accumulates continuously. In the present work we propose the concept of reinforcement learning with decision inertia (the status quo bias) that opens a gate to applying the formalism of reinforcement learning to describing human intermittent control. The basic feature of such reinforcement learning is that human behavior in a sequence of selecting available options exhibits quasi-continuous dynamics. Numerical simulation based on a fairly simple model demonstrates that the proposed formalism does possess the required properties of quasi-continuous behavior.

[i-lubash-107-032-10:2017] Marie Watanabe Ren Namae and Ihor Lubashevsky. Gray color categorical perception: asymptotics of psychometric function and mean decision time. In *Fechner Day 2017 Conference Proceedings, The 33rd Annual Meeting of the International Socieity for Psychophysics, 22-26 October 2017, Fukuoka, Japan*, pages 57–62, 2017.

We summarize the results of our experiments on categorical perception with respect to gray color categorization into two and three classes. Namely, the

subjects were instructed to categorize shades of gray (generated in a random sequence) making selection between light-gray and dark-gray (first set of experiments) or between light-gray, gray, and dark-gray (second set of experiments). The collected data are analyzed employing (i) the asymptotics of the constructed psychometric functions and (ii) the mean decision time in categorizing a given gray shade. A plausible macro-level mechanism governing gray color categorization is discussed.

[i-lubash-107-032-11:2017] Takashi Suzuki and Ihor Lubashevsky. Can the delay time of subject's response be a true component of the theory of human intermittent control. In *Fechner Day 2017 Conference Proceedings, The 33rd Annual Meeting of the International Socieity for Psychophysics, 22-26 October 2017, Fukuoka, Japan*, pages 203–207, 2017.

We report the results of our experiments on human response delay in balancing virtual pendulums with overdamped dynamics. The overdamping eliminates the effect of inertia, thereby, reduces the dimensionality of the system under control, and enables us to measure the delay time directly in the stream of subject's actions. Based on these results we demonstrate that the delay time of human response, at least under the analyzed conditions, is an essentially random variable characterized by (i) a wide distribution, (ii) weak correlations in the sequence of subject's actions, and (iii) the substantial dependence of its probabilistic properties on the particular details of the balancing. Besides, we raise a doubt about the universality of the classical approach to modeling human intermittent control based on delay-differential equations because their generalization going beyond the fixed delay time approximation becomes extremely overcomplicated and, as a result, intractable.

[i-lubash-107-032-12:2017] Takashi Suzuki and Ihor Lubashevsky. Can the delay time of subject's response be a true component of the theory of human intermittent control. In *Fechner Day 2017 Conference Proceedings, The 33rd Annual Meeting of the International Socieity for Psychophysics, 22-26 October 2017, Fukuoka, Japan*, pages 203–207, 2017.

We report the results of our experiments on human response delay in balancing virtual pendulums with overdamped dynamics. The overdamping eliminates the effect of inertia, thereby, reduces the dimensionality of the system under control, and enables us to measure the delay time directly in the stream of subject's actions. Based on these results we demonstrate that the delay time of human response, at least under the analyzed conditions, is an essentially random variable characterized by (i) a wide distribution, (ii) weak correlations

in the sequence of subject's actions, and (iii) the substantial dependence of its probabilistic properties on the particular details of the balancing. Besides, we raise a doubt about the universality of the classical approach to modeling human intermittent control based on delay-differential equations because their generalization going beyond the fixed delay time approximation becomes extremely overcomplicated and, as a result, intractable.

[i-lubash-107-032-13:2017] Ihor Lubashevsky. Concept of dynamical traps in modeling human behavior. In *Proceedings, The 8th International Conference on Computational Methods, Guilin City, Guangxi Province, China, 25th-29th July 2017*, 2017.

The proposed work discusses the human fuzzy rationality being a particular implementation of the bounded capacity of human cognition. Humans just are not able to distinguish between two strategies of behavior similar in property. So when the dynamics of a system governed by an individual (operator) deviates from the optimal conditions not too substantially the operator sees no reason to correct it. Therefore the active behavior of the operator is stagnated until the system deviates substantial form the optimal conditions. Then, naturally, the operator corrects the system motion returning it to some proximity of the optimal motion. This behavior is called the fuzzy rationality. If the optimal motion can be treated as some equilibrium point then the system dynamics inside its certain neighborhood will be also stagnated, reasoning us to regard this effect as dynamical traps. The particular goal is to demonstrate that the fuzzy rationality can be responsible for complex emergent phenomena in social systems.

[i-lubash-107-032-14:2017] Ihor Lubashevsky and Takashi Suzuki. Quantum Mechanics Formalism in Describing Human Intermittent Control. In *Proceedings, The 49th ISCIE International Symposium on Stochastic Systems Theory and Its Applications, November 3-4, 2017, Hiroshima*, 2017/2018.

In the present work we detail our approach to describing human behavior in controlling unstable systems, in particular, human response to their deviation from the desired equilibrium, that turns to the formalism of quantum mechanics. The gist of our approach is the phenomenological theory of the human mind developed in XX century which copes with human consciousness as a certain integral entity. Based on this theory we put forward the concept of two-component description of human behavior dealing with the objective

and subjective components governed by their individual laws and interacting with each other..

[i-lubash-107-032-15:2017] Ihor Lubashevsky Ren Namae. Towards Emergent Mechanism of Categorical Perception. In *Proceedings, The 49th ISCIE International Symposium on Stochastic Systems Theory and Its Applications, November 3-4, 2017, Hiroshima*, 2017/2018.

In the given work, first, we summarize the previous investigations and demonstrate their common features which enabled us to pose the given hypothesis. Second, we present results of our new experiments on perceptual categorization where none of the physical senses are involved in the object evaluation. Namely, it is a process of selecting or rejecting a visualized number related to a certain game aimed at accumulating a maximal amount, which is governed solely by mental evaluation.

[i-lubash-107-032-16:2017] Ihor Lubashevsky Ren Namae. Towards Emergent Mechanism of Categorical Perception. In *Proceedings, The 49th ISCIE International Symposium on Stochastic Systems Theory and Its Applications, November 3-4, 2017, Hiroshima*, 2017/2018.

In the given work, first, we summarize the previous investigations and demonstrate their common features which enabled us to pose the given hypothesis. Second, we present results of our new experiments on perceptual categorization where none of the physical senses are involved in the object evaluation. Namely, it is a process of selecting or rejecting a visualized number related to a certain game aimed at accumulating a maximal amount, which is governed solely by mental evaluation.

[i-lubash-107-032-17:2017] Ihor Lubashevsky Takashi Suzuki. Human Response Delay Time in Pendulum Balancing as Random Variable with Nonlinear Properties. In *Proceedings, The 49th ISCIE International Symposium on Stochastic Systems Theory and Its Applications, November 3-4, 2017, Hiroshima*, 2017/2018.

In conclusion, the obtained results provide experimental evidence for the nonlinear properties of human response characterized by essentially random delay time. It is substantial that the noted properties were detected for one system, which enables us to pose a question about the necessity of developing a novel mathematical formalism for such human behavior. This formalism should allow for these properties in a certain inherent way.

[i-lubash-107-032-18:2017] Ihor Lubashevsky. Holistic ceteris paribus laws. In *Proceedings, 5 th International Conference on Social Sciences Research 2017 (ICSSR 2017), 27–28th March 2017 at Berjaya Times Square, Kuala Lumpur, Malaysia.*, 2017.

The laws describing human behavior and phenomena in social systems have exceptions and, thus, cannot be strict and universal. In philosophy such regularities are called 'ceteris paribus' ('with other things being the same', Latin) laws—CP-laws—to emphasize the existence of other possible factors affecting a given phenomenon and whose direct control is not feasible. In spite of the fact that ceteris paribus laws are not strict they do play a remarkable role in explanation and prediction of various phenomena in such sciences as economics, psychology, and sociology. In the present work I discuss a special kind of CP-laws that can hold in social systems with cooperative dynamics. The mechanisms governing such systems synchronize the behavior of their members and keep up them within certain, maybe, rather narrow boundaries. These CP-laws to be called holistic ceteris paribus laws describe regularities in the behavior of individuals belonging to a certain cooperative social system and possess the following properties: they concern explicitly described phenomena in individuals' behavior; they are statistically normal for a given social system, meaning that their implementation is of high probability and possible exceptions are rare and may be treated as random events; in studding the individual behavior of a person, similar actions of the other system members have to be treated as external factors known explicitly; uncontrollable factors able to affect the analyzed phenomena are implicitly governed by the cooperative mechanisms endowing the given social system with integrity. Introducing holistic CP-laws we (i) focus out attention on a particular phenomenon described explicitly, and (ii) suppose the other essential factors to be implicitly controlled by the hidden interaction between the given person and the other members of this system. Exactly this interaction keeps the 'ceteris paribus' factors within the same boundaries, which endows the analyzed relationships with reproducibility with high probability. It should be emphasized that this reproducibility is of probabilistic nature. Indeed, because of human individuality, it is inevitable that the system members from time to time will deviate in their behavior from the norms accepted within the given system. However, these events must be relatively rare, otherwise, if individuals violate the norms rather often then either they will be rejected by the system or the system as a whole entity will be destroyed.

[i-lubash-107-032-19:2017] Ihor Lubashevsky. Distributed mechanism of self-regulation in hierarchically organized markets. In *Proceedings, 3rd International Conference on Advanced Research in Business and Social Sciences 2017 29th to 30th March, Langkawi 2017*, 2017.

We study a model for a market which has a tree form structure. Each branch of the tree is composed of identical firms. The branch of the first level is formed by the firms producing raw material, and the branches of the last level are the retail outlets. The branching points (tree nodes) are micromarkets for firms forming branches connected with a given node. The prices and the production rate are controlled by the balance in supply and demand. Due to the material conservation law the network nodes in such a market function perfectly: the prices are specified by the production expense only, whereas demand determines the production rate. We construct an efficiency functional with an extremal that gives the governing equations for the market. It turns out that this ideal market is degenerated with respect to its structure. It is shown that such a market functions ideally: the prices are determined by the costs of producing the goods, and the level of production of goods of any kind is defined only by demand. We propose a simple model of trade interaction among firms which are able to join together in order to decrease total cost. It is shown that self-organization, due to optimization of each firm's profit, leads to hierarchical organization of the trade network.

[i-lubash-107-032-20:2017] Ihor Lubashevsky Takashi Suzuki. Human Response in Pendulum Balancing: Probabilistic Properties and Space-Time Cloud Formalism. In *Proceedings, Physical Society of Japan, Fall Meeting*, 2017.

We present the results of our experiments on studying the probabilistic properties of human response delay in balancing virtual pendulum with overdamped dynamics. Two types simulators were employed, one of them hides the pendulum when it is located in some neighborhood of the upward position, the other just makes the stick inaccessible for subjects' control. The pendulum balancing is implemented via computer mouse movements. These simulators enable us to measure directly the delay time as the time lag between the moment when the pendulum becomes visible or accessible and the moment when a subject starts to move the mouse. It is demonstrated that the response delay time is characterized by (i) a wide distribution sensitive to the particular details of balancing process, (ii) weak correlations in the stream of subject's actions in pendulum correction, (iii) strong effects of anticipation. To describe

such subject's behavior we propose a new formalism dealing with space-time clouds representing point-like objects reflected in the human mind with some uncertainty. The nonlinear Schrodinger equation with dissipation is proposed for describing the dynamics of space-time clouds.

[m-ryzhii-107-032-08:2017] D. Yadav, Y. Tobah, J. Mitsushio, G. Tamamushi, T. Watanabe, A.A Dubinov, M. Ryzhii, V. Ryzhii, and T. Otsuji. Broadband terahertz-light emission by current-injection distributed-feedback dual-gate graphene-channel field-effect transistor. In *CLEO: Applications and Technology, CLEO 2017*, page AM2B.7, San Jose, United States, May 2017. OSA, OSA - The Optical Society of America.

We report on amplified spontaneous broadband terahertz emission in 1-7.6 THz range at 100 K via current injection in a distributed-feedback (DFB) dual-gate graphene-channel transistor. The device exhibited a nonlinear threshold-like behavior with respect to the currentinjection level. A precise DFB cavity design is expected to transcend the observed spontaneous broadband emission to single-mode THz lasing.

[m-ryzhii-107-032-09:2017] D. Yadav, Y. Tobah, K. Sugawara, J. Mitsushio, G. Tamamushi, T. Watanabe, A.A Dubinov, M. Ryzhii, V. Ryzhii, and T. Otsuji. Terahertz LED based on current injection dual-gate graphene-channel field effect transistors. In *75th Annual Device Research Conference, DRC 2017*, page 7999519, University of Notre Dame South Bend, USA, August 2017. MRS, IEEE.

Previous studies have shown that optical and/or injection pumping of graphene can enable negative-dynamic conductivity in the terahertz (THz) spectral range, which may lead to new types of THz lasers and light-emitting devices. Recently we obtained preliminary results of single-mode THz lasing in a forward-biased graphene structure with a lateral p-i-n junction in a distributed-feedback dual-gate graphene-channel field-effect transistor (DFB-DG-GFET). In this work, we experimentally observe amplified spontaneous broadband THz emission from 1 to 7.6 THz at 100K by carrier-injection in a population-inverted DFB-DG-GFET, demonstrating the birth of a new type of THz light-emitting diodes.

[m-ryzhii-107-032-10:2017] D. Yadav, Y. Tobah, K. Sugawara, J. Mitsushio, G. Tamamushi, T. Watanabe, A.A Dubinov, M. Ryzhii, V. Ryzhii,

and T. Otsuji. Terahertz light emitting transistor based on current injection dualgate graphene-channel FET. In *42nd Int. Conference on Infrared, Millimeter, and Terahertz Waves, IRMMW-THz 2017*, page 8067215, Cancun Quintana Roo Mexico, October 2017. IEEE, IEEE Computer Society.

We report on amplified spontaneous broadband terahertz emission in 1-7.6 THz range at 100 K via current injection in a distributed-feedback dual-gate graphene-channel field effect transistor (DFB-DG GFET). The device exhibited a nonlinear threshold-like behavior with respect to the current-injection level. A precise DFB cavity design is expected to transcend the observed spontaneous broadband emission to single-mode THz lasing.

[m-ryzhii-107-032-11:2017] M. Ryzhii, V. Ryzhii, T. Otsuji, and M.S. Shur. Detection and up-conversion of infrared radiation using van der Waals heterostructures with graphene layers. In *2017 IEEE Int. Conference on Microwaves, Antennas, Communications and Electronic Systems (COMCAS)*, page 8067215, Tel-Aviv, Israel, November 2017. IEEE, IEEE.

We review the performance of terahertz and infrared graphene photodetectors using heterostructures enabled by van der Waals bonding and the application of these devices for up-conversion to visible or UV range.

[m-ryzhii-107-032-12:2017] D. Yadav, Y. Tobah, G. Tamamushi, J. Mitsushio, T. Watanabe, A.A. Dubinov, M. Ryzhii, V. Ryzhii, and T. Otsuji. Current-injection terahertz emission in distributed-feedback dual-gate graphene-channel field-effect transistor. In *OTST17: Int. Conf. Optical Terahertz Science and Technology*, volume 1, page 66, London, United Kingdom, April 2017. Instiute of Physics (IOP), Instiute of Physics (IOP).

Negative-dynamic conductivity in the terahertz (THz) spectral range can be induced by either optical or injection pumping of graphene, which may lead to new types of THz lasers. We implement a forward-biased graphene structure with a lateral p-i-n junction in a distributed-feedback dual-gate graphene-channel field-effect transistor (DFB-DG-GFET) and experimentally observe amplified spontaneous THz emission in a wide frequency range (1-7.6 THz) at 100K.

[m-ryzhii-107-032-13:2017] V. Ryzhii, T. Otsuji, M. Ryzhii, V.G. Leiman, D. Svintsov, V. Mitin, and M.S. Shur. Effect of selective doping on character-

istics of graphene-van der Waals heterostructure terahertz and infrared detectors. In *The 38th PIERS: Progress in Electromagnetics Research Symposium*, pages 1P_10–12, St. Petersburg Russia, May 2017. Electromagnetics Academy, Electromagnetics Academy.

In this communication, we show that the selective doping of the barrier layers by acceptors and donors can result in a substantial increase in the detector responsivity, particularly, in the terahertz range. This is due to a strong effect of such a doping on the potential relief around the GLs and, hence, the capture efficiency of the propagating electrons into the GLs and the probability of the tunneling escape of the photoexcited electrons from the GLs.

[m-ryzhii-107-032-14:2017] T. Otsuji, D. Yadav, T. Watanabe, S.A. Boubanga-Tombet, V. Ryzhii, A.A. Dubinov, D. Svintsov, M. Ryzhii, V. Mitin, and M.S. Shur. Broadband terahertz light emission and lasing in graphene-based van der Waals heterostructures. In *EMN: Energy Materials Nanotechnology Lyon Meeting on 2D Materials*, pages 42–44, Lyon, France, August 2017. EMN, Springer.

We designed and fabricated a dual-gate lateral p-i-n graphene channel transistor (DG-GFET) incorporating a distributed feedback cavity by using teeth-brash-shaped dual-gate metal electrodes. Recently we succeeded in observing broadband (1-7.6 THz range) amplified spontaneous incoherent LED-like emission as well as single mode lasing at the DFB fundamental mode frequency of 5.2 THz at 100K.

Unrefeered proceedings of an academic conference

[arkady-107-032-03:2017] Zgonnikov, Arkady and Kenny, Aisling and O'Hora, Denis and Wong-Lin, KongFatt. Capturing decision confidence through response trajectories and willingness to gamble. In *Proceedings of the Annual Meeting of the International Society for Psychophysics*, volume 2017, pages 70–73, 2017.

Writing a textbook or technical book

[i-lubash-107-032-21:2017] I. Lubashevsky. *Physics of the Human Mind*. Springer International Publishing AG, Cham, Switzerland, 2017.

Summary of Achievement

This book tackles the challenging question which mathematical formalisms and possibly new physical notions should be developed for quantitatively describing human cognition and behavior, in addition to the ones already developed in the physical and cognitive sciences. Indeed, physics is widely used in modeling social systems, where, in particular, new branches of science such as sociophysics and econophysics have arisen. However, many if not most characteristic features of humans like willingness, emotions, memory, future prediction, and moral norms, to name but a few, are not yet properly reflected in the paradigms of physical thought and theory. The choice of a relevant formalism for modeling mental phenomena requires the comprehension of the general philosophical questions related to the mind-body problem. Plausible answers to these questions are investigated and reviewed, notions and concepts to be used or to be taken into account are developed and some challenging questions are posed as open problems. This text addresses theoretical physicists and neuroscientists modeling any systems and processes where human factors play a crucial role, philosophers interested in applying philosophical concepts to the construction of mathematical models, and the mathematically oriented psychologists and sociologists, whose research is fundamentally related to modeling mental processes.

Writing a part of textbook or technical book

[i-lubash-107-032-22:2017] Ihor Lubashevsky. *Human Fuzzy Rationality as a Novel Mechanism of Emergent Phenomena*, chapter 38, pages 827–877. Chapman and Hall/CRC, Boca Raton, FL, 2016/2017.

The given chapter presents the general notion of dynamica traps and the phase transitions of new type which is not met in the physical systems.

Research grants from scientific research funds and public organizations

[i-lubash-107-032-23:2017] Ihor Lubashevsky. Human Intermittent Control as Probabilistic Transitions in the Space of Strategies of Behavior: Model of Reinforcement Learning with Decision Inertia and Hamiltonian Description, 2017.

[m-ryzhii-107-032-15:2017] M. Ryzhii (collaborator). "Development and application of the new principle terahertz optoelectronic devices based on two-

dimensional atom thin film heterojunction" Grant-in-Aid for Scientific Research (S) from the JSPS, 2016-2020.

[m-ryzhii-107-032-16:2017] M. Ryzhii. "Computer modeling of cardiac conduction system with nonlinear oscillators" Grant-in-Aid for Scientific Research (C) from JSPS, 2017-2019.

Academic society activities

[i-lubash-107-032-24:2017] Ihor Lubashevsky, 2017.

Autumn and Fall Meeting

[i-lubash-107-032-25:2017] Ihor Lubashevsky, 2017.

Annual Meeting

[m-ryzhii-107-032-17:2017] M. Ryzhii, December 1996-present.

Senior Member

[m-ryzhii-107-032-18:2017] M. Ryzhii, July 1995-present.

Member (lifelong)

[m-ryzhii-107-032-19:2017] M. Ryzhii, 2017.

Member of Editorial Board of Nano- and Microsystems Technology journal

[m-ryzhii-107-032-20:2017] M. Ryzhii, 2017.

Reviewer for Optics Express journal

[m-ryzhii-107-032-21:2017] M. Ryzhii, 2017.

Reviewer for Remote Sensing journal

[m-ryzhii-107-032-22:2017] M. Ryzhii, September 2017.

Reviewer for Applied Nanotechnology and Nanoscience International Conference (ANNIC) 2017

[m-ryzhii-107-032-23:2017] M. Ryzhii, 2017.

Reviewer for Superlattices and Microstructures journal

[m-ryzhii-107-032-24:2017] M. Ryzhii, 2017.

Reviewer for Biomedical Signal Processing and Control journal

[m-ryzhii-107-032-25:2017] M. Ryzhii, 2017.

Reviewer for Chaos journal

Advisor for undergraduate research and graduate research

[i-lubash-107-032-26:2017] Kaito Morimura. Non-stationary Car-Following Dynamics: Driving Simulator Experiments, Undergraduate, 2017.

The car-driving simulator used my research experiments was the open source engine,TORCS. We investigated the features of human behavior in car-driving within the car-following setup. Four subjects with different skill and history in real cars help these experiments. They tests two experiments.One is velocity is constant and the other is velocity is irregular. Previously we have demonstrated that driver actions are intermittent. But some subjects may find the position in the lead car and do not change the velocity for long time. The research goal was to clarify this issue. For this purpose we compared the case where the speed of the lead car is constant and the case where it is irregular. Intermittency in the driver behavior have been held also in the case when the motion of the lead car is not strictly predictable.

[i-lubash-107-032-27:2017] Kosei Nihei. Statistical Properties of Number Categorization: Asymptotics of Psychometric Function and Mean Decision Tim, Undergraduate, 2017.

The human perception of abstract objects like numbers are analyzed using psychometric function and the mean decision time.

[i-lubash-107-032-28:2017] Kosuke Hijikata. Dual Channel Reinforcement Learning with Decision-Making Inertia: Model and Statistical Properties, Graduate, 2017.

Nowadays human intermittent control has become a dominant paradigm of describing human behavior in controlling various unstable systems. It assumes a human operator to activate and then halt the control alternatively instead of keeping it active continuously though the whole course of actions. The event-driven mechanism of human intermittent control is now accepted to be the main

mechanism governing such human actions. According to the event-driving scenario the operator activates the control when the state of controlled system deviates from the desired one substantially and halts the control when this difference becomes rather small and the operator cannot recognize or affect it with a required accuracy. The threshold model of control activation is rather popular in mathematical description of human intermittent control. It assumes an operator to activate the control when the difference between the current and desired states exceeds a certain threshold and to halt it in the opposite case. However, recently Prof. Lubashevsky et al., based on conducting experiments on balancing overdamped pendulum, proposed a novel concept of control activation. It is called the noise-induced activation and implies the control activation to be probabilistic in nature. In particular, the noise-induced activation represents a certain interplay between the necessity of starting the control process and the possibility of postponing it until this necessity becomes absolutely clear. A double-well potential model has been developed to describe human decision-making in activating and halting the control. Unfortunately, this model is based on a certain time-continuous stochastic process, which, as I show in the present thesis, is inconsistent with the physics of such human actions. To overcome this problem we turn to the reinforcement learning paradigm developed for describing discrete human-decision making in changing environment. Because this paradigm cannot be employed directly for modeling human actions in intermittent control we have developed its generalization allowing for the decision inertia. Its pivot point is the introduction of two channels of information processing in the human mind. One of them is responsible for the deliberate analysis of the current situation and taken actions; it is described by the standard model of reinforcement learning. The other allows for human bias in decision-making with respect to keeping the current choice. As demonstrated numerically the developed model possesses the desired property; namely, it is able to describe step-wise changes in taking different actions separated by time intervals much larger than the time step in decision-making. Actually this result opens a gate to describing time continuous processes governed by human decision-making aimed at keeping a system under control within some proximity to the desired state.

[i-lubash-107-032-29:2017] Ryoji Yamauchi. Mesolevel Intermittency in Dynamics of Car-Following Caused by Human Bounded Rationality: Car Driving Simulator Experiments and Dynamical Trap Model, Graduate, 2018.

A rather simple car-driving simulator was created based on the available open source engine TORCS and used to analyze the basic features of human behavior

in car-driving within the car-following setup. Eight subjects with different skill in driving real cars participated in these experiments. They were instructed to drive a virtual car without overtaking the lead car driven by a computer at a fixed speed and not to lose sight of it. In a series of experiments, the lead car speed was set equal to 60, 80, 100, and 120 km/h. Previously we have demonstrated that the car-driving should be categorized as a generalized intermittent control with noise-driven activation. In the present work based on the collected data we single out three characteristic styles of car-driving. Namely, we analyze the statistical properties and time patterns of the car pedal position–the pedal position directly reflects subject actions. The discriminated typical styles of driving can be classified as pulsating, 'stationary,' and the mixture of the previous two styles. The latter style admits the interpretation as intermittent transitions between the pulsating and stationary styles, we call this phenomena mesolevel intermittency of human control. But mesolevel intermittency has a open problem because its transition cannot be event-driven. So I constructed the dynamical trap model to analyze the mechanism of mesolevel intermittency.

Contributions related to syllabus preparation

[i-lubash-107-032-30:2017] Graduate Cource: Appied Statistics

[i-lubash-107-032-31:2017] Graduate Course: Computer Simulation of Stochastic Processes and Visualization with Python

[i-lubash-107-032-32:2017] Undergradute Course: Thermodynamics and Statistical Mechanics

Contribution related to planning administration for research, research conferences, or international research

[m-ryzhii-107-032-26:2017] Member of the Steering Committee Russia-Japan-USA-Europe Symposium on Fundamental and Applied Problems of Terahertz Devices and Technologies (RJUSE TeraTech)

[m-ryzhii-107-032-27:2017] Program Committee Member of Applied Nanotechnology and Nanoscience International Conference (ANNIC 2017), Rome, Italy

Other significant contribution toward university planning, management, or administration

[m-ryzhii-107-032-28:2017] Library Committee Member, University of Aizu