Preview of Award 1311165 - Annual Project Report

Cover

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Federal Grant or Other Identifying Number Assigned by Agency:	1311165
Project Title:	US-German Collaboration: Strategy Change in Cognitive Biological and Technical Systems
PD/PI Name:	Robert Kozma, Principal Investigator
Recipient Organization:	University of Memphis
Project/Grant Period:	10/01/2013 - 09/30/2017
Reporting Period:	10/01/2015 - 09/30/2016
Submitting Official (if other than PD\PI):	N/A
Submission Date:	N/A
Signature of Submitting Official (signature shall be submitted in accordance with agency specific instructions)	N/A

Accomplishments

* What are the major goals of the project?

The major goal of this project is to mathematically model and investigate the mechanism of strategy change in biological and technical systems under controlled conditions. Based on data of animal behavior experiments, strategy changes seem to be a rather fast transition in time from one behavior to another. This phenomenon can be described as the 'aha' effect. Linear learning theories like classical conditioning and reinforcement learning fail to explain this sudden qualitative change in the behavior. The qualitative change of behavior (strategy change) seem to occur not only after the environment changed and the learning system is forced to adapt to a new strategy, but such strategy changes can be observed during stable environmental conditions as well; i.e., stable in terms of stable contingency conditions.

This project aims at studying strategy change based on a collaborative approach between US and German scientists. The international, interdisciplinary team includes American scientists based at the Dept. of Mathematical Sciences, University of Memphis, TN, who develop mathematical models of strategy change, to interpret neuroscience observations. The German team conducts experimental work, coordinated by the Leibniz Institute of Neuroscience, Magdeburg, Germany. The joint work program serves the following goals: a) develop testable predictions from the theoretical hypotheses of strategy change; b) measure neural patterns in animals and perform these tests on the experimental data; and c) use the results to refine the model and thereby suggest concepts for improved performance of technical systems. The results are of benefit for better understanding of biological and artificial cognitive systems.

The main tasks in the collaborative team are divided as follows:

The German partner conducts experiments with Mongolian gerbils and it provides the obtained data to the American team for further analysis and interpretation. New and modified experiments are designed and executed based on the feedback from the US team. The gerbils are chronically implanted with multi-site electrodes in three different brain structures, namely, auditory cortex, striatum, and prefrontal cortex. After a short recovery period trained in either a Go/NoGo avoidance detection or a Go/NoGo avoidance discrimination task. During behavior neural signals, such as local field potentials and action potentials are recorded. In both tasks a gerbil is placed in a 2-compartment cage (shuttle box) with a little hurdle separating the two compartments. The animal is trained to cross this hurdle in response to an acoustic signal, called the condoning stimulus (CS)) in order to avoid an aversive electrical stimulation ("foot shock") via the floor grid. This is achieved by consequently preceding the foot shock with the sensory stimulus.

The US team develops models to explain experimental data from German team regarding sudden strategy changes in stable conditions in the framework of neurodynamics. The overall research strategy is illustrated in Fig. 1. The goal is to describe the learning system (the brain) by hierarchical coupled oscillators producing complex spatial-temporal patterns of simulated neural activity. These patterns can be explained as trajectories in phase spaces using tools of nonlinear systems theory. In our theoretical approach, the learning system continuously accumulates incremental changes during learning, which can be described by established learning rules and models. However, above a certain threshold, the system changes its properties in a qualitative manner. The overall goal of our team is to interpret such qualitative changes in the context of identified strategy changes in the gerbil.

Our US team had the following major goals for the project:

1. Analyze the measured electrophysiological data as trajectories in a high dimensional state space. From multi-site electrodes a state space can be reconstructed, where each recording site is a dimension of the state space. The corresponding oscillation amplitudes of the electrodes form a sequence of amplitude modulated (AM) patterns in the state space.
2. Interpret each of these AM patterns as one point in the reconstructed state space. The trajectory is the result of the change of the patterns over time. With this technique we are in the position, to compare directly the emerging patterns, respectively trajectories, from the model system and the biological system.
3. Develop a hierarchical mathematical model using graph theory for the KIV sets in order to describe the gerbil's learning and cognitive activity. Adapt the KIV model that has been previously used for goal-oriented navigation control purposes. Specify the structure of the model, its learning dynamics, and the readout signals in the form of amplitude-modulated (AM) patterns of neural activity that are experimentally observed.
4. Study dynamical properties of the developed model. Implement adaptation and learning strategies to replicate the behavior of the animal in the shuttle box paradigms. Compare the emerging phase transitions and meta-stable oscillations in the model with the patterns and trajectories of the measured data in gerbils. This comparison serves also to identify and label these meta-stable patterns, which are responsible for decision making.
5. Use the trained KIV model to replicate the behavior of the gerbil in the shuttle box. The main focus is not just to simulate number of correct responses, but to achieve a typical shift of strategy as implied by the reaction time-trial function.
6. Refinement of the theoretical model to the degree of its usability for solving engineering problems. The target problem can include learning goal-oriented navigation and control by an autonomous machinery, based on our previous work in mobile robot test beds.

*** What was accomplished under these goals (you must provide information for at least one of the 4 categories below)?**

Major Activities: **Graph theory model studies**

- Extending previous work (in Y1-Y2) on generalized bootstrap percolation on graphs, which are obtained by the combination of regular lattices and random graphs with scale-free edge length distribution. According to the adopted update rule, a vertex at the next time step is active if the total number of active neighbors exceeds a given threshold k, where k is a nonnegative integer. This update rule produces non-monotonous bootstrap percolation process.
- In the extended bootstrap percolation model, two types of nodes are included, namely, excitatory and inhibitory ones. This model is able to produce more complex dynamics than the model with a single type of nodes, namely oscillatory behavior. An important activity targets the study of these mathematical models.

Experimental data analysis and interpretation

- Experimental studies have been conducted by the LIN team in Germany, extending the work (in Y2) based on 3 gerbils, by additional 5 gerbils, in total of 8 gerbils. LIN team provided us the new data sets and we conducted through statistical studies of these data.
- Our analysis included standard spectral analysis of the measured signals of the array across the auditory cortex, as well as causality analysis of the signal between electrode pairs. We applied a generalized causality metric called new causality (NC), which avoids some pitfalls observed in Granger causality (GC) when applied to brain data.

Broader applications of the developed approaches and techniques

- It is expected that the graph theory-based mathematical model developed for the cortical tissue to describe sudden strategy change in the gerbil behavior can be useful in describing other transient processes with rapid variation in other natural processes. Potential applications may include early detection of natural and man-made disasters, financial transients, or transient stars in distant galaxies.
- The developed models of strategy change in animals can be implemented in autonomous systems and robotics test beds. We have explored various options for such implementations, and in the reporting period we identified the possibility of collaborating with the Biologically-inspired Neural and Dynamics Systems (BINDS) lab, in addition to NASA/JPL Robotics.

Specific Objectives: **Graph theory model studies**

- The resulting generalized model with two types of vertices is very complex, and in the general case it does not allow a full analytic treatment. The objective is to derive exact results on the behavior where it is feasible. If exact solutions are not feasible, conduct numerical evaluation of the mathematical formula when no analytic solution is within reach.
- Study how perturbations influence the dynamical behavior of the model. In particular, introduce periodic perturbations of the activations of a subset of nodes. Determine, how the frequency of the external oscillation interferes with the inherent oscillations of the coupled excitatory-inhibitory system.
- Study dynamical effects caused by the changing structure of the random graph with variable long-range connections, coupled to the fixed regular lattice. Interpret the observed dynamic effects in terms of possible structural changes due to learning in the neural tissues.

Experimental data analysis and interpretation

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- The objective of the studies involving 8 gerbils has been to validate the preliminary results obtained in Y2 about sudden changes in neural correlates related to strategy changes observed at the behavioral level. By comparing and integrating the available data for all gerbils, we can confirm or reject the preliminary results on the presence of inverse causal link between some electrode pairs and the absence of such causal link for some other pairs.
- Important objective is to identify potential learning effects in the experimental data, including changes in the amplitude modulation patterns over the 4x5 electrode arrays on the auditory cortex, and the evolution (enhancement) of the inverse causality link between some electrode pairs.
- Study the spatial distribution of the effects over the auditory cortex of the gerbils attributable to reinforcement learning and identify potential “hot spots” and crucial connectivity patterns if any. This way, either provide convincing evidence on the hypothesis about the formation of Hebbian cell assemblies, or refute this hypothesis.

Explore broader applications of the developed approaches and techniques

- The graph theory-based mathematical model developed for the cortical tissue to describe sudden strategy change in the gerbil behavior is expected to be useful in describing transient processes with rapid variation in other natural processes. Potential applications may include early detection of natural and man-made disasters, financial transients, or transient stars in distant galaxies.
- The developed models of strategy change in animals can be implemented in autonomous systems and robotics test beds. We have explored various options for such implementations, and in the reporting period we identified the possibility of collaborating with the Biologically-inspired Neural and Dynamics Systems (BINDS) lab, in addition to NASA/JPL Robotics.

Significant Results:

Graph Theory Modeling

- Mathematical analysis of the generalized bootstrap percolation model with two types of vertices has been conducted in mean field approximation. We have proven that the mean-field model with two types of units will produce eventually inactive excitatory and inhibitory populations if the initialization probability p is smaller that the critical probability obtained for pure excitatory populations (in Y2).
- We demonstrated the existence of limit cycle oscillations by evaluating the exact mathematical equations numerically. Specifically, we showed that there is limit cycle oscillation if the threshold parameter is k=2 for the excitatory population and k=3 for inhibitory population. Limit cycle oscillations appear when the ratio of excitatory nodes is around 0.75 in the absence of long edges, and the oscillations decrease and ultimately diminish when more and more long-range edges are added to the coupled graph. This process is characterized in details in our evaluations.
- Analytical study of appearance of limit cycle in the two-dimensional excitatory-

inhibitory discrete dynamical system has been conducted through Neimark-Sacker bifurcation at a fixed point. In order to get the desirable bifurcation, we determined the fixed point so that the Jacobian evaluated at the fixed point has complex conjugate pair of eigenvalues with unit absolute value for some value of the parameter. In this case, a closed invariant curve may appear, which encircles the fixed point. Our results show the presence of such invariant curve at given parameter combinations.

- In order to determine biologically plausible conditions that would allow a neo-cortex-like network to support experimentally observed properties of large-scale oscillations, we explored the parameter space of the graph theoretical model of the neocortex with interacting excitatory and inhibitory populations. Our studies focused on the respiratory modulation of gamma power. Our results show increased gamma activity during the segment of the respiratory cycle with increasing amplitudes (inhalation). On the other hand, gamma activity is significantly reduced when the respiratory signal is in the decreasing stage (exhalation). The above results are in agreement with observations made during the ECoG experiments. Our graph-theoretical model using modulation of soft gamma oscillators is able to reproduce and interpret basic properties of the experimentally observed phase-locking between respiration and gamma modulation.

Neuroscience Experimental Studies

- We applied causality analysis to ECoG data recorded from 8 Mongolian gerbils during performance of an auditory Go/NoGo discrimination task. In particular, we investigated how pairwise causal interactions between channels of the surface electrode array were affected by different stages of the learning process. In the analysis we defined an inverse causality metrics based on Granger Causality (GC) and the recently introduced New Causality (NC).
- Our main findings are summarized as follows:

1. The number of channel pairs, that were collected based on the criterion of inverse causality flow for the CS+ vs. CS- stimuli, significantly increased for both causality methods after the animals transitioned to the avoidance stage;
2. Spatial patterns of “core pairs” emerged after the transition to the avoidance stage, indicating the formation of localized connectivity patterns between cortical areas as the result of the learning process;
3. The core pairs have been evaluated for classification performance regarding CS+ and CS- conditions, and they have demonstrated statistically significant discrimination power after the transition to avoidance behavior.
4. At the initial phase of the learning process, the channels in the collected pairs appeared to be broadly distributed across the array. After the transition to the avoidance phase, some local areas exhibit higher activation according to the combined data of pooled gerbils. This may imply that the implicated local areas (“hot spots”) play a key role in forming category information during the learning process.
5. The criterion of inverse causality seems particularly suited to reveal potential functional reorganization of intra-cortical interactions during learning, because it emphasizes qualitative changes in the directional component of pairwise interactions that emerge over the course of the training, as opposed to quantitative changes in the absolute magnitude of unidirectional causal flows.

- These findings emphasize the importance of functional connectivity changes in lower level sensory areas, including the primary auditory cortex, as potential neural correlates of behavioral changes.
- We presented new evidence that respiration has a direct influence on oscillatory

cortical activity, including gamma oscillations, and on transitions between synchronous and asynchronous cortical network states (phase transitions) in both rodents and humans. Our findings suggest that respiratory influence on cortical activity is present in most, and possibly in all areas of the neocortex. Cortical gamma oscillations and phase transitions have been strongly implicated in cognitive processes. The time-locking of these two activity patterns to respiratory phase suggests a direct influence of respiration on cognitive processing, a possible neuronal mechanism behind the well-documented but unexplained effects of respiratory exercises on emotional and cognitive function. Taken together, our findings suggest that respiration acts as master clock exerting a subtle but unfailing synchronizing influence on the temporal organization of large-scale, dynamic cortical activity patterns

Broader aspects and consequences

- The densely interconnected cortical tissue, the neuropil, is the most complex substance in the known Universe. The behavior of the cortex with the immense number of neurons and synapses has been typically modeled using differential equations as the major tool of scientific explorations in the past 300+ years since the revolutionary era of Newton, Leibnitz and fmany other scientists. These equations suffice empirically to replicate the time series and spatial patterns of wave packets, but they have great difficulties in describing rapid transients. Thus, productive it has been, the trail of Newtonian description now leads to an impasse.
- Random graph theory offers a fresh beginning, in which the discreteness of neurons and synapses can be approximated with numerical representations in percolation theory, which is used to describe forest fires and epidemics. It is readily adapted to describing neural nets at the microscopic level, and it is easily adapted to describe nodes at mesoscopic and macroscopic levels as well.
- Transient dynamics in a wide range of disciplines may benefit from the new computational approach using graph theory. An example of complex quasi-periodic behavior in nature is observed in transient stars in distant galaxies. In an exploratory study, we model quasi-periodic light curves using neuropercolation, which describes complex spatio-temporal oscillations arising from random cellular automata near criticality. We show that neuropercolation is able to model lightcurves from various stars of the gamma-Doradus constellation with high accuracy even in the presence of missing data points and unevenly distributed time series. We provide physical interpretation of the obtained results using the example of the Gamma Doradus constellation.

Key outcomes or Other achievements:

A key outcome is the formulation of the generalized bootstrap percolation model with two types of vertices, which is described in the yet unpublished manuscript: R Kozma, Y. Sokolob, M. Ruszinko, "A Modified Bootstrap Percolation with Two Types of Vertices," (2016). The analysis of the model is extremely challenging, but we produced some very important theoretical results on the existence of limit cycle oscillations. To illustrate the potential importance of this result, I mention that I have just returned from the Conference on Complex Systems (CCS2016), Amsterdam last week, where Dr. Hans Herrmann (ETH, Zurich) had a plenary on "Abrupt Epidemic Spreading." His key message was the observation of oscillations in epidemic models, which have close resemblance to the oscillations in our cortical models, and we cna theoretically describe the process using graph theory.

In the experimental domain, it is absolutely crucial that now we have conclusively demonstrated (based on 8 gerbils) that learning produces observable changes on the auditory cortex in the form of "hot spots" detected by our proposed inverse causality metric. There are widespread hypotheses in the literature concerning the formation of cell assemblies corresponding to learnt patterns, which could be viewed as neural correlates of category learning and strategy formation. However, our results provides an clear evidence of this effects, which is very significant novel result. The main results are summarized in the manuscript "Causality Flow Analysis of Discrimination Learning in the Gerbil Auditory Cortex," a joint work with our German colleagues aimed at high impact neuroscience journal (under revision).

It is also very encoraging, and surprising taht the neurally-inspired graph theory model can be successfully applied to describe transient processes in a completely different domain, i.e., supernova transients in far away galaxies. This result lends support to the argument that teh applicability of our neuropercolation modelling approach is not limited to brain processes, but may be beneficial in a wide rande of natural or man-made transient processes.

* What opportunities for training and professional development has the project provided?

Dr. Robert Kozma (PI) is involved in graduate and undergraduate teaching, and mentoring and the results from this project benefit students in the classes by learning on various benefits/applications of the abstract concepts the study.

Dr. Yury Sokolov (grad student and postdoc), has completed and successfully defended his PhD dissertation at the Mathematics Department, University of Memphis on the theoretical aspects of this project.

- He received the Mortond Dissertation Award at University of Memphis, which is bestowed to the best PhD work in the given year (2016).
- He also received the 2016 Faudree Award of Research Students at the Math. Department, U of Memphis.
- He gave Oral Presentation on his PhD research at AMS Regional Conference, October, 2015, Memphis, TN, USA.
- Started his new 2-year postdoc assignment in mathematical biology at University of Pittsbugh.

Mr. Thomas P. Watson (undergrad student) is a talented student who attended my undergraduate calculus class and got involved in the research related to this project.

- Summer 2016 he has been awarded an Internship at WPAFB on a research topic colsely related to this project.
- Presently we are preparing a joint paper on the results to be submitted to a quality international confernece in 2017.

* How have the results been disseminated to communities of interest?

Publications (see products section for details)

6 journal articles, 4 conference papers, 1 PhD Dissertation.

Lectures/presentations (12 presentations by team members)

- Kozma, R., Y. Sokolov, M. Puljic, M. Ruszinko, S.Q. Hu (2016) “Modeling Learning and Strategy Formation as Phase Transitions in Cortical Networks,” IEEE Systems, Man, and Cybernetics Conference SMC2017, October 9-12, 2016, Budapest, Hungary (upcoming).
- J. Zhang, M. Chen, S. Hu, R. Kozma (2016) “PNN for EEG-based Emotion Recognition,” IEEE Systems, Man, and Cybernetics Conference SMC2017, October 9-12, 2016, Budapest, Hungary (upcoming).
- R. Kozma (2016) “Mass Action in Brains and Computers – A Tribute to Walter Freeman,” IEEE Systems, man, and Cybernetics Conference SMC2017, October 9-12, 2016, Budapest, Hungary (upcoming).
- R. Kozma, Invited Talk: “Cinematic Theory of Cognition - Application of Random Graphs & Networks,” at Symposium on Complexity in Personalized Dynamical Networks for Mental Health, Conference on Complex Systems, September 19-22, 2016, Amsterdam, The Netherlands.
- M. Ruszinko, Invited talk: "A modified bootstrap percolation on a random graph coupled with a lattice," Hungarian – Israeli

Meeting in Combinatorics in memory of Paul Erdos, August 23-25, 2016, Technion, Israel.

- R. Kozma, Tutorial presentation “Graph Theory Approaches to Neural Structures and Dynamics: Models and Applications,” at World Congress in Computational Intelligence WCCI2016/IJCNN2016, July 25-29, 2016, Vancouver, Canada.
- Elzo, K., P. Estevez, R. Kozma (2016) “Modeling Quasi-Periodic Lightcurves using Neuropercolation,” IEEE World Congress on Computational Intelligence, 22-29, July, 2016, Vancouver, Canada.
- Zhuo, H., S.Q. Hu, M. Myers, J. Zhang, W. Kong, Y. Cao, R. Kozma (2016) “Causality Analysis during Shared Intentionality,” Proc. 12th World Congress on Intell. Control and Automation, Guilin, China, June 12-15, 2016.
- R. Kozma, Plenary Talk “Big Data Challenges in Large-Scale Networks - From Brains to Stars,” at IEEE CIS Winter School on Big Data, February 19-21, 2016, Washington DC.
- R. Kozma, Invited Talk “Stability properties of coupled nonlinear masses modeled by lattice graphs,” School of Mathematics & Physics, Dept. Electrical Engineering, University of Chile, January 27, 2016, Santiago, Chile.
- Kozma, R., D. Heck, Y. Liu, S. McAfee, R. Rezaie, A. Babajani-Feremi, A. Papanicolaou, J. Wheeless (2015) “Hilbert analysis of the relation between respiration and LFP/ECoG,” *Society for Neuroscience Congress (SfN2015),* Chicago., USA, November 17-21, 2015, Paper # 479.02/ B15.
- Liu, Y., S. McAfee, R. Rezaie, A. Babajani-Feremi, A. Papanicolaou, J. Wheeless, R. Kozma, D. Heck, (2015) “Respiratory modulation of brain activity,” *Society for Neuroscience Congress (SfN2015),* Chicago., USA, November 17-21, 2015, Paper # 479.03/ B16.

* What do you plan to do during the next reporting period to accomplish the goals?

Theoretical Modeling

- Finalize the publication of the paper of teh generalized percolation with two types of node.
- Develop coupled excitatory-inhibitory models with adaptive connections to describe learning effects.

Experiments

- Finalize the publication of the paper on the results of causality analysis.
- Publish the results that learning effects are seen only using inverse causality analysis and not by direct classification of the AM patterns (using, e.g., MLP).

Intelligent systems test bed

- Implement a prototype adaptive autonomous system using percolation-based control model
- Hardware domain is implemented at UMass Amherst/BINDS Lab, and/or NASA Jet Propulsion Laboratory, Robot Autonomy Lab.

Products

Books

Robert Kozma and Walter J. Freeman (2016). *Cognitive Phase Transitions in the Cerebral Cortex - Enhancing the Neuron Doctrine by Modeling Neural Fields 1st ed.* Thomas Ditzinger. Springer Verlag. Heidelberg. Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes ; ISBN: 978-3-319-24404-4

Book Chapters

Inventions

Journals or Juried Conference Papers

Chakraborty, G., Kozma, R., Murata, T., Zhao, Q. (2016). Awareness in the brain, society, and beyond. *IEEE Systems, Man, & Cybernetics Magazine*. 1(3) (3), 8-16. Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes ; OTHER: http://ieeexplore.ieee.org/document/7426516/

Elzo, K., P. Estevez, R. Kozma (2016). Modeling Quasi-Periodic Lightcurves using Neuropercolation. *IEEE World Congress on Computational Intelligence, 22-29, July, 2016, Vancouver, Canada..* . Status = PUBLISHED; Acknowledgment of Federal

Support = Yes ; Peer Reviewed = Yes

Heck, D., McAfee, S., Liu, Y., Babajani-Feremi, A., Rezaie, R., Freeman, W.J., Wheless, J., Papanicolaou, A.C., Ruszinko, M., Sokolov, Y., Kozma, R. (2016). Breathing as a fundamental rhythm of brain function. *Frontiers in Neuroscience*. . Status = SUBMITTED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes

Kozma, R. (2016). Mass Action in Brains and Computers – A Tribute to Walter Freeman. *Proc. IEEE Systems, man, and Cybernetics Conference SMC2017, October 9-12, 2016, Budapest, Hungary.*. . Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes

Kozma, R. (2016). Reflections on a Giant of Brain Science. *Cognitive Neurodynamics*. . Status = ACCEPTED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes

Kozma, R., Hu, S.Q. (2016). Stochastic causality, criticality, and non-locality in brain networks. *Physics of Life Reviews*. 15 133. Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes ; DOI: http://dx.doi.org/10.1016/j.plrev.2015.10.006

Kozma, R., Y. Sokolov, M. Puljic, M. Ruszinko, S.Q. Hu (2016). Modeling Learning and Strategy Formation as Phase Transitions in Cortical Networks. *Proc. IEEE Systems, Man, and Cybernetics Conference SMC2017, October 9-12, 2016, Budapest, Hungary.*. . Status = ACCEPTED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes

Zhuo, H., S.Q. Hu, M. Myers, J. Zhang, W. Kong, Y. Cao, R. Kozma (2016). Causality Analysis during Shared Intentionality. *Proc. 12th World Congress on Intell. Control and Automation, Guilin, China, June 12-15, 2016.*. . Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes ; OTHER:

Licenses

Other Conference Presentations / Papers

Kozma, R., D. Heck, Y. Liu, S. McAfee, R. Rezaie, A. Babajani-Feremi, A. Papanicolaou, J. Wheeless (2015). *Hilbert analysis of the relation between respiration and LFP/ECoG, Paper # 479.02/ B15.*. Society for Neuroscience Congress (SfN2015), November 17-21, 2015.. Chicago., USA. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Liu, Y., S. McAfee, R. Rezaie, A. Babajani-Feremi, A. Papanicolaou, J. Wheeless, R. Kozma, D. Heck (2015). *Respiratory modulation of brain activity*. Society for Neuroscience Congress (SfN2015). Chicago, USA. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Other Products

Other Publications

Kozma, R., Ruszinko, M., and Sokolov, Y., (2016). *A Modified Bootstrap Percolation with Two Types of Vertices*. This is Part II of the paper on generalized percolation using excitatory and inhibitory units. The first part with pure excitation has been displayed on arxiv.. Status = OTHER; Acknowledgement of Federal Support = Yes

Heck, D., McAfee, S.S., Liu, Y., Babajani-Feremi, A., Wheless, J.W., Papanicolaou, A.C., Ruszinkó, M, Kozma, R. (2016). *Cortical rhythms are modulated by respiration*. http://biorxiv.org/content/early/2016/04/16/049007. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Patents

Technologies or Techniques

Thesis/Dissertations

Sokolov, Y.. *Dynamics of Discrete and Continuous Spatially Distributed Systems*. (2016). University of Memphis, TN, USA. Acknowledgement of Federal Support = Yes

Websites

Participants/Organizations

What individuals have worked on the project?

Name	Most Senior Project Role	Nearest Person Month Worked
Kozma, Robert	PD/PI	2
Freeman, Walter	Faculty	0
Sokolov, Yury	Postdoctoral (scholar, fellow or other postdoctoral position)	10
Hu, Sanqing	Staff Scientist (doctoral level)	0
Ruszinko, Miklos	Staff Scientist (doctoral level)	4
Dutta, Jayanta	Graduate Student (research assistant)	1
Watson, Thomas	Undergraduate Student	1

Full details of individuals who have worked on the project:

Robert Kozma
Email: rkozma@memphis.edu
Most Senior Project Role: PD/PI
Nearest Person Month Worked: 2

Contribution to the Project: Overall responsibility for project coordination as PI, including technical oversight. collaboration coordination, and financial areas. Specific research contributions focus on developing network/graph model of sensory (auditory) cortex and statistical analysis of neuroscience data obtained by the German counterpart at LIN Magdeburg, Germany.

Funding Support: NSF CRCNS Grant through the DMS, grant # DMS-13-11165. U Tenn Medical School, iRISE: Analysis of the interrelationship between cortical activity and respiratory rhythms (with D. Heck). FedEx Institute of Technology, U of Memphis: DRONES Program.

International Collaboration: Yes, Germany
International Travel: No

Walter J. Freeman
Email: dfreeman@berkeley.edu
Most Senior Project Role: Faculty
Nearest Person Month Worked: 0

Contribution to the Project: Provides advice (for free) on experimental analysis and interpretation of experiments.

Funding Support: NSF CRCNS Grant, DMS-1311165

International Collaboration: No
International Travel: No

Yury Sokolov

Email: ysokolov@memphis.edu
Most Senior Project Role: Postdoctoral (scholar, fellow or other postdoctoral position)
Nearest Person Month Worked: 10

Contribution to the Project: Analysis of phase transitions in the neuropercolation model and statistical analysis of gerbil EEG data.

Funding Support: NSF CRCNS Grant, DMS-1311165 FedEx Institute of Technology, U of Memphis: DRONES Program: "Integrated Platforms and Algorithms of Multi-sensory Data Capture and Decision Support for Autonomous Vehicles."

International Collaboration: No
International Travel: No

Sanqing Hu
Email: sqhu@hdu.edu.cn
Most Senior Project Role: Staff Scientist (doctoral level)
Nearest Person Month Worked: 0

Contribution to the Project: Conduct causality analysis of gerbil ECoG array data using Granger Causality (GC) and generalized New Causality (NC) metrics.

Funding Support: National Natural Science Foundation of China under GrantsNo. 61473110, No. 61100102. Natural Science Foundation of Zhejiang Province, China, under Grant No. LZ13F030002.

International Collaboration: Yes, China
International Travel: No

Miklos Ruszinko
Email: ruszinko.miklos@renyi.mta.hu
Most Senior Project Role: Staff Scientist (doctoral level)
Nearest Person Month Worked: 4

Contribution to the Project: Graph theoretical model of brain networks

Funding Support: NSF CRCNS Grant DMS-13-11165. U Tennessee HSC Memphis, iRISE Initiative: “Experimental and theoretical analysis of the interrelationship between cortical activity and respiratory rhythms,”

International Collaboration: Yes, Hungary
International Travel: No

Jayanta Kumar Dutta
Email: jkdutta@memphis.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 1

Contribution to the Project: Development of a computer code for the analysis of EEG/ECoG array data.

Funding Support: NSF CRCNS-DMS-13-11165

International Collaboration: No
International Travel: No

Thomas P Watson
Email: tpwatson@memphis.edu
Most Senior Project Role: Undergraduate Student
Nearest Person Month Worked: 1

Contribution to the Project: Computational analysis of emergent symbolic representations in brain-inspired deep learning architectures. Develop statistical measures to identify sudden jumps (phase transitions) at critical layers from input to output.

Funding Support: FedEx Institute of Technology, U of Memphis: DRONES Program: "Integrated Platforms and Algorithms of Multi-sensory Data Capture and Decision Support for Autonomous Vehicles."

International Collaboration: No
International Travel: No

What other organizations have been involved as partners?

Name	Type of Partner Organization	Location
Leibniz Institute of Neuroscience (LIN), U Magdeburg	Academic Institution	Magdeburg, Germany
University of Tennessee Health Science Center	Academic Institution	Memphis, TN

Full details of organizations that have been involved as partners:

Leibniz Institute of Neuroscience (LIN), U Magdeburg

Organization Type: Academic Institution
Organization Location: Magdeburg, Germany

Partner's Contribution to the Project:
Collaborative Research
Personnel Exchanges

More Detail on Partner and Contribution: LIN, Germany designs and conducts animal experiments (with gerbils) at its facilities, provides the data for us for analysis. They also contribute to the interpretation of the results and use these insights in the design of new experiments.

University of Tennessee Health Science Center

Organization Type: Academic Institution
Organization Location: Memphis, TN

Partner's Contribution to the Project:
Collaborative Research

More Detail on Partner and Contribution: The graph theory model of the cortex developped at the PI's group has been used to interpret experimental data obtained previously on small rodents (mice) and human volunteers at the group pf Dr. Detlef Heck, Department of Anatomy and Neurobiology, University of TN HSC.

What other collaborators or contacts have been involved?

Explored collaboration opportunities with Prof. Hava Siegelmann, U Massachusetts Amherst, on the hardware implementation of our brain-inspired decision support approach using intelligent robotics platforms.

Impacts

What is the impact on the development of the principal discipline(s) of the project?

The research results have impact on both the theory of learning in mammals, including normal and abnormal conditions, and the exploitation of the developed theoretical insights for the design of technical systems.

- Current physiological and theoretical frameworks of learning focus on incremental learning mechanisms (as exemplified by the reinforcement learning framework) giving rise to quasi-continuous learning dynamics, the discontinuous nature of behavioral development observed as sudden transitions in strategy change is not well understood neither concerning its underlying neurophysiological mechanisms nor in terms of a possible algorithmic implementation that would allow its exploitation in technical systems.
- The developed tools in graph theory (percolation theory) help to solve problems also in other areas of mathematics, such as determinstic and stochastic dynamical systems in space and time domains. We have analyzed strategy change in the brain, and proposed graph theretical models for implementing the biologicallymotivated principles of strategy change in engineering domains (intelligent/autonomous robots).

What is the impact on other disciplines?

This project supports not only the deeper understanding of biological and cognitive processes related to strategy changes under stable conditions, but it provides a platform for developing robust decision support systems that operate in dynamically changing scenarios in the style of brains.

- Detailed analysis of the mechanisms underlying strategy change in biological systems will allow us and other groups to equip various technical/enginnering systems with this fundamental property of cognition.
- Potential applications include robust decision support system under rapidly changing scenarios, intelligent control of autonomous vehicles under unpredicted conditions.
- This work addresses important societal needs by creating the foundations of cognitive engineering systems supporting emergency response to natural disasters and rapid response to cyber security threats by adversaries.

What is the impact on the development of human resources?

This research contribute to the development of human resources through the PI's involvement in academic education. The University of Memphis has a diverse student population with significant participation of minorities, who have access to and contribute to the results in various ways.

- For example, the courses taught by Dr Kozma included results achieved in this project in the lectures and also in class projects. Students participate in these classes and the proejct results contribute to their professional development and improves their position in the marketplace after graduation.
- An example is the involvement of undergraduate students, e.g., T. Watson in project related research.
- A former graduate student in our project, Dr. Yuruy sokolov has successfully graduated with his PhD, and recently started a postdoc position at the Biological mathematics area at U Pittsburgh.

What is the impact on physical resources that form infrastructure?

The U of Memphsi has renovated a previously unused basement area for use by the present project in possible hardware tests.

What is the impact on institutional resources that form infrastructure?

There are no significant impact to report in the infrastructure development area.

What is the impact on information resources that form infrastructure?

Nothing to report.

What is the impact on technology transfer?

Nothing to report.

What is the impact on society beyond science and technology?

This work produces results, which have impact on the society not only in science and engineering, but in other areas of significant societal needs by:

- Contributing to the foundations of cognitive engineering systems supporting emergency response to natural disasters.
- A related area of great importance to which our project provides important inputs, is the rapid response to cyber security threats by adversaries.
- Strategy development is an important task of goverment organizations in the society, starting with local governments, to state, and national levels. Our results on strategy change produce important insights that are applicable to the formation of strategical thinking and policy making at varous levels of government.

Changes/Problems

Changes in approach and reason for change

One of our team members, Dr. Walter J. Freeman, UC Berkeley, Department of Molecular and Cell Biology, Division of Neurobiology, has passed away on April 26th, 2016.

- He acted as unpaid consultant on our project. His contribution will be greatly missed.
- At this final stage of the project his absence will not cause unsolvable difficulties in wrapping up the work.
- At the moment we finalize several papers/publications in which he still contributed and which will be part of the final project report.
- His obituary is on several locations, e.g., https://www.sfn.org/Member-Center/Member-Obituaries/AF/Walter-Jackson-Freeman.
- It may make sense reflect his crucial contribution to various NSF funded research projects also using a suitable NSF online format.

Actual or Anticipated problems or delays and actions or plans to resolve them

Nothing to report.

Changes that have a significant impact on expenditures

Nothing to report.

Significant changes in use or care of human subjects

Nothing to report.

Significant changes in use or care of vertebrate animals

Nothing to report.

Significant changes in use or care of biohazards

Nothing to report.