Studies in Systems, Decision and Control 39

Robert Kozma
Walter J. Freeman

Cognitive Phase Transitions in the Cerebral Cortex - Enhancing the Neuron Doctrine by Modeling Neural Fields

Springer

Studies in Systems, Decision and Control

Volume 39

About this Series

The series "Studies in Systems, Decision and Control" (SSDC) covers both new developments and advances, as well as the state of the art, in the various areas of broadly perceived systems, decision making and control- quickly, up to date and with a high quality. The intent is to cover the theory, applications, and perspectives on the state of the art and future developments relevant to systems, decision making, control, complex processes and related areas, as embedded in the fields of engineering, computer science, physics, economics, social and life sciences, as well as the paradigms and methodologies behind them. The series contains monographs, textbooks, lecture notes and edited volumes in systems, decision making and control spanning the areas of Cyber-Physical Systems, Autonomous Systems, Sensor Networks, Control Systems, Energy Systems, Automotive Systems, Biological Systems, Vehicular Networking and Connected Vehicles, Aerospace Systems, Automation, Manufacturing, Smart Grids, Nonlinear Systems, Power Systems, Robotics, Social Systems, Economic Systems and other. Of particular value to both the contributors and the readership are the short publication timeframe and the world-wide distribution and exposure which enable both a wide and rapid dissemination of research output.

More information about this series at http://www.springer.com/series/13304

Robert Kozma · Walter J. Freeman

Cognitive Phase Transitions in the Cerebral Cortex - Enhancing the Neuron Doctrine by Modeling Neural Fields

With Commentaries by: Kazuyuki Aihara and Timothy Leleu, Bernard Baars, Steven Bressler, Ray Brown and Morris Hirsch, Péter Érdi and Zoltán Somogyvári, Hans Liljenström, Frank Ohl, Ichiro Tsuda, Giuseppe Vitiello, Paul Werbos, and James Wright

Springer

Robert Kozma
Department of Mathematical Sciences
University of Memphis
Memphis, TN
USA

Walter J. Freeman
Division of Neurobiology
University of California at Berkeley
Berkeley, CA
USA

ISSN 2198-4182 ISSN 2198-4190 (electronic)
Studies in Systems, Decision and Control
ISBN 978-3-319-24404-4 ISBN 978-3-319-24406-8 (eBook)
DOI 10.1007/978-3-319-24406-8

Library of Congress Control Number: 2015950877

Springer Cham Heidelberg New York Dordrecht London

Printed on acid-free paper

Springer International Publishing AG Switzerland is part of Springer Science+Business Media (www.springer.com)

This work is dedicated to scientists who persevere in questioning prevailing dogma in search of wisdom in the frontiers of neuroscience

Preface

Everyday subjective experience of the stream of consciousness suggests continuous cognitive processing in time. Brain monitoring techniques with markedly improved spatiotemporal resolution, however, provide an evidence of discontinuities between transiently stationary dynamics in brains. We observe spatiotemporal cortical dynamics as giving sequences of metastable spatial patterns of coherent population activity. Each metastable pattern manifests a cortical state (corresponding to a cinematic frame) that collapses in transient desynchronization (analogous to a shutter), followed by the rapid emergence of a new pattern. The temporal sequence of metastable spatial patterns is closely correlated with intentional behaviors. Each frame manifests the action–perception cycle [1] by which animals probe their environments and learn about them by accommodating to the impact of their own actions on their sensory systems.

Patterns of microscopic pulse trains from depth recordings, mesoscopic action potentials from intracranial assemblies, macroscopic surface electrocorticograms (ECoG), scalp electroencephalograms (EEG) and magnetoencephalograms (MEG), and high-resolution functional magnetic resonance images (fMRI) reveal a hierarchy of brain states across temporal and spatial scales. The observed neural processes have significant high-frequency spatiotemporal components. The high-frequency oscillatory components measured by brain monitoring techniques are widely viewed as noise and/or artifacts and eliminated by averaging and band-pass filtering. However, the seemingly erratic dynamic behavior of neural field potentials contains recognizable patterns, which have been measured after appropriate decomposition into wavelets [2].

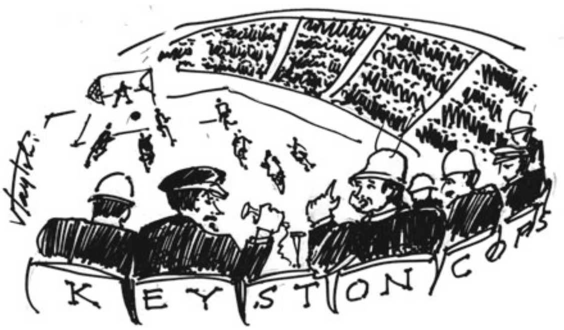
Analysis of high-frequency evoked potentials measured by high-resolution brain imaging techniques point to frequent transitions between periods of large-scale synchronization and intermittent desynchronization at alpha-theta rates. These observations support the hypothesis about the cinematic model of cognitive processing, according to which higher cognition can be viewed as multiple movies superimposed in time and space. The metastable spatial patterns of field potentials manifest the frames, and the rapid transitions provide the shutter from each pattern to the next in multiple streams of various sizes.

The alternating states offer a stark contrast in organization of activity between a low-energy, sparsely firing state that we analogize to a gas-like phase and a high-energy liquid-like phase, still sparsely firing but synchronized. We analogize the onset as a phase transition of condensation, followed by evaporation after 3 to 5 cycles of the oscillation [3]. The cortex holds itself in a state of criticality, which is manifested in a readiness to reorganize itself from random noise into synchronization of immense populations. The synchrony may not be apparent in single cell recordings, partly because the cortical neurons are time-multiplexing to distribute the computational load over a large number of participants, and partly because many of the neurons in a pattern are being held silent, told to shut up, because every pattern requires both light and dark.

What this analysis tells us is that the firing of pulses by axons (and by some dendrites) is only a part of the story being told by brain activity. The other part is told by the flows of ionic current from dendrites that determine the firing. The value of this other part is enhanced by the fact that the discovery of large-scale synchronization–desynchronization transitions in brains open new opportunities to the development of brain computer interfaces (BCIs). In clinical settings, BCIs can help to diagnose, predict, and treat cognitive diseases at the early stage; they can also drastically improve the quality of life of disabled people. The potential benefits are enormous. The implementations can be divided into two broad groups. Invasive techniques involve the placement of implants on brains by opening the skull. The implants can have single electrodes or multiple arrays. Rapid technological development allows to access information from individual neurons and to achieve the goal of breaking the neural code of the brain to be able to zero in on individual neurons [4, 5]. But there is no one code, if there is any at all, and if one is to be accepted for axons, another must be accepted for dendrites.

In noninvasive devices, the electrodes are located on the scalp far from the cortical neurons. As a result, the recorded signals and images lack the high resolution observed in invasive devices and cannot give us an axonal code. Noninvasive approaches give us access to dendritic codes, as they are applicable in everyday life. As a result, noninvasive BCIs are increasingly accessible, for example, in the entertainment industry, as well as serving as personal assistants in physical training and exercises.

BCIs are young and immature technologies, and they are still at the very early stage of their development. In spite of the advances with noninvasive approaches, extracting meaningful information from the signals of remotely located electrodes may seem daunting. Indeed, significant exponents of the neuroscience community consider the obstacles impenetrable and the related activities outright meaningless. The task of noninvasive brain monitoring has been ridiculed by comparing it to the assumed “impossibility” of the assignment of Keystone Cops to eavesdrop on a single conservation in a stadium from outside:



Keystone Cops in a crowded stadium, illustrating the alleged paradox of brain monitoring using noninvasive devices (Illustration by Vladimir Taytslin)

> External devices, such as the brainwave-reading skull cap … marketed as “having applications for wellness, education and entertainment,” have none of these risks. But because their sensors are so far removed from individual neurons, they are also far less effective. They are like Keystone Cops trying to eavesdrop on a single conversation from outside a giant football stadium. [4].

This misguided simile betrays the lack of awareness of large-scale brain dynamics. To pursue the simile, the *roar of the crowd at a football game* is not the sum of many thousands of conversations. It is the collective action of spectators engaged in a social ritual, for which the stadium was built at enormous expense. The crowd has convened with extensive planning in advance to enjoy participation in the realization of social solidarity. Comparably, millions of neurons form collectives that transcend pairwise synaptic exchanges. The collective that they form has the power of numbers in synchronized discharges sweeping through the basal ganglia and brain stem. The firings are far better positioned and organized than the spike trains of networks of a few tens of neurons in an unknown number of networks widely spaced in cortex. Undeniably there must be private conversations among neurons, but they are not the whole story. Collective actions take precedence, and these are observable without need for neurosurgeons.

The alternation between synchronized and desynchronized states is by no means obvious in casual recordings of ECoG or scalp EEG. Some form of temporal filtering is required [2, 6] used the spatial gradient of the alpha amplitude in the scalp EEG. Brockmeier [7] used ICA; Ruiz et al. [8] used the Rician statistics to specify a band of beta activity. Zhang et al. [9] used the phase coherence in the beta and gamma bands. Panagiotides et al. [10] used the spatial standard deviation of the beta amplitudes as a marker. Each of these measures gave access to the AM patterns that provided the neural correlates of perception of conditioned stimuli in the several modalities. The techniques also served to show that the low-energy gas-like supervenes in a resting state that was observed in animals and humans when they are placed in monotonous and unchanging environment that induces awake rest. This enabled us to define the resting state seen also under light anesthesia as a sustained ground state with a simple $1/f^{\alpha}$ canonical EEG/ECoG temporal spectrum with no peaks in the beta or gamma ranges, and $2 \leq \alpha \leq 4$ [11].

The neurodynamics of the resting and active states thus defined have been tested for stationarity and linearity. This was done by perturbing the cortex with electric impulses modeled with the Dirac delta function and measuring the impulse responses by fitting them with wavelets consisting of sums of linear basis functions [12]. The basis functions yielded the characteristic frequencies of the cortices in their normal operating range, which was defined by the range of ± 3 standard deviations of the amplitude of the resting or working EEG/ECoG. Compliance with superposition in the small signal range thus defined made it possible to model the cortical dynamics with the solutions to ordinary differential equations (ODEs). That in turn made it feasible to model the strengths and signs of synaptic couplings with adaptive coefficients and to replace the nonlinear gain curve with the slope of the tangent to the curve at the estimated operating point.

By these steps it became possible to model the dynamics on both sides of the phase transition, the random ground phase and the high-energy active phase. However, the ODE could not model the phase transition between them. Two approaches have been adopted. The more speculative approach is to use the continuous equations of many-body physics to model the interactions of neural populations that are sufficiently large to enable us to define activity density functions for axonal pulses and postsynaptic potentials (EPSPs and IPSPs) [13].

The more advanced approach is to use Random Graph Theory (RGT) [14, 15] to devise a discrete calculus in which the element is not a neuron but a functional element corresponding to the collective of neurons that participate in time-sharing. Both approaches depend on the basic assumption that the neuropil has the property to sustain pulse trains from many if not most of its neurons but also the property of ephapsis, which operates in a continuum across the sustaining neural population. Ephasis can be modeled by the discrete particles required for digital approximations in both ODE and RGT. The aim of this book is to establish a branch of RGT that supplements and may eventually replace ODE with *neuropercolation* as the basis for modeling neural population dynamics on digital platforms.

In the corresponding mathematical theories, brains are perceived as open thermodynamic systems [3, 16] converting broadly fluctuating sensory data into meaningful knowledge. Among the wide range of approaches addressing discontinuities in brain dynamics, random graphs have unique advantages by characterizing cortical processes as phase transitions and transient percolation processes in probabilistic cellular automata (PCA). The corresponding model is called neuropercolation, which uses results of RGT as a rigorous mathematical approach to formulate the fundamental relationship between transient neural processes in the cortex and the structure of the embedding brain graph. RGT has distinct advantages as compared to differential equations when describing discontinuities in cortical dynamics. It presents a paradigm shift from modeling of individual neurons to modeling the collective behavior of neural populations.

The caricatures provide metaphors to illustrate this paradigm shift and expose the limitations of analytic tools for describing microscopic pulse logic and macroscopic wave dynamics. Just as it is impossible to understand or even conceive the collective dynamics of the football stadium by trying to listen to the individual conversations in the audience; it is a feeble attempt to gain insight into brain dynamics by limiting the scope to individual neurons. Brains are large-scale systems, in which the components produce field effects as emergent phenomenon. It is the fields that provide promise to monitor and understand brain dynamics by attempting to take it apart and then learn how the neurons generate the populations and in turn how the neurons are influenced and controlled by the populations in circular causality.

Our premise is that the repetitive sudden transitions observed in the cortex are maintained by neural percolation processes in the brain as a large-scale random graph near criticality, which is self-organized in collective neural populations formed by synaptic activity. Neuropercolation addresses the complementary aspects of neocortex, manifesting complex information processing in microscopic networks of specialized spatial modules, and developing macroscopic patterns evidencing that brains are holistic, multi-tasking organs. The present volume reviews neurophysiological evidences of collective brain dynamics and proposes neuropercolation as a mathematical model to interpret experimental findings. Potential benefits to brain computer interfaces are indicated, as well.

We are delighted to present this book, which was born out of the many discussions we had in the past 10 years about the role of scale-free structure and dynamics in producing intelligent behavior in brains. The discussions started to converge during the Spring 2006 of Robert's sabbatical visit at Walter's Lab at UC Berkeley. Clearly, the question of scale-free structure and behavior is a controversial and a very contentious issue in the literature. This controversy was apparent in the failed attempts to publish such results in the journal of Behavioral and Brain Science first in 2007 by Walter, then in 2014 as a joint endeavor by two of us. It became clear that different research groups had their vested interests in one or another aspects of the issue and were not interested in hearing or considering alternative points of views. As a result, we have received feedbacks, which in our judgment transcended the boundaries expected in civilized and scientifically solid and justified constructive debates.

Following extensive discussions with our colleagues, we decided to produce this volume, which has a somewhat unorthodox structure. The first half (Part I and II) summarizes our views on the relevant experimental and theoretical findings and methodological issues on intermittent spatiotemporal neurodynamics in the brain and the key role of large-scale, collective oscillations in producing higher cognition and consciousness. The second half of the book (Part III, IV, and V) includes commentaries by leading experts in the field of neuroscience, cognitive science, and theoretical/mathematical modeling of the relationship between microscopic neural level (neuron doctrine) and macroscopic behavioral level (field theories) of brain operation.

We greatly appreciate those who supported our endeavor by contributing to this volume with their commentaries, Kazuyuki Aihara and Timothy Leleu, Bernard Baars, Steven Bressler, Ray Brown and Morris Hirsch, Peter Erdi and Zoltan Somogyvari, Hans Liljenstrom, Frank Ohl, Ichiro Tsuda, Giuseppe Vitiello, Paul Werbos, and James Wright. With their help we are able to present a broad range of

views, extending beyond our own constraints and helping to stimulate productive discussions and further breakthroughs in understanding the codes of the brain.

We are thankful for the helpful comments and critical insight by Scott Kelso and Jose Principe, and for encouragement and support from our Springer editors Janusz Kaczprzyk and Thomas Ditzinger.

This volume could not be realized without the support during the past decade from so many of our colleagues, collaborators, mentors, and students, including Paul Balister, Bela Bollobas, Mike Breakspear, A. Brockmeier, Gyuri Buzsaki, Tian Yu Cao, Antonio Capolupo, Jim Caulfield, Joshua Davis, Toshi Fukuda, Grant Gillett, Derek Harter, Mark Holmes, Sanqing Hu, Terry Huntsberger, Roman Ilin, Guang Li, C.T. Lin, Roberto Livi, Vinod Menon, Mark Myers, Masashi Obinata, Sean O'Nuallain, Heracles Panagiotides, Leonid Perlovsky, Sue Pockett, Karl Pribram, Marko Puljic, Rodrigo Quian-Quirga, Misha Rabinovich, Ceon Ramon, Oliver Riordan, Jose Rodriguez, Yusely Ruiz, Miklos Ruszinko, Hava Siegelmann, Rodrigo Silva, Yury Sokolov, Eddie Tunstel, Jun Wang, Anne Warlamount, Ludmilla Werbos, Jian Zhai, and many many more. The excellent drawings by Vladimir Taytslin and Chris Gralapp of EyeArt provide very compelling perspectives to illustrate our messages.

The intended audience of this book includes researchers, postdocs, and graduate students working towards novel approaches in brain science in order to better understand the operation of this very precious and delicate organ we are all equipped with. The results can be useful to maintain normal operation of our brain, help to improve the quality of life of the elderly, and develop novel treatments and approaches for people with cognitive or mental disabilities. In short, help to fulfill the human potential to the highest level and to support the sustainable development of humanity.

Acknowledgments

This work has been supported in part by NSF CRCNS Program DMS-13-11165, DARPA Physical Intelligence Program through HRL subcontract, by AFOSR Lab Task in the Mathematics and Cognition Program to RK, and by grants from the National Institute of Mental Health NIMH (MH06686) to WJF.

Memphis Robert Kozma
Berkeley Walter J. Freeman
November 2014

References

1. Merleau-Ponty M (1945) Phnomnologie de la perception. Gallimard, Paris
2. Freeman WJ, Quian Quiroga R (2013) Imaging brain function with EEG: advanced temporal and spatial analysis of electroencephalographic and electrocorticographic signals. Springer, New York
3. Capolupo A, Freeman WJ, Vitiello G (2013) Dissipation of 'dark energy' by cortex in knowledge retrieval. Phys Life Rev, Online. doi:10.1016/j.plrev.2013.01.001
4. Marcus G, Koch C (2014) The future of brain implants. The Wall Street Journal. Dow Jones and Co, S. Brunswick, NJ
5. Sanchez JC, Principe JC (2007). Brain-machine interface engineering (Vol 17). Morgan and Claypool Publishers, LaPorte, Colorado
6. Lehmann WK, Strik B, Henggeler T, Koenig M, Koukkou (1998) Brain electric microstates and momentary conscious mind states as building blocks of spontaneous thinking, I. Visual imagery and abstract thoughts. Int J Psychophysiol 29:111
7. Brockmeier AJ, Hazrati MK, Freeman WJ, Li L, Prncipe JC (2012) Locating spatial patterns of waveforms during sensory perception in scalp EEG. In Engineering in Medicine and Biology Society (EMBC), 2012 Annual International Conference of the IEEE (pp. 2531–2534)
8. Ruiz Y, Pockett S, Freeman WJ, Gonzales E, Guang Li (2010) A method to study global spatial patterns related to sensory perception in scalp EEG. J Neurosci Methods 191:110–118
9. Zhang T, Dai L, Freeman WJ, Li G (2013) EEG spatiotemporal pattern classification of the stimuli on different fingers. In: 4th International Conference on Cognitive Neurodynamics (ICCN2013), Sweden, Springer, Germany
10. Panagiotides H, Freeman WJ, Holmes M, Pantazis D (2008) Behavioral states exhibit distinct spatial EEG patterns. In: Proceedings of the 62nd Annual Meeting, American Epilepsy Society, Seattle, WA, 2008
11. Freeman WJ, Zhai J (2009) Simulated power spectral density (PSD) of background electrocorticogram (ECoG). Cogn Neurodyn 3(1):97–103
12. Freeman WJ (1975/2004) Mass action in the nervous system. Academic, New York. Electronic version 2004. http://sulcus.berkeley.edu/MANSWWW/MANSWWW.html
13. Freeman WJ, Livi R, Obinata M, Vitiello G (2012) Cortical phase transitions, nonequilibrium thermodynamics and time-dependent Ginzburg-Landau equation. Int J Mod Phys B 26 (06):1250035
14. Albert R, Barabasi A-L (2002) Statistical mechanics of complex networks. Rev Mod Phy 74:47–97
15. Freeman WJ, Kozma R, Bollobas B, Riordan O (2009) Chapter 7. Scale-free cortical planar network. In: Bollobas B, Kozma R, Miklos D (eds) Handbook of large-scale random networks. Series: Bolyai mathematical studies, vol 18. Springer, New York, pp. 277–324
16. Freeman WJ, Kozma R, Vitiello G (2012) Adaptation of the generalized Carnot cycle to describe thermodynamics of cerebral cortex. In: The 2012 International Joint Conference on Neural Networks (IJCNN). IEEE, pp 1–8

Commentators

Prof. Kazuyuki Aihara
Institute of Industrial Science
University of Tokyo
4-6-1, Komaba, Meguro-ku
Tokyo 153-8505, Japan
aihara@sat.t.u-tokyo.ac.jp

Dr. Bernard J. Baars, Ph.D., CEO
Society for Mind-Brain Sciences
The Neurosciences Institute
La Jolla, CA, USA
baarsbj@gmail.com
http://www.MBScience.org

Prof. Steven L. Bressler, Ph.D.
Center for Complex Systems and Brain Sciences
Department of Psychology, 777 Glades Road
Florida Atlantic University
Boca Raton, FL 33431, USA
bressler@fau.edu

Dr. Ray Brown, President
EEASI, 2100 Winrock, #64
Houston, TX 77057, USA
raybrown.easi@gmail.com

Prof. Péter Érdi, Henry R. Luce
Center for Complex Systems Studies
1200 Academy Street

Kalamazoo College
Kalamazoo, MI 49006, USA
Peter.Erdi@kzoo.edu

Prof. Morris W. Hirsch, Emeritus UCB
7926 Albe Road
Cross Plains, WI 53528-9350, USA
mwhirsch@chorus.net

Dr. Timothy Leleu
Institute of Industrial Science
University of Tokyo
4-6-1, Komaba, Meguro-ku
Tokyo 153-8505, Japan

Prof. Hans Liljenström
Agora for Biosystems, Director
Department of Energy and Technology
SLU, P.O. Box 7032
750 07 Uppsala, Sweden
Hans.Liljenstrom@slu.se

Prof. Dr. Frank W. Ohl
Leibniz Institute for Neurobiology
Department of Systems Physiology of Learning
Brenneckestr. 6
D-39118 Magdeburg, Germany
frank.ohl@ifn-magdeburg.de

Dr. Zoltan Somogyvari
Wigner Research Center for Physics
Hungarian Academy of Sciences
Konkolyi Thege M. ut 29-33
H-1121 Budapest, Hungary

Prof. Ichiro Tsuda
Research Institute for Electronic Science
Hokkaido University
Kita 12 Nishi 6, Kita-ku
Sapporo 060-0812, Japan
Tsuda@math.sci.hokudai.ac.jp

Prof. Giuseppe Vitiello, Ph.D.
Department of Physics "E.R. Caianiello"
University of Salerno
Baronissi (SA) 84100, Italy
vitiello@sa.infn.it