Contents

List of Contributors XVII

1 Introduction 1
Dietmar Plenz and Ernst Niebur
1.1 Criticality in Neural Systems 1

2 Criticality in Cortex: Neuronal Avalanches and Coherence Potentials 5
Dietmar Plenz
2.1 The Late Arrival of Critical Dynamics to the Study of Cortex Function 5
2.1.1 Studying Critical Dynamics through Local Perturbations 7
2.1.2 Principles in Cortex Design that Support Critical Neuronal Cascades 8
2.2 Cortical Resting Activity Organizes as Neuronal Avalanches 11
2.2.1 Unbiased Concatenation of Neuronal Activity into Spatiotemporal Patterns 11
2.2.2 The Power Law in Avalanche Sizes with Slope of \(-3/2\) 15
2.2.3 Neuronal Avalanches are Specific to Superficial Layers of Cortex 17
2.2.4 The Linking of Avalanche Size to Critical Branching 17
2.3 Neuronal Avalanches: Cascades of Cascades 20
2.4 The Statistics of Neuronal Avalanches and Earthquakes 23
2.5 Neuronal Avalanches and Cortical Oscillations 23
2.6 Neuronal Avalanches Optimize Numerous Network Functions 28
2.7 The Coherence Potential: Threshold-Dependent Spread of Synchrony with High Fidelity 30
2.8 The Functional Architecture of Neuronal Avalanches and Coherence Potentials 33
Acknowledgement 36
References 36
3 Critical Brain Dynamics at Large Scale  43
Dante R. Chialvo
3.1 Introduction  43
3.1.1 If Criticality is the Solution, What is the Problem?  43
3.2 What is Criticality Good for?  45
3.2.1 Emergence  46
3.2.2 Spontaneous Brain Activity is Complex  46
3.2.3 Emergent Complexity is Always Critical  47
3.3 Statistical Signatures of Critical Dynamics  47
3.3.1 Hunting for Power Laws in Densities Functions  48
3.3.2 Beyond Fitting: Variance and Correlation Scaling of BrainNoise  50
3.3.2.1 Anomalous Scaling  51
3.3.2.2 Correlation Length  52
3.4 Beyond Averages: Spatiotemporal Brain Dynamics at Criticality  55
3.4.1 fMRI as a Point Process  56
3.4.2 A Phase Transition  57
3.4.3 Variability and Criticality  59
3.5 Consequences  60
3.5.1 Connectivity versus Functional Collectivity  60
3.5.2 Networks, Yet Another Circuit?  62
3.5.3 River Beds, Floods, and Fuzzy Paths  62
3.6 Summary and Outlook  63
References  64

4 The Dynamic Brain in Action: Coordinative Structures, Criticality, and Coordination Dynamics  67
J. A. Scott Kelso
4.1 Introduction  67
4.2 The Organization of Matter  68
4.3 Setting the Context: A Window into Biological Coordination  72
4.4 Beyond Analogy  74
4.5 An Elementary Coordinative Structure: Bimanual Coordination  75
4.6 Theoretical Modeling: Symmetry and Phase Transitions  76
4.7 Predicted Signatures of Critical Phenomena in Biological Coordination  80
4.7.1 Critical Slowing Down  80
4.7.2 Enhancement of Fluctuations  81
4.7.3 Critical Fluctuations  81
4.8 Some Comments on Criticality, Timescales, and Related Aspects  82
4.9 Symmetry Breaking and Metastability  84
4.10 Nonequilibrium Phase Transitions in the Human Brain: MEG, EEG, and fMRI  87
4.11 Neural Field Modeling of Multiple States and Phase Transitions in the Brain  88
4.12 Transitions, Transients, Chimera, and Spatiotemporal Metastability 89
4.13 The Middle Way: Mesoscopic Protectorates 92
4.14 Concluding Remarks 94
Acknowledgments 95
References 96

5 The Correlation of the Neuronal Long-Range Temporal Correlations, Avalanche Dynamics with the Behavioral Scaling Laws and Interindividual Variability 105
Jaakko Matias Palva and Satu Palva
5.1 Introduction 105
5.2 Criticality in the Nervous System: Behavioral and Physiological Evidence 106
5.2.1 Human Task Performance Fluctuations Suggest Critical Dynamics 106
5.2.2 Two Lines of Empirical Evidence for Critical-State Dynamics in Neuronal Systems 108
5.3 Magneto- and Electroencephalography (M/EEG) as a Tool for Noninvasive Reconstruction of Human Cortical Dynamics 109
5.4 Slow Neuronal Fluctuations: The Physiological Substrates of LRTC 111
5.4.1 Infra-Slow Potential Fluctuations Reflect Endogenous Dynamics of Cortical Excitability 111
5.4.2 Slow Fluctuations in Oscillation Amplitudes and Scalp Potentials are Correlated with Behavioral Dynamics 113
5.4.3 Slow BOLD Signal Fluctuations in Resting-State Networks 114
5.5 Neuronal Scaling Laws are Correlated with Interindividual Variability in Behavioral Dynamics 115
5.6 Neuronal Avalanches, LRTC, and Oscillations: Enigmatic Coexistence? 117
5.6.1 The Mechanistic Insights from Interindividual Variability in Scaling Laws 118
5.7 Conclusions 119
Acknowledgment 120
References 120

6 The Turbulent Human Brain: An MHD Approach to the MEG 127
Arnold J. Mandell, Stephen E. Robinson, Karen A. Selz, Constance Schrader, Tom Holroyd, and Richard Coppola
6.1 Introduction 127
6.2 Autonomous, Intermittent, Hierarchical Motions, from Brain Proteins Fluctuations to Emergent Magnetic Fields 129
6.3 Magnetic Field Induction and Turbulence; Its Maintenance, Decay, and Modulation 130
6.4 Localizing a Time-Varying Entropy Measure of Turbulence, *Rank Vector Entropy* (RVE) \[35, 107\], Using a *Linearly Constrained Minimum Variance* (LCMV) *Beamformer* Such as *Synthetic Aperture Magnetometry* (SAM) \[25, 34\], Yields State and Function-Related Localized Increases and Decreases in the RVE Estimate 139

6.5 Potential Implications of the MHD Approach to MEG Magnetic Fields for Understanding the Mechanisms of Action and Clinical Applications of the Family of TMS (Transcranial Magnetic Stimulation) Human Brain Therapies 142

6.6 Brief Summary of Findings 145

References 145

7 Thermodynamic Model of Criticality in the Cortex Based on EEG/ECoG Data 153

Robert Kozma, Marko Puljic, and Walter J. Freeman

7.1 Introduction 153

7.2 Principles of Hierarchical Brain Models 154

7.2.1 Freeman K-Models: Structure and Functions 154

7.2.2 Basic Building Blocks of Neurodynamics 155

7.2.3 Motivation of Neuropercolation Approach to Neurodynamics 157

7.3 Mathematical Formulation of Neuropercolation 158

7.3.1 Random Cellular Automata on a Lattice 158

7.3.2 Update Rules 159

7.3.3 Two-Dimensional Lattice with Rewiring 160

7.3.4 Double-Layered Lattice 161

7.3.5 Coupling Two Double-Layered Lattices 162

7.3.6 Statistical Characterization of Critical Dynamics of Cellular Automata 163

7.4 Critical Regimes of Coupled Hierarchical Lattices 164

7.4.1 Dynamical Behavior of 2D Lattices with Rewiring 164

7.4.2 Narrow Band Oscillations in Coupled Excitatory–Inhibitory Lattices 165

7.5 BroadBand Chaotic Oscillations 167

7.5.1 Dynamics of Two Double Arrays 167

7.5.2 Intermittent Synchronization of Oscillations in Three Coupled Double Arrays 170

7.5.3 Hebbian Learning Effects 170

7.6 Conclusions 173

References 174

8 Neuronal Avalanches in the Human Brain 177

Oren Shriki and Dietmar Plenz

8.1 Introduction 177

8.2 Data and Cascade-Size Analysis 178

8.3 Cascade-Size Distributions are Power Laws 181
8.4 The Data are Captured by a Critical Branching Process 181
8.5 Discussion 186
8.6 Summary 188
Acknowledgements 188
References 188

9 Critical Slowing and Perception 191
Karl Friston, Michael Breakspear, and Gustavo Deco
9.1 Introduction 191
9.1.1 Perception and Neuronal Dynamics 191
9.1.2 Overview 192
9.2 Itinerant Dynamics 193
9.2.1 Chaotic Itinerancy 193
9.2.2 Heteroclinic Cycling 194
9.2.3 Multistability and Switching 194
9.2.4 Itinerancy, Stability, and Critical Slowing 195
9.3 The Free Energy Principle 196
9.3.1 Action and Perception 197
9.3.2 The Maximum Entropy Principle and the Laplace Assumption 198
9.3.3 Summary 199
9.4 Neurobiological Implementation of Active Inference 199
9.4.1 Perception and Predictive Coding 202
9.4.2 Action 204
9.4.3 Summary 204
9.5 Self-Organized Instability 205
9.5.1 Conditional Lyapunov Exponents and Generalized Synchrony 205
9.5.2 Critical Slowing and Conditional Lyapunov Exponents 207
9.5.3 Summary 210
9.6 Birdsong, Attractors, and Critical Slowing 211
9.6.1 A Synthetic Avian Brain 212
9.6.2 Stimulus Generation and the Generative Model 213
9.6.3 Perceptual Categorization 214
9.6.4 Perceptual Instability and Switching 216
9.6.5 Perception and Critical Slowing 219
9.6.6 Summary 221
9.7 Conclusion 223
References 224

10 Self-Organized Criticality in Neural Network Models 227
Matthias Rybarsch and Stefan Bornholdt
10.1 Introduction 227
10.2 Avalanche Dynamics in Neuronal Systems 228
10.2.1 Experimental Results 228
10.2.2 Existing Models 229
<table>
<thead>
<tr>
<th>Chapter</th>
<th>Title</th>
<th>Authors</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>13.1</td>
<td>Introduction</td>
<td></td>
<td>293</td>
</tr>
<tr>
<td>13.2</td>
<td>Properties of Scale-Free Time Series</td>
<td></td>
<td>294</td>
</tr>
<tr>
<td>13.2.1</td>
<td>Self-Affinity</td>
<td></td>
<td>294</td>
</tr>
<tr>
<td>13.2.2</td>
<td>Stationary and Nonstationary Processes</td>
<td></td>
<td>298</td>
</tr>
<tr>
<td>13.2.3</td>
<td>Scaling of an Uncorrelated Stationary Process</td>
<td></td>
<td>298</td>
</tr>
<tr>
<td>13.2.4</td>
<td>Scaling of Correlated and Anticorrelated Signals</td>
<td></td>
<td>300</td>
</tr>
<tr>
<td>13.3</td>
<td>The Detrended Fluctuation Analysis (DFA)</td>
<td></td>
<td>302</td>
</tr>
<tr>
<td>13.4</td>
<td>DFA Applied to Neuronal Oscillations</td>
<td></td>
<td>304</td>
</tr>
<tr>
<td>13.4.1</td>
<td>Preprocessing of Signals</td>
<td></td>
<td>304</td>
</tr>
<tr>
<td>13.4.2</td>
<td>Filter Design</td>
<td></td>
<td>305</td>
</tr>
<tr>
<td>13.4.3</td>
<td>Extract the Amplitude Envelope and Perform DFA</td>
<td></td>
<td>305</td>
</tr>
<tr>
<td>13.4.4</td>
<td>Determining the Temporal Integration Effect of the Filter</td>
<td></td>
<td>305</td>
</tr>
<tr>
<td>13.5</td>
<td>Insights from the Application of DFA to Neuronal Oscillations</td>
<td></td>
<td>305</td>
</tr>
<tr>
<td>13.5.1</td>
<td>DFA as a Biomarker of Neurophysiological Disorder</td>
<td></td>
<td>309</td>
</tr>
<tr>
<td>13.6</td>
<td>Scaling Behavior of Oscillations: a Sign of Criticality?</td>
<td></td>
<td>310</td>
</tr>
<tr>
<td>13.6.1</td>
<td>CROS Produces Neuronal Avalanches with Balanced Ex/In Connectivity</td>
<td></td>
<td>311</td>
</tr>
<tr>
<td>13.6.2</td>
<td>CROS Produces Oscillations with LRTC When there are Neuronal Avalanches</td>
<td></td>
<td>313</td>
</tr>
<tr>
<td>13.6.3</td>
<td>CROS Produces Oscillations with LRTC When there are Neuronal Avalanches</td>
<td></td>
<td>315</td>
</tr>
<tr>
<td>13.6.4</td>
<td>Multilevel Criticality: A New Class of Dynamical Systems?</td>
<td></td>
<td>315</td>
</tr>
<tr>
<td>13.6.5</td>
<td>Acknowledgment</td>
<td></td>
<td>316</td>
</tr>
<tr>
<td>14</td>
<td>Critical Exponents, Universality Class, and Thermodynamic “Temperature” of the Brain</td>
<td>Shan Yu, Hongdian Yang, Oren Shriki, and Dietmar Plenz</td>
<td>319</td>
</tr>
<tr>
<td>14.1</td>
<td>Introduction</td>
<td></td>
<td>319</td>
</tr>
<tr>
<td>14.2</td>
<td>Thermodynamic Quantities at the Critical Point and Their Neuronal Interpretations</td>
<td></td>
<td>320</td>
</tr>
<tr>
<td>14.3</td>
<td>Finite-Size Scaling</td>
<td></td>
<td>324</td>
</tr>
<tr>
<td>14.4</td>
<td>Studying the Thermodynamics Properties of Neuronal Avalanches at Different Scales</td>
<td></td>
<td>325</td>
</tr>
<tr>
<td>14.5</td>
<td>What Could be the “Temperature” for the Brain?</td>
<td></td>
<td>330</td>
</tr>
<tr>
<td>14.6</td>
<td>Acknowledgment</td>
<td></td>
<td>331</td>
</tr>
<tr>
<td>15</td>
<td>Peak Variability and Optimal Performance in Cortical Networks at Criticality</td>
<td>Hongdian Yang, Woodrow L. Shew, Rajarshy Roy, and Dietmar Plenz</td>
<td>335</td>
</tr>
<tr>
<td>15.1</td>
<td>Introduction</td>
<td></td>
<td>335</td>
</tr>
<tr>
<td>15.2</td>
<td>Fluctuations Are Highest Near Criticality</td>
<td></td>
<td>336</td>
</tr>
</tbody>
</table>
Acknowledgment 434
References 434

21 Nonconservative Neuronal Networks During Up-States Self-Organize Near Critical Points 437
Stefan Mihalas, Daniel Millman, Ramakrishnan Iyer, Alfredo Kirkwood, and Ernst Niebur

21.1 Introduction 437
21.2 Model 439
21.2.1 Analytical Solution 440
21.2.2 Numerical Evolution of the Fokker–Planck Equation 441
21.2.3 Fixed-Point Analysis 442
21.3 Simulations 444
21.3.1 Up- and Down-States 444
21.3.1.1 Up-/Down-State Transitions 446
21.3.2 Up-States are Critical; Down-States are Subcritical 448
21.3.3 More Biologically Realistic Networks 449
21.3.3.1 Small-World Connectivity 449
21.3.3.2 NMDA and Inhibition 450
21.3.4 Robustness of Results 452
21.4 Heterogeneous Synapses 454
21.4.1 Influence of Synaptic Weight Distributions 454
21.4.2 Voltage Distributions for Heterogeneous Synaptic Input 455
21.4.3 Results for Realistic Synaptic Distributions in the Absence of Recurrence and STSD 456
21.4.4 Heterogeneous Synaptic Distributions in the Presence of Synaptic Depression 458
21.5 Conclusion 460
Acknowledgment 460
References 460

22 Self-Organized Criticality and Near-Criticality in Neural Networks 465
Jack D. Cowan, Jeremy Neuman, and Wim van Drongelen

22.1 Introduction 465
22.1.1 Neural Network Dynamics 466
22.1.2 Stochastic Effects Near a Critical Point 468
22.2 A Neural Network Exhibiting Self-Organized Criticality 468
22.2.1 A Simulation of the Combined Mean-Field Equations 470
22.2.2 A Simulation of the Combined Markov Processes 471
22.3 Excitatory and Inhibitory Neural Network Dynamics 472
22.3.1 Equilibria of the Mean-Field Wilson–Cowan Equations 473
22.4 An E–I Neural Network Exhibiting Self-Organized Near-Criticality 475
22.4.1 Modifiable Synapses 475
22.4.2 A Simulation of the Combined Mean-Field E/I equations 477
Participants of the ‘Criticality in Neural Systems’ conference held April 30 - May 1st, 2012, at the National Institutes of Health, Bethesda, MD, USA. The conference was organized to increase the coherence of the volume at hand.