

Contents

<i>Preface</i>	<i>page</i> xiii
1. Introduction	1
Part I Background	
2. Basic Neuroscience	7
2.1 Neurons	7
2.2 Action Potentials or Spikes	8
2.3 Dendrites and Axons	9
2.4 Synapses	9
2.5 Spike Generation	10
2.6 Adapting the Connections: Synaptic Plasticity	11
2.6.1 LTP	11
2.6.2 LTD	11
2.6.3 STDP	11
2.6.4 Short-Term Facilitation and Depression	13
2.7 Brain Organization, Anatomy, and Function	13
2.8 Summary	16
2.9 Questions and Exercises	17
3. Recording and Stimulating the Brain	18
3.1 Recording Signals from the Brain	18
3.1.1 Invasive Techniques	18
3.1.2 Noninvasive Techniques	26
3.2 Stimulating the Brain	32
3.2.1 Invasive Techniques	32
3.2.2 Noninvasive Techniques	33
3.3 Simultaneous Recording and Stimulation	34
3.3.1 Multielectrode Arrays	35
3.3.2 Neurochip	35

3.4	Summary	36
3.5	Questions and Exercises	37
4.	Signal Processing	39
4.1	Spike Sorting	39
4.2	Frequency Domain Analysis	40
4.2.1	Fourier Analysis	40
4.2.2	Discrete Fourier Transform (DFT)	43
4.2.3	Fast Fourier Transform (FFT)	45
4.2.4	Spectral Features	45
4.3	Wavelet Analysis	45
4.4	Time Domain Analysis	46
4.4.1	Hjorth Parameters	46
4.4.2	Fractal Dimension	48
4.4.3	Autoregressive (AR) Modeling	49
4.4.4	Bayesian Filtering	49
4.4.5	Kalman Filtering	52
4.4.6	Particle Filtering	54
4.5	Spatial Filtering	54
4.5.1	Bipolar, Laplacian, and Common Average Referencing	55
4.5.2	Principal Component Analysis (PCA)	56
4.5.3	Independent Component Analysis (ICA)	60
4.5.4	Common Spatial Patterns (CSP)	61
4.6	Artifact Reduction Techniques	63
4.6.1	Thresholding	64
4.6.2	Band-Stop and Notch Filtering	65
4.6.3	Linear Modeling	65
4.6.4	Principal Component Analysis (PCA)	66
4.6.5	Independent Component Analysis (ICA)	66
4.7	Summary	68
4.8	Questions and Exercises	68
5.	Machine Learning	71
5.1	Classification Techniques	72
5.1.1	Binary Classification	72
5.1.2	Ensemble Classification Techniques	78
5.1.3	Multi-Class Classification	80
5.1.4	Evaluation of Classification Performance	84
5.2	Regression	87
5.2.1	Linear Regression	88
5.2.2	Neural Networks and Backpropagation	89
5.2.3	Radial Basis Function (RBF) Networks	92
5.2.4	Gaussian Processes	93

5.3	Summary	96
5.4	Questions and Exercises	96
Part II Putting It All Together		
6.	Building a BCI	101
6.1	Major Types of BCIs	101
6.2	Brain Responses Useful for Building BCIs	101
6.2.1	Conditioned Responses	101
6.2.2	Population Activity	102
6.2.3	Imagined Motor and Cognitive Activity	103
6.2.4	Stimulus-Evoked Activity	103
6.3	Summary	104
6.4	Questions and Exercises	105
Part III Major Types of BCIs		
7.	Invasive BCIs	109
7.1	Two Major Paradigms in Invasive Brain-Computer Interfacing	109
7.1.1	BCIs Based on Operant Conditioning	109
7.1.2	BCIs Based on Population Decoding	111
7.2	Invasive BCIs in Animals	113
7.2.1	BCIs for Prosthetic Arm and Hand Control	113
7.2.2	BCIs for Lower-Limb Control	126
7.2.3	BCIs for Cursor Control	129
7.2.4	Cognitive BCIs	132
7.3	Invasive BCIs in Humans	137
7.3.1	Cursor and Robotic Control Using a Multielectrode Array Implant	138
7.3.2	Cognitive BCIs in Humans	143
7.4	Long-Term Use of Invasive BCIs	143
7.4.1	Long-Term BCI Use and Formation of a Stable Cortical Representation	144
7.4.2	Long-Term Use of a Human BCI Implant	144
7.5	Summary	146
7.6	Questions and Exercises	147
8.	Semi-Invasive BCIs	149
8.1	Electrocorticographic (ECoG) BCIs	149
8.1.1	ECoG BCIs in Animals	150
8.1.2	ECoG BCIs in Humans	151
8.2	BCIs Based on Peripheral Nerve Signals	169
8.2.1	Nerve-Based BCIs	170
8.2.2	Targeted Muscle Reinnervation (TMR)	173

x **Contents**

8.3 Summary	174
8.4 Questions and Exercises	175
9. Noninvasive BCIs	177
9.1 Electroencephalographic (EEG) BCIs	177
9.1.1 Oscillatory Potentials and ERD	178
9.1.2 Slow Cortical Potentials	187
9.1.3 Movement-Related Potentials	189
9.1.4 Stimulus-Evoked Potentials	193
9.1.5 BCIs Based on Cognitive Tasks	199
9.1.6 Error Potentials in BCIs	200
9.1.7 Coadaptive BCIs	201
9.1.8 Hierarchical BCIs	203
9.2 Other Noninvasive BCIs: fMRI, MEG, and fNIR	203
9.2.1 Functional Magnetic Resonance Imaging-Based BCIs	204
9.2.2 Magnetoencephalography-Based BCIs	205
9.2.3 Functional Near Infrared and Optical BCIs	206
9.3 Summary	206
9.4 Questions and Exercises	207
10. BCIs that Stimulate	210
10.1 Sensory Restoration	210
10.1.1 Restoring Hearing: Cochlear Implants	210
10.1.2 Restoring Sight: Cortical and Retinal Implants	213
10.2 Motor Restoration	216
10.2.1 Deep Brain Stimulation (DBS)	216
10.3 Sensory Augmentation	217
10.4 Summary	219
10.5 Questions and Exercises	219
11. Bidirectional and Recurrent BCIs	221
11.1 Cursor Control with Direct Cortical Instruction via Stimulation	221
11.2 Active Tactile Exploration Using a BCI and Somatosensory Stimulation	224
11.3 Bidirectional BCI Control of a Mini-Robot	226
11.4 Cortical Control of Muscles via Functional Electrical Stimulation	229
11.5 Establishing New Connections between Brain Regions	230
11.6 Summary	234
11.7 Questions and Exercises	234
Part IV Applications and Ethics	
12. Applications of BCIs	239
12.1 Medical Applications	239
12.1.1 Sensory Restoration	239

xi

Contents

12.1.2	Motor Restoration	240
12.1.3	Cognitive Restoration	240
12.1.4	Rehabilitation	240
12.1.5	Restoring Communication with Menus, Cursors, and Spellers	241
12.1.6	Brain-Controlled Wheelchairs	241
12.2	Nonmedical Applications	242
12.2.1	Web Browsing and Navigating Virtual Worlds	243
12.2.2	Robotic Avatars	245
12.2.3	High Throughput Image Search	248
12.2.4	Lie Detection and Applications in Law	249
12.2.5	Monitoring Alertness	253
12.2.6	Estimating Cognitive Load	256
12.2.7	Education and Learning	258
12.2.8	Security, Identification, and Authentication	260
12.2.9	Physical Amplification with Exoskeletons	261
12.2.10	Mnemonic and Cognitive Amplification	262
12.2.11	Applications in Space	263
12.2.12	Gaming and Entertainment	265
12.2.13	Brain-Controlled Art	267
12.3	Summary	269
12.4	Questions and Exercises	269
13.	Ethics of Brain-Computer Interfacing	272
13.1	Medical, Health, and Safety Issues	272
13.1.1	Balancing Risks versus Benefits	272
13.1.2	Informed Consent	273
13.2	Abuse of BCI Technology	273
13.3	BCI Security and Privacy	274
13.4	Legal Issues	275
13.5	Moral and Social Justice Issues	276
13.6	Summary	277
13.7	Questions and Exercises	277
14.	Conclusion	279
<i>Appendix: Mathematical Background</i>		281
A.1	<i>Basic Mathematical Notation and Units of Measurement</i>	281
A.2	<i>Vectors, Matrices, and Linear Algebra</i>	282
A.2.1	<i>Vectors</i>	282
A.2.2	<i>Matrices</i>	284
A.2.3	<i>Eigenvectors and Eigenvalues</i>	287
A.2.4	<i>Lines, Planes, and Hyperplanes</i>	288
A.3	<i>Probability Theory</i>	288

xii

Contents

A.3.1	<i>Random Variables and Axioms of Probability</i>	288
A.3.2	<i>Joint and Conditional Probability</i>	289
A.3.3	<i>Mean, Variance, and Covariance</i>	290
A.3.4	<i>Probability Density Function</i>	291
A.3.5	<i>Uniform Distribution</i>	291
A.3.6	<i>Bernoulli Distribution</i>	291
A.3.7	<i>Binomial Distribution</i>	292
A.3.8	<i>Poisson Distribution</i>	292
A.3.9	<i>Gaussian Distribution</i>	293
A.3.10	<i>Multivariate Gaussian Distribution</i>	293
<i>References</i>		295
<i>Index</i>		307

Color plates follow page 176.