

Contents

1 Recent and Upcoming BCI Progress: Overview, Analysis, and Recommendations	1
Brendan Z. Allison, Stephen Dunne, Robert Leeb, José del R. Millán, and Anton Nijholt	
1.1 Introduction	1
1.2 Overview of This Book	2
1.2.1 Overview of Section One	3
1.2.2 Overview of Section Two	4
1.2.3 Overview of Section Three	6
1.2.4 Overview of Section Four	7
1.3 Predictions and Recommendations	8
1.4 Summary	11
References	12

Part I Sensors, Signals and Signal Processing

2 Hybrid Optical–Electrical Brain Computer Interfaces, Practices and Possibilities	17
Tomas E. Ward	
2.1 Introduction	17
2.2 The Underlying Physiological Origins of EEG and fNIRS	17
2.2.1 Origin of the EEG	18
2.2.2 Origin of fNIRS Responses	19
2.3 Signal Models	28
2.3.1 Modelling the Vascular Response	28
2.3.2 Spectrophotometric Translation	30
2.3.3 Synthetic Signal Generation	31

2.4	Combined EEG-fNIRS Measurements in Overt and Imagined Movement Tasks	33
2.4.1	fNIRS/EEG Sensor	33
2.4.2	Experimental Description	33
2.4.3	Signal Processing	34
2.4.4	Results	35
2.5	Conclusion	37
	References	38
3	A Critical Review on the Usage of Ensembles for BCI	41
	Aureli Soria-Frisch	
3.1	Introduction	41
3.2	Theoretical Background	43
3.2.1	Pattern Recognition Ensemble Definition and Context	43
3.2.2	Pattern Recognition Perspective on Fusion	44
3.2.3	Grounding the Superiority of Ensembles	46
3.3	Integration and Fusion Level	47
3.3.1	Feature Concatenation	47
3.3.2	Classification Concatenation	48
3.3.3	Classification Fusion	49
3.3.4	Decision Fusion	50
3.4	Ensemble Type	51
3.4.1	Classifier Ensembles	51
3.4.2	Stacked Ensemble	52
3.4.3	Multi-Channel Ensemble	52
3.4.4	Multimodal Ensemble	52
3.5	Resampling Strategies	52
3.5.1	Data Set Partitioning	53
3.5.2	Feature Space Partitioning	56
3.5.3	Signal Partitioning	57
3.6	Fusion Operators	57
3.6.1	Sample Based Fusion	58
3.6.2	Time Domain Fusion Operators	59
3.7	Summary of Ensembles Obtained Results	59
3.8	Final Remarks	60
	References	62
4	Improving Brain-Computer Interfaces Using Independent Component Analysis	67
	Yijun Wang and Tzzy-Ping Jung	
4.1	Introduction	67
4.2	ICA in EEG Signal Processing	68
4.3	ICA in BCI Systems	69
4.3.1	Artifact Removal	71
4.3.2	SNR Enhancement of Task-Related EEG Signals	72
4.3.3	Electrode Selection	73

4.4	ICA-Based Zero-Training-Training BCI.....	75
4.4.1	Experiment and Data Recording.....	75
4.4.2	Method.....	76
4.4.3	Results	78
4.5	Discussion and Conclusion	80
	References.....	81
5	Towards Electrographic Electrodes for Chronic Use in BCI Applications	85
	Christian Henle, Martin Schuettler, Jörn Rickert, and Thomas Stieglitz	
5.1	Introduction: From Presurgical Diagnostics to Movement Decoding.....	85
5.2	Approaches and Technologies for ECoG-Electrodes	88
5.3	ECoG Recordings in BCI Studies	91
5.4	High Channel ECoG Arrays for BCI	92
5.4.1	Manufacturing of Laser Structured Electrodes	93
5.4.2	Biological Evaluation/Results from First Studies	95
5.5	Towards Chronic Wireless Systems.....	97
	References.....	100

Part II Devices, Applications and Users

6	Introduction to Devices, Applications and Users: Towards Practical BCIs Based on Shared Control Techniques	107
	Robert Leeb and José d.R. Millán	
6.1	Introduction	107
6.2	Current and Emerging User Groups	109
6.3	BCI Devices and Application Scenarios.....	109
6.3.1	Communication and Control.....	110
6.3.2	Motor Substitution: Grasp Restoration	111
6.3.3	Entertainment and Gaming	113
6.3.4	Motor Rehabilitation and Motor Recovery	113
6.3.5	Mental State Monitoring	114
6.3.6	Hybrid BCI	114
6.4	Practical BCIs Based on Shared Control Techniques: Towards Control of Mobility	115
6.4.1	Tele-Presence Robot Controlled by Motor-Disabled People	116
6.4.2	BCI Controlled Wheelchair.....	118
6.5	Adaptation of Gesture Recognition Systems Using EEG Error Potentials	120
6.6	Conclusion	122
	References.....	123

7	Brain Computer Interface for Hand Motor Function Restoration and Rehabilitation	131
	Donatella Mattia, Floriana Pichiorri, Marco Molinari, and Rüdiger Rupp	
7.1	Introduction	131
7.2	Restoration of Hand Motor Functions in SCI: Brain-Controlled Neuroprostheses	132
7.2.1	Functional Electrical Stimulation of the Upper Extremity	133
7.2.2	Combining BCI and FES Technology	136
7.3	Rehabilitation of Hand Motor Functions After Stroke: BCI-Based Add-On Intervention	139
7.3.1	BCI in Stroke Rehabilitation: A State-of-the-Art	140
7.3.2	FES in Stroke Rehabilitation of Upper Limb	142
7.3.3	Combining BCI and FES Technology in Rehabilitation Clinical Setting: An Integrated Approach	143
7.4	Conclusion and Expectations for the Future	146
	References	148
8	User Centred Design in BCI Development	155
	Elisa Mira Holz, Tobias Kaufmann, Lorenzo Desideri, Massimiliano Malavasi, Evert-Jan Hoogerwerf, and Andrea Kübler	
8.1	Technology Based Assistive Solutions for People with Disabilities	156
8.1.1	Understanding and Defining Disability	156
8.1.2	Assistive Technologies and BCI	156
8.2	User Centred BCI Development	158
8.2.1	User Centred Design Principles	158
8.2.2	Working with End-Users in BCI Research	160
8.3	BCI for Supporting or Replacing Existing AT Solutions	166
8.3.1	Benefit in Different Fields	167
8.4	Conclusion	168
	References	169
9	Designing Future BCIs: Beyond the Bit Rate	173
	Melissa Quek, Johannes Höhne, Roderick Murray-Smith, and Michael Tangermann	
9.1	Introduction	173
9.2	Control Characteristics of BCI	174
9.2.1	Issues Specific to BCI Paradigms	175
9.2.2	Approaches to Overcoming the Limitations of BCI	176

9.3	BCI: From Usability Research to Neuroergonomic Optimization	177
9.3.1	Existing Literature on Determinants for ERP	177
9.3.2	Aesthetics, Interaction Metaphors, Usability and Performance	181
9.4	Shared Control	183
9.5	Creating an Effective Application Structure: A 3-Level Task	185
9.5.1	Low Level: BCI Control Signal	185
9.5.2	Mid Level: Application	186
9.5.3	High Level: User	186
9.6	Engaging End Users and the Role of Expectation.....	187
9.7	Investigating Interaction: Prototyping and Simulation	188
9.7.1	Low Fidelity Prototyping to Expose User Requirements	188
9.7.2	High Fidelity Simulations for Design and Development	190
9.8	Conclusion	192
	References.....	193
10	Combining BCI with Virtual Reality: Towards New Applications and Improved BCI	197
	Fabien Lotte, Josef Faller, Christoph Guger, Yann Renard, Gert Pfurtscheller, Anatole Lécuyer, and Robert Leeb	
10.1	Introduction	197
10.2	Basic Principles Behind VR and BCI Control	199
10.2.1	Definition of Virtual Reality	199
10.2.2	General Architecture of BCI-Based VR Applications	200
10.3	Review of BCI-Controlled VR Applications	202
10.3.1	Motor Imagery Controlled VR Environments	202
10.3.2	SSVEP Based VR/AR Environments	207
10.3.3	P300 Based VR Control	211
10.4	Impact of Virtual Reality on BCI	213
10.5	Conclusion	215
	References.....	216

Part III Application Interfaces and Environments

11	Brain-Computer Interfaces and User Experience Evaluation	223
	Bram van de Laar, Hayrettin Gürkök, Danny Plass-Oude Bos, Femke Nijboer, and Anton Nijholt	
11.1	Introduction	223
11.2	Current State of User Experience Evaluation of BCI	224
11.2.1	User Experience Affects BCI	224
11.2.2	BCI Affects User Experience	225

11.3	Applying HCI User Experience Evaluation to BCIs	226
11.3.1	Observational Analysis	227
11.3.2	Neurophysiological Measurement.....	228
11.3.3	Interviewing and Questionnaires	228
11.3.4	Other Methods.....	229
11.4	Case Studies	230
11.4.1	Case Study: Mind the Sheep!	230
11.4.2	Case Study: Hamster Lab	232
11.5	Discussion and Conclusion	234
	References	235
12	Framework for BCIs in Multimodal Interaction and Multitask Environments	239
	Jan B.F. van Erp, Anne-Marie Brouwer, Marieke E. Thurlings, and Peter J. Werkhoven	
12.1	Introduction	239
12.2	Challenges for the Use of BCIs in a Dual Task Environment.....	241
12.2.1	Psychological Models for Dual Task Situations and Coping with Conflicts	242
12.3	Combining BCIs	245
12.4	Integrating BCIs in a Multimodal User Interface: Relevant Issues	246
12.5	Discussion and Conclusion	247
	References	249
13	EEG-Enabled Human–Computer Interaction and Applications.....	251
	Olga Sourina, Qiang Wang, Yisi Liu, and Minh Khoa Nguyen	
13.1	Introduction	251
13.2	Brain State Recognition Algorithms and Systems	252
13.2.1	Neurofeedback Systems for Medical Application	252
13.2.2	Signal Processing Algorithms for Neurofeedback Systems	253
13.2.3	Neurofeedback Systems for Performance Enhancement	254
13.2.4	Emotion Recognition Algorithms	255
13.3	Spatio-Temporal Fractal Approach	256
13.3.1	3D Mapping of EEG for Visual Analytics	256
13.3.2	Fractal-Based Approach	258
13.3.3	Real-Time Brain State Recognition	259
13.3.4	Features Extraction	260
13.4	Real-Time EEG-Enabled Applications	261
13.4.1	Neurofeedback Training Systems	262
13.4.2	Real-Time EEG-Based Emotion Recognition and Monitoring	263
13.5	Conclusion	263
	References	265

14	Phase Detection of Visual Evoked Potentials Applied to Brain Computer Interfacing	269
	Gary Garcia-Molina and Danhua Zhu	
14.1	Introduction	269
14.2	Signal Processing and Pattern Recognition Methods	271
	14.2.1 Spatial Filtering	272
	14.2.2 Phase Synchrony Analysis	273
14.3	Experimental Evidence	273
	14.3.1 Optimal Stimulation Frequency	274
	14.3.2 Calibration of the BCI Operation	276
	14.3.3 BCI Operation and Information Transfer Rate	276
14.4	Discussion and Conclusion	278
	References	279
15	Can Dry EEG Sensors Improve the Usability of SMR, P300 and SSVEP Based BCIs?	281
	Günter Edlinger and Christoph Guger	
15.1	Motivation of BCI Research	281
15.2	Methods	284
	15.2.1 g.SAHARA Dry Electrode Sensor Concept	284
15.3	Experimental Setup	286
15.4	P300 BCI	287
15.5	Motor Imagery	287
15.6	SSVEP BCI	288
15.7	Results	289
15.8	P300 Paradigm	290
15.9	Motor Imagery	292
15.10	SSVEP Training	297
15.11	Discussion	297
	References	299

Part IV A Practical BCI Infrastructure: Emerging Issues

16	BCI Software Platforms	304
	Clemens Brunner, Giuseppe Andreoni, Lugi Bianchi, Benjamin Blankertz, Christian Breitwieser, Shin'ichiro Kanoh, Christian A. Kothe, Anatole Lécuyer, Scott Makeig, Jürgen Mellinger, Paolo Perego, Yann Renard, Gerwin Schalk, I Putu Susila, Bastian Venthur, and Gernot R. Müller-Putz	
16.1	Introduction	304
16.2	BCI2000	305
16.3	OpenViBE	308
16.4	TOBI	311
16.5	BCILAB	314

16.6	BCI++	316
16.7	xBCI	319
16.8	BF++	322
16.9	Pyff	323
16.10	Conclusion	326
	References	327
17	Is It Significant? Guidelines for Reporting BCI Performance	333
	Martin Billinger, Ian Daly, Vera Kaiser, Jing Jin, Brendan Z. Allison, Gernot R. Müller-Putz, and Clemens Brunner	
17.1	Introduction	333
17.2	Performance Measures	334
	17.2.1 Confusion Matrix	334
	17.2.2 Accuracy and Error Rate	336
	17.2.3 Cohen's Kappa	336
	17.2.4 Sensitivity and Specificity	337
	17.2.5 <i>F</i> -Measure	338
	17.2.6 Correlation Coefficient	338
17.3	Significance of Classification	339
	17.3.1 Theoretical Level of Random Classification	339
	17.3.2 Confidence Intervals	340
	17.3.3 Summary	342
17.4	Performance Metrics Incorporating Time	342
17.5	Estimating Performance Measures on Offline Data	344
	17.5.1 Dataset Manipulations	345
	17.5.2 Considerations	346
17.6	Hypothesis Testing	346
	17.6.1 Student's <i>t</i> -Test vs. ANOVA	347
	17.6.2 Repeated Measures	347
	17.6.3 Multiple Comparisons	348
	17.6.4 Reporting Results	350
17.7	Conclusion	350
	References	351
18	Principles of Hybrid Brain–Computer Interfaces	355
	Gernot R. Müller-Putz, Robert Leeb, José d.R. Millán, Petar Horki, Alex Kreiling, Günther Bauernfeind, Brendan Z. Allison, Clemens Brunner, and Reinhold Scherer	
18.1	Introduction	355
18.2	hBCI Based on Two Different EEG-Based BCIs	356
	18.2.1 BCIs Based on ERD and Evoked Potentials	356
	18.2.2 Combined Motor Imagery and SSVEP Based BCI Control of a 2 DoF Artificial Upper Limb	358

18.3	hBCI Based on EEG-Based BCI and a Non-EEG Based BCI	359
18.4	hBCI Based on EEG-Based BCI and Another Biosignal	362
18.4.1	Heart Rate Changes to Power On/Off an SSVEP-BCI	362
18.4.2	Fusion of Brain and Muscular Activities	363
18.5	hBCI Based on EEG-Based BCI and EEG-Based Monitoring	365
18.5.1	Simultaneous Usage of Motor Imagery and Error Potential	365
18.6	hBCI Based on EEG-Based BCI and Other Signals	366
18.6.1	Combination of an EEG-Based BCI and a Joystick	366
18.7	Outlook: hBCI Based on EEG-Based BCI and EEG-Based Monitoring and Other Biosignals	369
18.8	Conclusion and Future Work	370
	References	371
19	Non-visual and Multisensory BCI Systems: Present and Future	375
	Isabella C. Wagner, Ian Daly, and Aleksander Väljamäe	
19.1	Introduction	375
19.2	P300 Based BCI Systems	376
19.2.1	The “P300” Matrix Speller	376
19.2.2	Moving Beyond the “Matrix”: Other Oddball Paradigms	377
19.2.3	Tactile P300 Based BCIs	379
19.3	BCIs Based on Steady-State Evoked Responses	379
19.3.1	Auditory Steady-State Responses	379
19.3.2	Tactile Steady-State Responses	380
19.4	Controlling BCIs with Slow Cortical Potentials	381
19.5	Sensorimotor Rhythms and Different Mental Tasks	382
19.5.1	Sonification of Motor Imagery	382
19.5.2	Somatosensory Feedback for Motor Imagery	382
19.5.3	BCIs Based Upon Imagination of Music and Rhythmization	383
19.5.4	BCIs Based Upon Speech	384
19.5.5	Conceptual BCIs	385
19.6	New Directions for Multisensory BCI Research	385
19.6.1	Combining Visual P300 BCIs with Other Modalities	386
19.6.2	Combining Visual SSVEP BCIs with Other Modalities	387
19.6.3	Combining Visual Feedback with Other Modalities	387
19.6.4	Mental Tasks and Multisensory Feedback	387
19.7	Conclusion	388
	References	389

20 Characterizing Control of Brain–Computer Interfaces with BioGauges 395
Adriane B. Randolph, Melody M. Moore Jackson, and Steven G. Mason

20.1 Introduction 395

20.2 Key Factors for BCI Use 396

20.3 Characterizing BCI Systems 398

20.3.1 BioGauges and Controllability 399

20.3.2 Transducer Categories 399

20.3.3 The BioGauges Experimental System..... 401

20.3.4 Analysis Methods 403

20.3.5 Validation 404

20.4 Summary and Future Work 405

References 406

Index 409