Contents

Preface **xiii**

1 Brain–computer interfaces and electroencephalogram: basics and practical issues **1**
Mahnaz Arvaneh and Toshihisa Tanaka

Abstract 1
1.1 Introduction 1
1.2 Core components of a BMI system 2
1.3 Signal acquisition 3
1.3.1 Electroencephalography 4
1.3.2 Positron emission tomography 4
1.3.3 Magnetoencephalography 4
1.3.4 Functional magnetic resonance imaging 4
1.3.5 Near-infrared spectroscopy 5
1.3.6 Commonly used method in BMI—why EEG? 5
1.4 Measurement of EEG 6
1.4.1 Principle of EEG 6
1.4.2 How to measure EEG 6
1.4.3 Practical issues 7
1.5 Neurophysiological signals in EEG for driving BMIs 9
1.5.1 Evoked potentials 9
1.5.2 Spontaneous signals 10
1.6 Commonly used EEG processing methods in BMI 11
1.6.1 Preprocessing 11
1.6.2 Re-referencing 12
1.6.3 Feature extraction 13
1.6.4 Classification 14
1.7 Feedback 14
1.8 BMI applications 15
1.9 Summary 16
References 16

2 Discriminative learning of connectivity pattern of motor imagery EEG **23**
Xinyang Li, Cuntai Guan, and Huijuan Yang

Abstract 23
2.1 Introduction 23
2.2 Discriminative learning of connectivity pattern of motor imagery EEG 26
2.2.1 Spatial filter design for variance feature extraction 26
2.2.2 Discriminative learning of connectivity pattern 27
2.3 Experimental study 28
2.3.1 Experimental setup and data processing 28
2.3.2 Correlation results 29
2.3.3 Classification results 35
2.4 Relations with existing methods 36
2.5 Conclusion 36
References 37

3 An experimental study to compare CSP and TSM techniques to extract features during motor imagery tasks **41**
Matteo Sartori, Simone Fiori, and Toshihisa Tanaka

Abstract 41
3.1 Introduction 42
3.2 Theoretical concepts and methods 44
3.2.1 Averaging techniques of SCMs 44
3.2.2 SCM averages in CSP and TSM methods 46
3.2.3 Multidimensional scaling (MDS) algorithm 47
3.3 Experimental results 48
3.3.1 Classification accuracy 48
3.3.2 SCMs distributions on tangent spaces 54
3.4 Conclusions 58
References 58

4 Robust EEG signal processing with signal structures **61**
Hiroshi Higashi and Toshihisa Tanaka

Abstract 61
4.1 Introduction 61
4.2 Source analysis 63
4.3 Regularization 65
4.4 Filtering in graph spectral domain 67
4.4.1 Graph Fourier transform 67
4.4.2 Smoothing and dimensionality reduction by GFT 70
4.4.3 Tangent space mapping from Riemannian manifold 72
4.4.4 Smoothing on functional brain structures 74
4.5 Conclusion 76
References 76

5 A review on transfer learning approaches in brain–computer interface **81**
Ahmed M. Azab, Jake Toth, Lyudmila S. Mihaylova, and Mahnaz Arvaneh

Abstract 81
5.1 Introduction 81
5.2 Transfer learning 82
5.2.1 History of transfer learning 82
5.2.2 Transfer learning definition 83
5.2.3 Transfer learning categories 84
5.3 Transfer learning approaches 85
5.3.1 Instance-based transfer learning 85
5.3.2 Feature-representation transfer learning 85
5.3.3 Classifier-based transfer learning 85
5.3.4 Relational-based transfer learning 86
5.4 Transfer learning methods used in BCI 86
5.4.1 Instance-based transfer learning in BCI 86
5.4.2 Feature-representation transfer learning in BCI 88
5.4.3 Classifier-based transfer learning in BCI 92
5.4.4 Unsupervised transfer learning 96
5.5 Challenges and discussion 96
5.5.1 Instance-based transfer learning in BCI 96
5.5.2 Feature-representation transfer learning in BCI 97
5.5.3 Classifier-based transfer learning in BCI 97
5.6 Summary 97
References 98

6 Unsupervised learning for brain–computer interfaces based on event-related potentials **103**
Pieter-Jan Kindermans, David Hübner, Thibault Verhoeven, Klaus-Robert Müller, and Michael Tangermann

Abstract 103
6.1 Introduction 103
6.2 Event-related potential based brain–computer interfaces 106
6.3 Decoding based on expectation maximisation 107
6.3.1 The probabilistic model for ERP BCI 107
6.3.2 Training the model 108
6.4 Decoding based on learning from label proportions 110
6.4.1 Learning from label proportions 110
6.4.2 A modified ERP paradigm 111
6.4.3 Training of the LLP model 112
6.5 Combining EM and LLP decoders analytically 113
6.5.1 Training the MIX model 114

6.6 Experimental setup 114
6.6.1 Data 114
6.6.2 Data processing 115
6.6.3 Methods and hyperparameters 115
6.7 Results 116
6.8 Conclusion 120
Acknowledgements 120
References 121

7 Covariate shift detection-based nonstationary adaptation in motor-imagery-based brain–computer interface 125
Haider Raza and Dheeraj Rathee

Abstract 125
7.1 Introduction 125
7.2 Background 127
7.2.1 Covariate shift in EEG signals 127
7.2.2 Adaptive learning methods in EEG-based BCI 127
7.3 Covariate shift detection-based nonstationary adaptation (CSD-NSA) algorithm 129
7.3.1 Problem formulation 129
7.3.2 Covariate shift detection (CSD) test 130
7.3.3 Supervised CSD–NSA algorithm 131
7.3.4 Unsupervised CSD-NSA algorithm 132
7.4 Experimental validation of the CSD-NSA algorithms 135
7.4.1 EEG dataset 135
7.4.2 Signal processing and feature extraction 135
7.4.3 Feature selection and parameter estimation 136
7.4.4 Empirical results 137
7.5 Discussion and future prospects 138
References 139

8 A BCI challenge for the signal-processing community: considering the user in the loop 143
Fabien Lotte, Camille Jeunet, Jelena Mladenovic, Bernard N'Kaoua, and Léa Pillette

Abstract 143
8.1 Introduction 144
8.2 Modeling the user 145
8.2.1 Estimating and tracking the user's mental states from multimodal sensors 146
8.2.2 Quantifying users' skills 148
8.2.3 Creating a dynamic model of the users' states and skills 149

8.3 Improving BCI user training 155
8.3.1 Designing features and classifiers that the user can understand and learn from 156
8.3.2 Identifying when to update classifiers to enhance learning 157
8.3.3 Designing BCI feedbacks ensuring learning 158
8.4 Conclusion 163
Acknowledgments 164
References 164

9 Feedforward artificial neural networks for event-related potential detection 173
Hubert Cecotti

Abstract 173
9.1 Introduction 173
9.2 Event-related potentials 175
9.3 Feedforward neural networks 176
9.3.1 Activation functions 177
9.3.2 Error evaluation 178
9.3.3 Architectures 178
9.4 Methods 183
9.5 Experimental protocol 184
9.5.1 Conv nets 184
9.5.2 Performance evaluation 186
9.6 Results 186
9.7 Discussion 188
9.8 Conclusion 190
References 190

10 Signal models for brain interfaces based on evoked response potential in EEG 193
Yeganeh M. Marghi, Paula Gonzalez-Navarro, Fernando Quivira, James McLean, Bruna Girvent, Mohammad Moghadamfalahi, Murat Akcakaya, and Deniz Erdogmus

Abstract 193
10.1 ERP-based BCIs 193
10.1.1 Multidimensional EEG classification 195
10.1.2 Nonstationarities in EEG signals 195
10.1.3 Noise in the class labels 196
10.2 ERP-based inference 197
10.2.1 ERP detection 197
10.2.2 Linear model and covariance matrix structures 198
10.2.3 Nonstationarities detection 203
10.2.4 Decoupling the class label from ERP detection 205

10.3 Experimental results and discussions 206
10.3.1 ERP-based BCI typing system 206
10.3.2 ERP-based BCI with tactile stimuli 210
10.4 Summary 213
References 214

11 Spatial filtering techniques for improving individual template-based SSVEP detection 219
Masaki Nakanishi, Yijun Wang, and Tzyy-Ping Jung

Abstract 219
11.1 Introduction 219
11.2 Individual template-based SSVEP detection 222
11.2.1 Basic framework 222
11.2.2 Ensemble strategy 223
11.2.3 Filter bank analysis 224
11.3 Spatial-filtering techniques 225
11.3.1 Average combination 225
11.3.2 Minimum energy combination 225
11.3.3 Canonical correlation analysis 228
11.3.4 Independent component analysis 229
11.3.5 Task-related component analysis 230
11.4 Material and methods 231
11.4.1 Dataset 231
11.4.2 Performance evaluation 232
11.5 Results and discussions 233
11.5.1 Signal features of SSVEPs after spatial filtering 233
11.5.2 A comparison of frameworks for SSVEP detection 233
11.5.3 A comparison of electrodes settings 236
11.5.4 Toward further improvement 238
11.5.5 Challenges and future direction 238
11.6 Conclusions 239
References 239

12 A review of feature extraction and classification algorithms for image RSVP-based BCI 243
Zhengwei Wang, Graham Healy, Alan F. Smeaton, and Tomas E. Ward

Abstract 243
12.1 Introduction 243
12.2 Overview of RSVP experiments and EEG data 245
12.2.1 RSVP experiment for EEG data acquisition 245
12.2.2 Brief introduction to RSVP-EEG pattern 246

12.2.3 RSVP-EEG data preprocessing and properties 249
12.2.4 Performance evaluation metrics 250
12.3 Feature extraction methods used in RSVP-based BCI research 251
12.3.1 Spatial filtering 251
12.3.2 Time-frequency representation 256
12.3.3 Other feature extraction methods 257
12.3.4 Summary 258
12.4 Survey of classifiers used in RSVP-based BCI research 258
12.4.1 Linear classifiers 258
12.4.2 Neural networks 262
12.5 Conclusion 264
Acknowledgment 265
References 265

13 Decoding music perception and imagination using deep-learning techniques 271
Sebastian Stober and Avital Sternin

Abstract 271
13.1 Introduction and motivation 271
13.1.1 Evidence from research on auditory perception and imagination 271
13.1.2 Existing auditory and music-based BCIs 273
13.2 Deep learning for EEG analysis – the state of the art 274
13.2.1 Challenges 274
13.2.2 Deep learning applied to EEG analysis 275
13.2.3 Custom solutions developed for EEG analysis 276
13.2.4 The need for open science 277
13.2.5 Summary 277
13.3 Experimental design 278
13.3.1 Stimulus selection 278
13.3.2 Equipment and procedure 279
13.3.3 Preprocessing 281
13.4 Representation learning techniques for pre-training 282
13.4.1 Basic auto-encoder 282
13.4.2 Cross-trial encoder 285
13.4.3 Hydra-net cross-trial encoder 286
13.4.4 Similarity-constraint encoder 286
13.4.5 Siamese networks and triplet networks 290
13.5 Interpreting trained models 291
13.6 Conclusions 293
References 295

14 Neurofeedback games using EEG-based brain–computer interface technology **301**
A.P. Vinod and Kavitha P. Thomas

Abstract 301
14.1 Introduction 302
14.2 Generic framework of a neurofeedback game using BCI technology 303
14.2.1 Data acquisition 303
14.2.2 Data processing 304
14.2.3 Control signal generation 304
14.2.4 Gaming interface 305
14.3 Classification of neurofeedback games based on BCI interaction 305
14.3.1 Active BCI games 305
14.3.2 Reactive BCI games 310
14.3.3 Passive BCI games 314
14.3.4 Hybrid games 318
14.4 EEG devices for neurofeedback development 319
14.5 Benefits of neurofeedback games 320
14.5.1 Novel entertainment modality 320
14.5.2 Cognitive enhancement tool in the neurologically challenged as well as healthy 321
14.5.3 BCI performance booster 321
14.6 Challenges in practical implementation 322
14.7 Conclusion 324
References 324

Index **331**