

# Brain–Computer Interfaces Handbook

## Technological and Theoretical Advances

Edited by  
Chang S. Nam  
Anton Nijholt  
Fabien Lotte



**CRC Press**

Taylor & Francis Group  
Boca Raton London New York

---

CRC Press is an imprint of the  
Taylor & Francis Group, an **informa** business

MATLAB® and Simulink® are trademarks of The MathWorks, Inc. and are used with permission. The MathWorks does not warrant the accuracy of the text or exercises in this book. This book's use or discussion of MATLAB® and Simulink® software or related products does not constitute endorsement or sponsorship by The MathWorks of a particular pedagogical approach or particular use of the MATLAB® and Simulink® software.

CRC Press  
Taylor & Francis Group  
6000 Broken Sound Parkway NW, Suite 300  
Boca Raton, FL 33487-2742

© 2018 by Taylor & Francis Group, LLC  
CRC Press is an imprint of Taylor & Francis Group, an Informa business

No claim to original U.S. Government works

Printed on acid-free paper

International Standard Book Number-13: 978-1-4987-7343-0 (Hardback)

This book contains information obtained from authentic and highly regarded sources. Reasonable efforts have been made to publish reliable data and information, but the author and publisher cannot assume responsibility for the validity of all materials or the consequences of their use. The authors and publishers have attempted to trace the copyright holders of all material reproduced in this publication and apologize to copyright holders if permission to publish in this form has not been obtained. If any copyright material has not been acknowledged please write and let us know so we may rectify in any future reprint.

Except as permitted under U.S. Copyright Law, no part of this book may be reprinted, reproduced, transmitted, or utilized in any form by any electronic, mechanical, or other means, now known or hereafter invented, including photocopying, microfilming, and recording, or in any information storage or retrieval system, without written permission from the publishers.

For permission to photocopy or use material electronically from this work, please access [www.copyright.com](http://www.copyright.com) (<http://www.copyright.com/>) or contact the Copyright Clearance Center, Inc. (CCC), 222 Rosewood Drive, Danvers, MA 01923, 978-750-8400. CCC is a not-for-profit organization that provides licenses and registration for a variety of users. For organizations that have been granted a photocopy license by the CCC, a separate system of payment has been arranged.

**Trademark Notice:** Product or corporate names may be trademarks or registered trademarks, and are used only for identification and explanation without intent to infringe.

---

#### Library of Congress Cataloging-in-Publication Data

---

Names: Nam, Chang S., editor. | Nijholt, Anton, 1946- editor. | Lotte, Fabien, editor.  
Title: Brain-computer interfaces handbook : technological and theoretical advances / edited by Chang S. Nam, Anton Nijholt, Fabien Lotte.  
Description: Boca Raton : Taylor & Francis, CRC Press, 2018. | Includes bibliographical references and index.  
Identifiers: LCCN 2017035052 | ISBN 9781498773430 (hardback : alk. paper)  
Subjects: LCSH: Neuroergonomics. | Brain-computer interfaces. | Self-help devices for people with disabilities. | Brain--Research. | Computer games--Equipment and supplies. | Augmented reality. | Human-machine systems.  
Classification: LCC QP360.7 .B7345 2018 | DDC 612.80285--dc23  
LC record available at <https://lccn.loc.gov/2017035052>

---

Visit the Taylor & Francis Web site at  
<http://www.taylorandfrancis.com>

and the CRC Press Web site at  
<http://www.crcpress.com>

---

# Contents

Foreword .....	xi
Preface.....	xiii
Handbook Website .....	xv
Editors .....	xvii
Contributors .....	xix
Reviewers.....	xxv

<b>Introduction: Evolution of Brain–Computer Interfaces .....</b>	<b>1</b>
<i>Fabien Lotte, Chang S. Nam, and Anton Nijholt</i>	

## ***PART I Brain–Computer Interface Applications***

### ***SECTION A Brain–Computer Interfaces Introduction***

<b>Chapter 1</b> Brain–Computer Interface .....	<b>11</b>
<i>Chang S. Nam, Inchul Choi, Amy Wadeson, and Mincheol Whang</i>	

<b>Chapter 2</b> Facilitating the Integration of Modern Neuroscience into Noninvasive BCIs.....	<b>53</b>
<i>Mark Wronkiewicz, Eric Larson, and Adrian K.C. Lee</i>	

<b>Chapter 3</b> Passive Brain–Computer Interfaces.....	<b>69</b>
<i>Laurens R. Krol, Lena M. Andreessen, and Thorsten O. Zander</i>	

### ***SECTION B Therapeutic Applications***

<b>Chapter 4</b> Brain–Computer Interfaces for Motor Rehabilitation, Assessment of Consciousness, and Communication .....	<b>89</b>
<i>Christoph Guger, Rossella Spataro, Jitka Annen, Rupert Ortner, Danut Irimia, Brendan Allison, Vincenzo La Bella, Woosang Cho, Günter Edlinger, and Steven Laureys</i>	

<b>Chapter 5</b> Therapeutic Applications of BCI Technologies .....	<b>101</b>
<i>Dennis J. McFarland</i>	

<b>Chapter 6</b> Neuroprosthetics.....	<b>113</b>
<i>Stuart Mason Dambrot</i>	

- Chapter 7** Design and Customization of SSVEP-Based BCI Applications Aimed for Elderly People ..... 133

*Piotr Stawicki, Felix Gemblar, and Ivan Volosyak*

## **SECTION C Affective and Artistic Brain–Computer Interfaces**

- Chapter 8** Affective Brain–Computer Interfacing and Methods for Affective State Detection ..... 147

*Ian Daly*

- Chapter 9** Toward Practical BCI Solutions for Entertainment and Art Performance..... 163

*Paruthi Pradhapan, Ulf Großekathöfer, Giuseppina Schiavone, Bernard Grundlehner, and Vojkan Mihajlović*

- Chapter 10** BCI for Music Making ..... 191

*Duncan A.H. Williams and Eduardo R. Miranda*

## **SECTION D BCI Control of Entertainment and Multimedia**

- Chapter 11** BCI and Games ..... 207

*Silvia E. Kober, Manuel Ninaus, Elisabeth V.C. Friedrich, and Reinhold Scherer*

- Chapter 12** Brain–Computer Interfaces for Mediating Interaction in Virtual and Augmented Reality ..... 233

*Josef Faller, Neil Weiss, Nicholas Waytowich, and Paul Sajda*

- Chapter 13** Brain–Computer Interfaces and Haptics..... 251

*Jan B.F. van Erp*

## **PART II Signal Acquisition and Open Source Platform in BCI**

- Chapter 14** Utilizing Subdermal Electrodes as a Noninvasive Alternative for Motor-Based BCIs..... 267

*Melissa M. Smith, Jared D. Olson, Felix Darvas, and Rajesh P.N. Rao*

- Chapter 15** Validation of Neurotrophic Electrode Long-Term Recordings in Human Cortex.... 277

*Philip R. Kennedy, Dinal S. Andreasen, Jess Bartels, Princewill Ehirim, Edward Joe Wright, Steven Seibert, and Andre Joel Cervantes*

Contents	vii
<b>Chapter 16</b> ECoG-Based BCIs .....	295
<i>Aysegul Gunduz and Gerwin Schalk</i>	
<b>Chapter 17</b> BCI Software.....	321
<i>Peter Brunner and Gerwin Schalk</i>	

### **PART III Signal Processing, Feature Extraction, and Classification in BCI**

<b>Chapter 18</b> Gentle Introduction to Signal Processing and Classification for Single-Trial EEG Analysis .....	343
<i>Benjamin Blankertz</i>	
<b>Chapter 19</b> Riemannian Classification for SSVEP-Based BCI .....	371
<i>Sylvain Chevallier, Emmanuel K. Kalunga, Quentin Barthélemy, and Florian Yger</i>	
<b>Chapter 20</b> The Fundamentals of Signal Processing for Evoked Potential BCIs .....	397
<i>Garett D. Johnson and Dean J. Krusienski</i>	
<b>Chapter 21</b> Bayesian Learning for EEG Analysis .....	407
<i>Yu Zhang</i>	
<b>Chapter 22</b> Transfer Learning for BCIs.....	425
<i>Vinay Jayaram, Karl-Heinz Fiebig, Jan Peters, and Moritz Grosse-Wentrup</i>	

### **PART IV Brain–Computer Interface Paradigms**

<b>Chapter 23</b> A Step-by-Step Tutorial for a Motor Imagery–Based BCI .....	445
<i>Hohyun Cho, Minkyu Ahn, Moonyoung Kwon, and Sung Chan Jun</i>	
<b>Chapter 24</b> Eye Gaze Collaboration with Brain–Computer Interfaces .....	461
<i>Gaye Lightbody, Chris P. Brennan, Paul J. McCullagh, and Leo Galway</i>	
<b>Chapter 25</b> Designing a BCI Stimulus Presentation Paradigm Using a Performance-Based Approach .....	487
<i>Boyla O. Mainsah, Leslie M. Collins, and Chandra S. Throckmorton</i>	

<b>Chapter 26</b>	Issues and Challenges in Designing P300 and SSVEP Paradigms.....	501
	<i>Ali Haider and Reza Fazel-Rezai</i>	
<b>Chapter 27</b>	Hybrid Brain–Computer Interfaces and Their Applications .....	525
	<i>Jiahui Pan and Yuanqing Li</i>	
<b>Chapter 28</b>	Augmenting Attention with Brain–Computer Interfaces.....	549
	<i>Mehdi Ordikhani-Seyedlar and Mikhail A. Lebedev</i>	

## ***PART V Human Factors, Design, and Evaluation in BCI***

<b>Chapter 29</b>	Toward Usability Evaluation for Brain–Computer Interfaces .....	563
	<i>Ilsun Rhiu, Yushin Lee, Inchul Choi, Myung Hwan Yun, and Chang S. Nam</i>	
<b>Chapter 30</b>	Why User-Centered Design Is Relevant for Brain–Computer Interfacing and How It Can Be Implemented in Study Protocols .....	585
	<i>Sonja C. Kleih and Andrea Kübler</i>	
<b>Chapter 31</b>	A Generic Framework for Adaptive EEG-Based BCI Training and Operation .....	595
	<i>Jelena Mladenović, Jeremie Mattout, and Fabien Lotte</i>	
<b>Chapter 32</b>	Mind the Traps! Design Guidelines for Rigorous BCI Experiments .....	613
	<i>Camille Jeunet, Stefan Debener, Fabien Lotte, Jeremie Mattout, Reinhold Scherer, and Catharina Zich</i>	
<b>Chapter 33</b>	Evaluation and Performance Assessment of the Brain–Computer Interface System .....	635
	<i>Md Rakibul Mowla, Jane E. Huggins, and David E. Thompson</i>	

## ***PART VI Emerging Issues and Future BCIs***

<b>Chapter 34</b>	Privacy and Ethics in Brain–Computer Interface Research .....	653
	<i>Eran Klein and Alan Rubel</i>	
<b>Chapter 35</b>	Associative Plasticity Induced by a Brain–Computer Interface Based on Movement-Related Cortical Potentials.....	669
	<i>Natalie Mrachacz-Kersting, Ning Jiang, and Dario Farina</i>	

Contents	ix
<b>Chapter 36</b> Past and Future of Multi-Mind Brain–Computer Interfaces.....	685
<i>Davide Valeriani and Ana Matran-Fernandez</i>	
<b>Chapter 37</b> Bidirectional Neural Interfaces .....	701
<i>Mikhail A. Lebedev and Alexei Ossadtchi</i>	
<b>Chapter 38</b> Perspectives on Brain–Computer Interfaces.....	721
<i>Gerwin Schalk</i>	
<b>Conclusion: Moving Forward in Brain–Computer Interfaces</b> .....	725
<i>Chang S. Nam, Fabien Lotte, and Anton Nijholt</i>	
<b>Author Index</b> .....	727
<b>Subject Index</b> .....	729