Brain-Computer Interfacing

The idea of interfacing minds with machines has long captured the human imagination. Recent advances in neuroscience and engineering are making this a reality, opening the door to restoring and potentially augmenting human physical and mental capabilities. Medical applications such as cochlear implants for the deaf and deep brain stimulation for Parkinson's disease are becoming increasingly commonplace. Brain-computer interfaces (BCIs) (also known as brain-machine interfaces or BMIs) are now being explored in applications as diverse as security, lie detection, alertness monitoring, telepresence, gaming, education, art, and human augmentation.

This introduction to the field is designed as a textbook for upper-level undergraduate and first-year graduate courses in neural engineering or brain-computer interfacing for students from a wide range of disciplines. It can also be used for self-study and as a reference by neuroscientists, computer scientists, engineers, and medical practitioners.

Key features include:

- Essential background in neuroscience, brain recording and stimulation technologies, signal processing, and machine learning
- Detailed description of the major types of BCIs in animals and humans, including invasive, semi-invasive, noninvasive, stimulating, and bidirectional BCIs
- In-depth discussion of BCI applications and BCI ethics
- Questions and exercises in each chapter
- Supporting Web site with annotated list of book-related links

Rajesh P. N. Rao is an associate professor in the Computer Science and Engineering department at the University of Washington, Seattle. He has been awarded an NSF CAREER award, an ONR Young Investigator Award, a Sloan Faculty Fellowship, and a David and Lucile Packard Fellowship for Science and Engineering. Rao has published more than 150 papers in conferences and leading scientific journals, including *Science, Nature*, and *PNAS*, and is the co-editor of *Probabilistic Models of the Brain* and *Bayesian Brain*. His research targets problems at the intersection of computational neuroscience, artificial intelligence, and brain-computer interfacing. His not-so-copious spare time is devoted to Indian art history and to understanding the ancient undeciphered script of the Indus civilization, a topic on which he has given a TED talk.

Brain-Computer Interfacing

AN INTRODUCTION

Rajesh P. N. Rao
Department of Computer Science and Engineering &
Neurobiology and Behavior Program
University of Washington, Seattle

CAMBRIDGE
UNIVERSITY PRESS

CAMBRIDGE
UNIVERSITY PRESS

32 Avenue of the Americas, New York, NY 10013-2473, USA

Cambridge University Press is part of the University of Cambridge.

It furthers the University's mission by disseminating knowledge in the pursuit of education, learning, and research at the highest international levels of excellence.

www.cambridge.org
Information on this title: www.cambridge.org/9780521769419

First published 2013

Printed in the United States of America

A catalog record for this publication is available from the British Library.

Library of Congress Cataloging in Publication data
Rao, Rajesh P. N.
Brain-computer interfacing : an introduction / Rajesh P. N. Rao.
pages cm
Includes bibliographical references and index.
ISBN 978-0-521-76941-9 (hardback)
1. Brain-computer interfaces. I. Title.
QP360.7.R36 2013
573.8′60113–dc23 2013009994

ISBN 978-0-521-76941-9 Hardback

Additional resources for this publication at bci.cs.washington.org

To Anu, Anika, and Kavi

Cambridge University Press
978-0-521-76941-9 - Brain-Computer Interfacing: An Introduction
Rajesh P.N. Rao
Frontmatter
More information

Contents

Cambridge University Press
978-0-521-76941-9 - Brain-Computer Interfacing: An Introduction
Rajesh P.N. Rao
Frontmatter
More information

Cambridge University Press
978-0-521-76941-9 - Brain-Computer Interfacing: An Introduction
Rajesh P.N. Rao
Frontmatter
More information

Preface

"*Scientists demo thought-controlled robots*" (*PC Magazine*, July 9, 2012)

"Bionic vision: Amazing new eye chip helps two blind Brits to see again" (*Mirror*, May 3, 2012)

"*Paralyzed, moving a robot with their minds*" (*New York Times*, May 16, 2012)

"Stephen Hawking trials device that reads his mind" (*New Scientist*, July 12, 2012)

These headlines, from just a few weeks of news stories in 2012, illustrate the growing fascination of the media and the public with the idea of interfacing minds with machines. What is not clear amid all this hype is: (a) What exactly can and cannot be achieved with current *brain-computer interfaces* (BCIs) (sometimes also called *brain-machine interfaces* or BMIs)? (b) What techniques and advances in neuroscience and computing are making these BCIs possible? (c) What are the available types of BCIs? and (d) What are their applications and ethical implications? The goal of this book is to answer these questions and provide the reader with a working knowledge of BCIs and BCI techniques.

Overview of the Book

The book provides an introduction to the field of *brain-computer interfacing* (the field also goes by the names of *brain-machine interfacing, neural interfacing, neural prosthetics*, and *neural engineering*). Several extremely useful edited volumes have been published on this topic over the past few years (Dornhege et al., 2007; Tan and Nijholt, 2010; Graimann et al., 2011; Wolpaw & Wolpaw, 2012). There has, however, been a growing need for an introductory textbook aimed specifically at those who do not have an in-depth background in either engineering or neuroscience. This book aims to serve this need. It can be used as a textbook in upper-level undergraduate and first-year graduate courses on brain-computer interfacing and neural engineering. It can also be used for self-study and as a reference by researchers, practitioners, and those interested in joining the field.

The book introduces the reader to essential ideas, concepts, and techniques in neuroscience, brain recording and stimulation technologies, signal processing, and machine learning before proceeding to the major types of BCIs and their applications. Exercises and questions at the end of each chapter provide readers with the opportunity to review their knowledge and test their understanding of the topics covered in the chapter. Some exercises (marked by the expedition icon) allow the student to go beyond what is discussed in the textbook by following leads in research publications and searching for new information on the Web.

The book is organized as follows: Chapters 1 through 5 of the book provide the necessary background in neuroscience and quantitative techniques to understand the terminology and methods used in building BCIs. In Chapter 6, we begin our journey into the world of BCIs by learning about the basic components that go into building a BCI. The next part of the book introduces the reader to the three major types of BCIs classified according to degree of invasiveness. Chapter 7 describes invasive BCIs, which utilize devices implanted inside the brain. Chapter 8 describes semi-invasive BCIs, which are based on nerve signals or devices implanted on the surface of the brain. Chapter 9 covers noninvasive BCIs such as those that record electrical signals from the scalp (EEG). Chapter 10 reviews BCIs that stimulate the brain in order to, for example, restore lost sensory or motor function. Chapter 11 introduces the most general type of BCIs, namely, BCIs that both record from and stimulate the brain. In each case, examples of classic experiments as well as the state-of-the-art technologies (circa 2013) are presented. Chapter 12 reviews some of the major applications of BCIs, and Chapter 13 considers the ethical issues pertaining to the development and use of BCI technology. We conclude in Chapter 14 with a summary of some of the limitations of present-day BCIs and speculate on the future of the field. The book also includes an Appendix that provides basic mathematical background in linear algebra and probability theory useful for understanding and implementing BCIs.

Web Site

The Web site for the book is bci.cs.washington.edu.

Since BCI is a rapidly growing field, the Web site will maintain a periodically updated list of useful links related to BCI research.

Additionally, given that this book contains upward of 101,000 words, it is very likely that errors and typos have crept in unbeknownst to the author. Therefore, any errors or typos brought to the notice of the author by discerning readers will be maintained in an up-to-date errata on the book Web site.

Cover Image

The image on the book's cover depicts a human brain in action when controlling a cursor with an electrocorticographic BCI (see Section 8.1). The bright red region on the brain indicates increased activity in the hand area of the motor cortex when the subject imagined hand movement to move the cursor toward a target on the computer screen. The image was generated by Jeremiah Wander, Bioengineering graduate student and member of the Grid Lab and Neural Systems Lab at the University of Washington.

Acknowledgments

I would like to thank Lauren Cowles of Cambridge University Press for her encouragement and continued support for this project despite many missed deadlines. Thanks are also due to the Center for Sensorimotor Neural Engineering (CSNE) and the BCI group at the University of Washington (UW), especially my collaborators Jeffrey Ojemann, Reinhold Scherer (now at TU Graz), Felix Darvas, Eb Fetz, and Chet Moritz, for numerous leads and many enriching discussions. Students in the Neural Systems Laboratory were a constant source of inspiration and new ideas in BCI research – I thank them for keeping me on my toes: Christian Bell, Tim Blakely, Matt Bryan, Rawichote Chalodhorn, Willy Cheung, Mike Chung, Beau Crawford, Abe Friesen, David Grimes, Yanping Huang, Kendall Lowrey, Stefan Martin, Kai Miller, Dev Sarma, Pradeep Shenoy, Aaron Shon, Melissa Smith, Sam Sudar, Deepak Verma, and Jeremiah Wander. Pradeep was a teaching assistant in an early BCI course that I taught and helped organize the structure of the course, which provided a foundation for this book. Sam was a teaching assistant in a later offering and provided valuable feedback on course material. Kai helped establish the early collaboration with the medical school in BCI research and played a key role in launching our electrocorticography-based BCI research.

A number of funding agencies and organizations supported my research as well as the writing of the book: the National Science Foundation (NSF), the Packard Foundation, National Institutes of Health (NIH), the Office of Naval Research (ONR) Cognitive Science Program, the NSF ERC for Sensorimotor Neural Engineering (CSNE), and the Army Research Office (ARO) – I thank them for their support. Parts of the book were written at the scenic Whiteley Writing Center at Friday Harbor Laboratories, which provided just the right environment for jump-starting the writing process when the need was acute.

For providing a solid mathematical and scientific foundation for a future career in research and teaching, I am grateful to my school teachers at Kendriya Vidyalaya Kanchanbagh (KVK) in India, my undergraduate professors at Angelo State University in Texas, my doctoral advisor Dana Ballard at the University of Rochester, and my postdoctoral advisor Terry Sejnowski at the Salk Institute. To my parents, I owe many thanks for their long-standing support and for piquing my scientific curiosity at an early age with a houseful of books. To my children Anika and Kavi, I owe an apology for not having given them as much attention during this book project as their unconditional love deserves. Last but not least, my wife Anu provided the inspiration and steadfast support that have kept me going through the many years of writing – this book would not have been possible without her.