The Plurality of Human Brain–Computer Interfacing

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I. OVERVIEW

The field of brain–computer interface (BCI) research began to develop about 25 years ago and transformed from initially isolated demonstrations by a few groups into a large scientific enterprise that is currently producing hundreds of peer-reviewed articles and several dedicated conferences and workshops each year. This level of productivity is reflective of the large and continually growing enthusiasm by the scientific community, funding agencies, and the public. BCI demonstrations described to date include seven-dimensional control of a robotic arm using implanted microelectrodes, three-dimensional control of a computer cursor using scalp-recorded EEG, and spelling at a rate of more than 20 characters per minute using subdurally recorded ECoG. While most of these BCI demonstrations to date have been accomplished in animals or healthy human users, an increasing number of studies have shown that BCI systems can also be used by people with disabilities. These encouraging initial demonstrations of BCI technology have focused primarily on communication and control applications. More recently, a new area of research is emerging that aims to evaluate the utility of BCI techniques in the context of neurorehabilitation.

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This Special Issue on brain-computer interfacing is dedicated to this growing and diversifying research enterprise, and features important review articles as well as some important current examples of research in this area. Articles in the Special Issue describe new advanced signal and machine learning methods, the use of hybrid BCIs (hBCIs) for people with disabilities in the context of communication, control of a neuroprosthesis and control of a telepresence robot, as well as the application of BCI technology to neurorehabilitation in people with chronic stroke.

The following paragraphs give brief introductions of the papers in this Special Issue.

II. MACHINE LEARNING METHODS

Advances in machine learning and signal processing have been instrumental for the progress of the BCI field (see, e.g., [1]–[5]).

Lotte addresses machine learning tools to reduce or overall suppress calibration times for BCIs. Among others, regularization, user-to-user transfer, semisupervised learning, and *a priori* physiological information are discussed and a novel approach for

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creating artificial EEG trials to augment training data is proposed and validated offline on a large set of BCI users—enabling practical guidelines.

Fazli *et al.* review the use of data fusion techniques for sensorimotor rhythm-based BCIs including machine learning for integration of complementary features of neural activation (e.g., NIRS, EEG), multiple previous sessions, and multiple subjects. In particular guidance for when fusion techniques can be profitably applied is given.

He *et al.* review the principles and approaches they have taken to develop a sensorimotor rhythm-based BCI. The methods include developing BCI systems incorporating the control of physical devices to increase user engagement, improving BCI systems by inversely mapping scalp-recorded EEG signals to the cortical source domain, integrating BCI with noninvasive neuromodulation strategies to improve learning, and incorporating mind-body awareness training to enhance BCI learning and performance.

III. HYBRID BCIs AND BCIs FOR REHABILITATION

Hybrid BCIs are systems that combine a BCI with other input signals, e.g., other biosignals or assistive devices. Importantly, a BCI channel must be available all the time [6]–[8]. This Special Issue includes three papers that describe a framework for hBCIs and a series of its applications, namely rehabilitation of individuals with spinal cord injury and neuroprosthesis control and for the control of telepresence robots. The fourth contribution in this section shows the effect of BCI technology in the use of stroke rehabilitation.

Müller-Putz *et al.* review the use of the hBCI approach for several end-user applications in the replace, restore, improve, and enhance scenarios. After describing a hBCI approach and framework, several studies applying this framework in applications for (mainly) end users are presented and discussed.

Ang and Guan review two strategies of using BCI for neurorehabilitation after stroke: detecting MI to trigger a feedback, and detecting MI with a robot to provide concomitant MI and proprioceptive feedback. Furthermore, three randomized control trials that employed these two strategies for upper limb rehabilitation are presented.

Rupp *et al.* give a concise overview of neuroprosthesis for the upper extremity in individuals with spinal cord injury and its control with noninvasive brain–computer interfaces. While the first part is about neuroprosthetics and its controllers, the second part describes BCIs that were used for control in end users.

Leeb *et al.* present an important step forward toward increasing the independence of people with severe motor disabilities by using BCIs. It introduces the concept of shared control, which interprets the user commands in context. Shared control empowers users to perform rather complex tasks without a high workload. Results of end users who were able to complete navigation tasks with a telepresence robot successfully in a remote environment are reported.

IV. CONCLUSION

This Special Issue aimed to provide an interesting cross section of current BCI research both for the general reader and also a reference for the specialist. Clearly, through the limits of this format, a number of research activities will not be covered in detail. Some aspects discussed in the manuscripts are very specific to BCIs, while others may be of wider technical interest beyond BCI, e.g., data fusion, signal processing and machine learning concepts, ideas for shared control, or human–machine interaction strategies.

It is interesting to ask why BCI research is attractive to an increasing number of researchers. First, the technical challenges are broad, bold, and enormous and ask for substantial scientific innovations. Second, the potential gain that BCI systems can bring to patients (and also to healthy users) is highly motivating. Third, the field is very interdisciplinary, so research may be more risky on one side but it holds genuine challenges that bear the potential for breakthroughs when progress can be achieved.

Overall, our hope is that this Special Issue will contribute to an increasing interest in the field and to attracting bright minds. We speculate and hope that not too far in the future that BCI technology will enter standard clinical practice and become a natural and robust part of our daily interaction modalities. ■

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ABOUT THE GUEST EDITORS

Gernot Müller-Putz received the M.Sc. and Ph.D. degrees from Graz University of Technology, Graz, Austria, in 2000 and 2004, respectively. He also received the "venia docendi" for medical informatics from the Faculty of Computer Science, Graz University of Technology, in 2008.

He is Head of the Institute for Knowledge Discovery and its associated BCI Lab. Since October 2014, he has been full Professor for semantic data analysis. He has gained extensive experience in the field of biosignal analysis, brain–computer interface research, EEG-based neuroprosthesis control, hybrid BCI systems, the human somatosensory system, and assistive technology over the past 15 years. He has also managed several national and international projects and is currently partner in two European Union FP7 projects (BackHome, ABC) and coordinator of BNCI Horizon 2020. Recently, he has received a Horizon 2020 project, MoreGrasp, which he will coordinate.

Prof. Müller-Putz organized and hosted six international Brain-Computer Interface Conferences over the last 13 years in Graz, the last one in September 2014 in Graz. He is also a steering board member for the International BCI Meeting, which takes place in the United States usually every three years (last time in 2013). He is a review editor of *Frontiers in Neuroprosthetics* and an Associate Editor of the *Brain-Computer Interface Journal* and of the IEEE Transactions of Biomedical Engineering.

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Dr. Millán was named the 2004 Research Leader by *Scientific American* for his work on brain-controlled robots. His research on brain-machine interfaces was a nominated finalist of the 2001 European Descartes Prize. He is the recipient of the 2011 IEEE-SMC Nobert Wiener Award for his seminal and pioneering contributions to noninvasive brain–machine interfaces.

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Dr. Schalk has won several awards, including the Pangborn Award and the Founders Award of Excellence. His work received extensive media coverage, including prominent features in Science Channel, CBS Sunday Morning, *Discover Magazine*, NPR, and *New York Times Magazine*.

Klaus-Robert Müller studied physics in Karlsruhe, Germany, from 1984 to 1989 and received the Ph.D. degree in computer science from the Technische Universität Karlsruhe, Karlsruhe, Germany, in 1992.

He has been a Professor of Computer Science at Technische Universität Berlin, Berlin, Germany, since 2006. At the same time he has been the Director of the Bernstein Focus on Neurotechnology Berlin. After completing a postdoctoral position at GMD FIRST in Berlin, he was a Research Fellow at the University of Tokyo, Tokyo, Japan, from 1994 to 1995. In 1995, he founded the Intelligent Data Analysis group at GMD-FIRST (later Fraunhofer FIRST) and directed it until 2008. From 1999 to 2006, he was a Professor at the University of Potsdam, Potsdam, Germany. His research interests are intelligent data analysis, machine learning, signal processing, and brain–computer interfaces.

Prof. Müller was awarded the 1999 Olympus Prize by the German Pattern Recognition Society, DAGM, and, in 2006, he received the SEL Alcatel Communication Award. In 2014, he received the Berliner Forschungspreis des regierenden Brgermeisters. In 2012, he was elected to be a member of the German National Academy of Sciences-Leopoldina.