BRAIN-COMPUTER INTERFACES

Brain-Computer Interfaces

An International Assessment of Research and Development Trends

by

THEODORE W. BERGER
University of Southern California, Los Angeles, CA, USA

JOHN K. CHAPIN
State University of New York, Downstate Medical Center, Brooklyn, NY, USA

GREG A. GERHARDT
University of Kentucky, Lexington, KY, USA

DENNIS J. McFARLAND
Wadsworth Centre, Albany, NY, USA

JOSÉ C. PRINCIPE
University of Florida, Gainesville, FL, USA

WALID V. SOUSSOU
University of Southern California, Los Angeles, CA, USA

DAWN M. TAYLOR
Case Western Reserve University, Cleveland, OH, USA

and

PATRICK A. TRESCO
University of Utah, Salt Lake City, UT, USA

Springer

This document was sponsored by the National Science Foundation (NSF) and other agencies of the U.S. Government under an award from the NSF (ENG-0423742) to the World Technology Evaluation Center, Inc. The Government has certain rights in this material. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the United States Goverment, the authors' parent institutions, or WTEC, Inc.

ISBN: 978-1-4020-8704-2 e-ISBN: 978-1-4020-8705-9

Library of Congress Control Number: 2008930994

Printed on acid-free paper.

9 8 7 6 5 4 3 2 1

springer.com

WTEC Panel on Brain-Computer Interfaces

Theodore W. Berger
University of Southern California, Los Angeles, CA, USA
John K. Chapin
State University of New York, Downstate Medical Center, Brooklyn, NY, USA
Greg A. Gerhardt
University of Kentucky, Lexington, KY, USA
Dennis J. McFarland
Wadsworth Center, Albany, NY, USA
José C. Principe
University of Florida, Gainesville, FL, USA
Walid V. Soussou
University of Southern California, Los Angeles, CA, USA
Dawn M. Taylor
Case Western Reserve University, Cleveland, OH, USA
Patrick A. Tresco
University of Utah, Salt Lake City, UT, USA

Acknowledgments

WTEC staff members wish to extend their gratitude and appreciation to all the panelists for their knowledge, enthusiasm, and dedication to this international benchmarking study of brain-computer interface R&D, and to all workshop presenters and site visit hosts for so generously sharing their time, expertise, and facilities with us. We also wish to thank Professor Jiping He of Arizona State University, who provided guidance and contacts regarding brain computer interface research laboratories in China, and Dr. Jason J. Burmeister of the University of Kentucky, who provided background material on sensor technologies for Chapter 2 of the report. For their sponsorship of this unique study, our sincere thanks go to the National Science Foundation, the Telemedicine and Advanced Technology Research Center of the U.S. Army Medical Research and Materiel Command, the National Institute of Neurological Disorders and Stroke of the National Institutes of Health, the National Space Biomedical Research Institute, the National Institute of Biomedical Imaging and Bioengineering of the National Institutes of Health, and the Margot Anderson Brain Restoration Foundation. Finally, our special thanks go to Dr. Semahat Demir for her vision and her unflagging support of the panel through all phases of this study.

R. D. Shelton
President, WTEC

Abstract

Brain-computer interface (BCI) research deals with establishing communication pathways between the brain and external devices. BCI systems can be broadly classified depending on the placement of the electrodes used to detect and measure neurons firing in the brain: in *invasive* systems, electrodes are inserted directly into the cortex; in *noninvasive* systems, they are placed on the scalp and use electro-encephalography or electrocorticography to detect neuron activity. This WTEC study was designed to gather information on worldwide status and trends in BCI research and to disseminate it to government decisionmakers and the research community. The study reviewed and assessed the state of the art in sensor technology, the biotic–abiotic interface and biocompatibility, data analysis and modeling, hardware implementation, systems engineering, functional electrical stimulation, noninvasive communication systems, and cognitive and emotional neuroprostheses in academic research and industry.

The WTEC panel identified several major trends in current and evolving BCI research in North America, Europe, and Asia. First, BCI research throughout the world is extensive, with the magnitude of that research clearly on the rise. Second, BCI research is rapidly approaching a level of first-generation medical practice; moreover, BCI research is expected to rapidly accelerate in nonmedical arenas of commerce as well, particularly in the gaming, automotive, and robotics industries. Third, the focus of BCI research throughout the world is decidedly uneven, with invasive BCIs almost exclusively centered in North America, noninvasive BCI systems evolving primarily from European and Asian efforts, and the integration of BCIs and robotics systems championed by Asian research programs.

In terms of funding, BCI and brain-controlled robotics programs have been a hallmark of recent European research and technological development. The range and investment levels of multidisciplinary, multinational, multilaboratory programs in Europe appear to far exceed that of most university and government-funded BCI programs in the United States and Canada. Although several U.S. government programs are advancing neural prostheses and BCIs, private sources have yet to make a major impact on BCI research in North America generally. However, the U.S. Small Business Innovative Research grants (SBIRs) and Small Technology Transfer Research grants (STTRs) have been effective in promoting transition from basic research to precommercialized prototypes. In Asia, China is investing heavily in biological sciences and engineering in general, and the extent of investment in BCI and BCI-related research has grown particularly rapidly; still, the panel observed little coordination between various programs. Japanese universities, research institutes, and laboratories also are increasing their investment in BCI research. Japan is especially vigorous in pursuing nonmedical applications and exploiting its expertise in BCI-controlled robotics.

The WTEC panel concludes that there are abundant and fertile opportunities for worldwide collaborations in BCI research and allied fields.

WTEC Mission

WTEC provides assessments of international research and development in selected technologies under awards from the National Science Foundation (NSF), the Office of Naval Research (ONR), and other agencies. Formerly part of Loyola College, WTEC is now a division of the World Technology Research Center, a separate nonprofit research institute. Michael Reischman, Deputy Assistant Director for Engineering, is NSF Program Director for WTEC. Sponsors interested in international technology assessments and related studies can provide support for the program through NSF or directly through separate grants or GSA task orders to WTEC.

WTEC's mission is to inform U.S. scientists, engineers, and policymakers of global trends in science and technology. WTEC assessments cover basic research, advanced development, and applications. Panels of typically six technical experts conduct WTEC assessments. Panelists are leading authorities in their field, technically active, and knowledgeable about U.S. and foreign research programs. As part of the assessment process, panels visit and carry out extensive discussions with foreign scientists and engineers in their labs.

The WTEC staff helps select topics, recruits expert panelists, arranges study visits to foreign laboratories, organizes workshop presentations, and finally, edits and publishes the final reports.

WORLD TECHNOLOGY EVALUATION CENTER, INC. (WTEC)

R. D. Shelton, President
Michael DeHaemer, Executive Vice President
Geoffrey M. Holdridge, Vice President for Government Services
David Nelson, Vice President for Development
Ben Benokraitis, Assistant Vice President

Other WTEC Staff Members and Subcontractors Involved in this Study

Hassan Ali, Director of International Study Operations
Grant Lewison (Evaluametrics, Ltd.), Advance Contractor, Europe
Gerald Hane (Globalvation), Advance Contractor, Asia
Maria L. DeCastro, Manuscript Development and Support
Patricia M.H. Johnson, Director of Publications
Halyna Paikoush, Event Planner and Office Manager

Foreword

> We have come to know that our ability to survive and grow as a nation to a very large degree depends upon our scientific progress. Moreover, it is not enough simply to keep abreast of the rest of the world in scientific matters. We must maintain our leadership.[1]

President Harry Truman spoke those words in 1950, in the aftermath of World War II and in the midst of the Cold War. Indeed, the scientific and engineering leadership of the United States and its allies in the twentieth century played key roles in the successful outcomes of both World War II and the Cold War, sparing the world the twin horrors of fascism and totalitarian communism, and fueling the economic prosperity that followed. Today, as the United States and its allies once again find themselves at war, President Truman's words ring as true as they did a half-century ago. The goal set out in the Truman Administration of maintaining leadership in science has remained the policy of the U.S. Government to this day: Dr. John Marburger, the Director of the Office of Science and Technology (OSTP) in the Executive Office of the President, made remarks to that effect during his confirmation hearings in October 2001.[2]

The United States needs metrics for measuring its success in meeting this goal of maintaining leadership in science and technology. That is one of the reasons that the National Science Foundation (NSF) and many other agencies of the U.S. Government have supported the World Technology Evaluation Center (WTEC) and its predecessor programs for the past 20 years. While other programs have attempted to measure the international competitiveness of U.S. research by comparing funding amounts, publication statistics, or patent activity, WTEC has been the most significant public domain effort in the U.S. Government to use peer review to evaluate the status of U.S. efforts in comparison to those abroad. Since 1983, WTEC has conducted over 50 such assessments in a wide variety of fields from advanced computing, to nanoscience and technology, to biotechnology.

The results have been extremely useful to NSF and other agencies in evaluating ongoing research programs and in setting objectives for the future. WTEC studies also have been important in establishing new lines of communication and identifying opportunities for cooperation between U.S. researchers and their colleagues abroad, thus helping to accelerate the progress of science and technology generally within the international community. WTEC is an excellent example of cooperation and coordination among the many agencies of the U.S. Government that are involved in funding research and development: almost every WTEC study has

[1] Remarks by President Harry S. Truman on May 10, 1950, on the occasion of the signing of the law that founded the National Science Foundation. Public Papers of the Presidents 120: p. 338.

[2] http://www.ostp.gov/html/01_1012.html.

been supported by a coalition of agencies with interests related to the particular subject at hand.

As President Truman said over 50 years ago, our very survival depends upon continued leadership in science and technology. WTEC plays a key role in determining whether the United States is meeting that challenge, and in promoting that leadership.

Michael Reischman
Deputy Assistant Director for Engineering
National Science Foundation

Table of Contents

APPENDICES

List of Figures

List of Tables

Preface

This benchmarking panel study on brain-computer interfaces had broad sponsorship from the U.S. Government agencies and private organizations listed in in the Acknowledgments page of the report; it was organized by the World Technology Evaluation Center (WTEC). As the lead sponsoring program director for this study, I present this final report to the global brain-computer interface community on behalf of all the study participants and sponsors. This has been an informative, productive journey for all involved in the study. I would like to start by thanking those who contributed so much to this final product.

First, many thanks go to the panel chair, Ted Berger, and to all of the BCI panelists: John Chapin, Greg Gerhardt, Dennis McFarland, José Principe, Dawn Taylor, Patrick Tresco, and Walid Soussou (associate panelist). Next, our thanks go to the numerous eminent researchers from around the world whose input is a fundamental merit of this study. Gary Birch, John Donoghue, Daryl Kipke, Dan Moran, Richard A. Normann, David A. Putz, Andrew B. Schwartz, William Shain, and Krishna V. Shenoy presented at our North American BCI workshop on February 27, 2006. Twenty-seven leading institutions in Europe and Asia hosted panelists during site visits in May and October 2006. We are deeply grateful to all of those institutions and the many individuals who so generously shared their work and their insights with the panel.

My personal thanks go to Mike Reischman, Lynn Preston, and Bruce Hamilton of NSF for supporting this idea and for co-funding this study with me from the beginning. I also thank the following government colleagues for co-sponsoring this study: Ephraim Glinert (NSF/CISE), Joseph Pancrazio (NIH/NINDS), Kenneth Curley (TATRC), and Grace Peng (NIH/NIBIB). Two non-governmental organizations contributed funds to the study; I appreciate the support of Jeffrey Sutton of the National Space Biomedical Research Institute and Herman Edel of the Margot Anderson Brain Restoration Foundation. In addition to the contributions of the above-mentioned colleagues, I would like to recognize the efforts of Mike Roco (NSF), Nancy Shinowara (NIH/NICHD), and Bob Jaeger (NIDRR, now with NSF) for their technical input to me, the WTEC team, and the panelists, and for attending the planning meetings and workshops.

I acknowledge the WTEC team with special thanks to Mike DeHaemer (Executive Vice-President of WTEC), Hassan Ali (the manager for this study), and Duane Shelton (President of WTEC). Mike, Hassan, and Duane worked diligently from the initiation of the study. Grant Lewison (Evaluametrics, Ltd.) arranged the site visits in Europe, and Gerald Hane (Globalvation) arranged the site visits in Asia. Roan Horning provided computing and website support. Ben Benokraitis coordinated and reviewed the substantive work on the report. Maria DeCastro and Pat Johnson contributed editing support.

The study has been a great journey since my email to a few colleagues on November 10, 2004, in which I first proposed a study on Brain-Computer

Interfaces, and my initial meeting with WTEC representatives on January 3, 2005. Milestones along the way included meetings with sponsors in March and April 2005; the sponsors and chair meeting on October 14, 2005; the kickoff meeting with the BCI panelists and sponsors on December 2, 2005; the North American workshop on February 27, 2006; site visits to Europe in May–June 2006; the workshop "Review of International Research on Brain-Computer Interfaces" on July 21, 2006; site visits to Asia in October 2006; and the BCI international benchmarking teleconference (Asia-Japan) on December 14, 2006. This report is the final result of the myriad efforts of the study team, and the vision realized of a benchmarking study on brain-computer interface R&D.

BRAIN-COMPUTER INTERFACE SCIENCE

Brain-computer interfaces (BCIs) are defined as the science and technology of devices and systems responding to neural processes in the brain that generate motor movements and to cognitive processes (e.g., memory) that modify the motor movements. Advances in neuroscience, computational technology, component miniaturization, biocompatibility of materials, and sensor technology have led to a much improved feasibility of useful BCIs that engineers, neuroscientists, physical scientists, and behavioral and social scientists can develop as a large-scope team effort.

The WTEC BCI international assessment panel defined BCI technologies as either "invasive" (multielectrode arrays of tens to hundreds of electrodes implanted into cortical tissue from which "movement intent" is decoded), or "noninvasive" (multielectrode arrays emplaced on the surface of the skull to record changes in EEG state) in their control of computer cursors or other systems. The study results presented at the workshops on February 27 and July 21, 2006, indicated that the majority of BCI science in North America involves invasive technologies, and the majority of BCI science in Europe involves noninvasive technologies and also the development of biologically inspired robots. The panel presented findings that European efforts are more often integrated within a larger research scope, and European BCI systems involve a wider range of EEG-based applications. Overall, the panelists felt that European and Asian BCI work is highly competitive with that of the United States and that many opportunities exist for collaboration.

As indicated in this report, engineers around the world are working, in collaboration with neuroscientists, physical scientists, and social and behavioral scientists, to integrate and converge engineering tools and methods in the areas of sensors and signal processing, noninvasive and minimally invasive recording techniques from the brain and the peripheral nervous system, neural tissue engineering, neural imaging, nonlinear dynamics, chemical and biological transport, computational neuroscience and multiscale modeling, nano/micro technological neuroscience, control theory, systems integration, and robotics in order to permit control of movement where normal neural pathways do not exist. Transformational solutions being pursued are leading to better understanding of the central and peripheral nervous systems and pushing forward the frontier of scientific discovery.

The principal goal of BCI work is to enable people with neural pathways that have been damaged by amputation, trauma, or disease to better function and control their environment, through either reanimation of paralyzed limbs or control of robotic devices. BCI also extends to the fields of neurobiomimetics and complex hybrid neurobionic systems. BCI systems will have great societal impact, with growing interest on the part of industry to commercialize and market BCI systems for medical and nonmedical applications in the long term. The WTEC study identifies the following opportunities for multidisciplinary BCI teams to find transformational solutions:

- Studying multiple levels and multiple scales of neural functions and neural code
- Developing long-term biocompatibility between electronics and neural tissues
- Establishing bidirectional communication between biomimetic devices and the nervous system
- Developing hierarchically organized control systems for robotics and biomimetics
- Developing biologically inspired systems that will push the frontier for the development of autonomous intelligent systems ("conscious" self-adaptive systems)
- Engineering practical BCIs and even integrating BCIs with cyberinfrastructure.

RELATED ACTIVITIES AT NSF

In parallel to the WTEC BCI benchmarking study, NSF has sponsored several related neuroscience activities; some of the BCI panelists and I participated in those activities. The Steering Group workshop, "Brain Science as a Mutual Opportunity for the Physical Sciences, Mathematics, Computational Sciences and Engineering," took place in Arlington, VA, on August 21–22, 2006. It identified as broad areas of opportunity (1) instrumentation and measurement; (2) data analysis, statistical modeling, and informatics; (3) conceptual and theoretical approaches; and (4) brain like devices and systems. These four opportunity areas align with the WTEC panel's transformational solutions noted above.

A second workshop, "Brain Science at the Interface of Biological, Physical and Mathematical Sciences, Computer Science and Engineering: Analysis of New Opportunities," took place in Arlington, VA, March 5–6, 2007. The BCI-related opportunities and challenges that were identified at this workshop were:

1. Brain, mind, cognition, behavior, learning, development
2. Multiscale complexity; connectivity; nonlinear, nonstationary, stochastic control; stability; and adaptability
   (a) Neural coding and decoding (cognitive vs. neurophysiological)

3. Bioinspired systems
   (a) Abstracting from neuroscience principles to develop bioinspired systems
   (b) Replicating neural computation
   (c) Next generation of computing systems
4. Sensors, smart sensing, and bidirectional communication.

Research in neuroscience and cognition needs “bridging” of experimental and modeling work at the different scales of time (nanoseconds to years), of length (nanometers to meters), and of biology (atoms; molecules; molecular complexes; subcellular, cellular, multicellular elements; tissue, organs, organ systems, and organisms, up to entire populations). The *natural (biological) interfaces* of nervous systems have to be studied with multiscale (multilevel) approaches by interdisciplinary teams of life scientists, physical scientists, social scientists, behavioral scientists, mathematicians, and engineers who must work within a broad research framework. Engineers bring to these multidisciplinary teams workable methods and tools for analysis, recording, modeling, and implementation of new BCI technologies.

Bridging the sciences in the field of BCI from discovery to application or translation is a significant challenge. The Bioengineering Consortium (BECON, chaired by Dr. Michael Huerta, NIH/NIMH) formed a subcommittee called BECON Bridges on March 1, 2007, which Dr. Albert Lee (NIH/NIBIB) and I co-chaired. This subcommittee will determine the research areas in which the sciences needs to be bridged and what mechanisms can enable the bridging. BCI is one of those areas.

On July 27, 2007, the NSF Engineering Directorate released two Emerging Frontiers in Research and Innovation 2008 topics (EFRI-2008), one of which is BCI-related: “Cognitive Optimization and Prediction: From Neural Systems to Neurotechnology (COPN).”[1] The goal of COPN is to motivate engineers to reverse-engineer the prediction and optimization capabilities of the brain to facilitate usable design. While my NSF colleague Dr. Paul Werbos and I were developing COPN, the results of the WTEC BCI study were helpful.

Section IV of *National Science Foundation Investing in America’s Future, Strategic Plan FY 2006–2011*[2] lists investment priorities for four strategic goals: Discovery, Learning, Research Infrastructure, and Stewardship. Under the Discovery strategic goal there are five topics listed (page 6 of the Strategic Plan), four of which are areas where BCI R&D can contribute.

[1] NSF. 2007. Emerging Frontiers in Research and Innovation, http://nsf.gov/publications/pub_summ.jsp?ods_key=nsf07579.

[2] NSF. 2006. The FY 2006–2011 strategic plan is available online at http://www.nsf.gov/pubs/2006/nsf0648/nsf0648.jsp.

SIGNIFICANCE OF BCI R&D TO THE U.S. ECONOMY AND SOCIETY

Based on the work of this panel and on the NSF discussions and activities noted above, it seems clear that BCI research and development activities can have an immediate and lasting impact on U.S. (and global) science and technology activities that far exceed their immediate, important, and exciting benefit to a relatively small number of citizens. The necessarily collaborative work towards BCI solutions depends on and at the same time advances work in many related high-tech fields. Thus, there is an inherently synergistic benefit to BCI work that operates on the cutting edge of many important fields of science and technology. At the same time, BCI work intersects with significant current trends in U.S. employment and in Federal support for science-based activities to enhance U.S. competitiveness relative to other nations.

BCI-Related Job and Educational Opportunities

According to the U.S. National Science Board,[3] occupational projections from the U.S. Bureau of Labor Statistics (BLS) predict that the employment in science and engineering occupations will increase faster then the overall growth rate for all occupations. In addition, the BLS Occupational Outlook Handbook, 2004–2005 edition, predicts that by 2012, top job growth will be in (1) healthcare and social assistance; and (2) biomedical, biotechnology, and bioengineering professions. Employment in biomedical engineering, biotechnology, and bioengineering is expected to increase by 21–35% by 2012. Thus, there are expected to be numerous promising career and job opportunities for biomedical engineers.

Education indicators sustain this outlook. The *IEEE Spectrum* survey results of February 2007, "Your Best Bet for the Future," identifies the top ten technology research and development fields that faculty would advise their students to pursue: the biomedical field is number one, and other fields in the top five, such as wireless/ mobile (number 2) and nanotechnology (number 5), are relevant to biomedical R&D as well. More specifically, based on the American Society for Engineering Education six-year trend analysis (1999–2005),[4] BME, while still representing a small proportion of overall undergraduate and graduate degrees conferred, is one of the two fastest-growing disciplines at U.S. universities (the other is aerospace engineering). Of special note is the fact that BME is a field in which women

---

[3] National Science Board. 2004. Science and Engineering Indicators—2004. NSB-04-1. Arlington, VA: NSF.

[4] ASEE. 2007. 2006 profiles of engineering and engineering technology colleges. Washington, DC: ASEE. See also an online profiles sample at http://www.asee.org/publications/profiles/upload/2006ProfileEng.pdf.

represent a higher proportion than other engineering fields of tenure/tenure-track teaching faculty and degree recipients. All these indicators are promising for the pipeline and the diversity of engineers that will enter BME careers in academia, industry, government, or independent consultancy.

BCI and the Innovation and Competitiveness Debate

On August 9, 2007, President George W. Bush signed into law the "America Creating Opportunities to Meaningfully Promote Excellence in Technology, Education and Science (COMPETES) Act." America COMPETES authorizes research programs at the National Science Foundation (NSF), the National Institute of Standards and Technology (NIST) of the Department of Commerce, and the Department of Energy (DOE) Office of Science, with near-term doubling of funding. The bill also authorized $33.6 billion over fiscal years 2008 through 2010 for research and education programs across the Federal Government. The bill is intended to strengthen education and research in the United States related to science, technology, engineering, and mathematics (STEM). Many provisions of the legislation were developed based on recommendations made in two reports on competitiveness: *American Competitiveness Initiative: Leading the World in Innovation*[5] and *Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future*.[6]

Other recent reports, articles, and statements have addressed the U.S. innovation and competitiveness debate. The American Competitiveness Initiative (ACI) recommends doubling funding over ten years on innovation-enabling research at three key Federal agencies (NSF, DOE, and NIST) that support high-leverage fields of of physical science, basic science, and engineering. ACI has three broad parts: (1) research in physical sciences and engineering (including 12 specific goals), (2) research and development (R&D) tax incentives, and (3) education and workforce. The report *Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future* makes recommendations for K-12 education, research, higher education, and economic policy. The *Innovate America*[7] executive summary also makes recommendations under talent, investment, and infrastructure. BCI research is a strong contender as a field to promote U.S. technical leadership toward enhanced innovation and improved competitiveness, bringing attendant economic benefits.

---

[5] Office of Science and Technology Policy Domestic Policy Council. 2006 (February). Available online at http://www.ostp.gov/html/ACIBooklet.pdf.

[6] Committee on Science, Engineering, and Public Policy: National Academy of Sciences, National Academy of Engineering, and Institute of Medicine. 2007. Washington, DC: National Academies Press.

[7] Committee on Science, Engineering, and Public Policy: National Academy of Sciences, National Academy of Engineering, and Institute of Medicine. 2007. Washington, DC: National Academies Press.

CONCLUDING REMARKS

The WTEC BCI study presents the current status and future trends of BCI research in North America, Europe, and Asia. It will assist NSF and other U.S. Government agencies to perform strategic planning for future STEM programs and to accelerate discoveries and the progress of science and engineering. These are exciting times for life scientists, physical scientists, and engineers to work together in inter-disciplinary, innovation-enabling research fields. BCI is one of those fields that will enrich the innovation and competitiveness debate globally.

Semahat S. Demir, Ph.D.
Program Director
Biomedical Engineering Program
National Science Foundation
September 2007

Executive Summary

Theodore W. Berger

Brain-Computer Interface (BCI) research deals with establishing communication pathways between the brain and external devices. To provide program managers in U.S. research agencies as well as researchers in the field with a better understanding of the status and trends in BCI research abroad, in December 2005 the WTEC International Assessment of Brain-Computer Interface R&D was organized. Sponsors included

- National Science Foundation (NSF)
- Telemedicine and Advanced Technologies Research Center (TATRC) of the U.S. Army Medical Research and Materiel Command
- National Institute of Neurological Disorders and Stroke (NINDS) of the National Institutes of Health (NIH)
- National Space Biomedical Research Institute
- National Institute of Biomedical Imaging and Bioengineering (NIBIB) of NIH
- Margot Anderson Brain Restoration Foundation .

The study was designed to gather information on the worldwide status and trends in BCI research and to disseminate it to government decisionmakers and the research community. The study reviewed and assessed the state of the art in sensor technology, the biotic–abiotic interface and biocompatibility, data analysis and modeling, hardware implementation, systems engineering, functional electrical stimulation (FES), noninvasive communication systems, and cognitive and emotional neuroprostheses in academic research and industry. To provide a basis for comparison, the study began on February 27, 2006 with a workshop held at NSF entitled "Review of North American Research on Brain-Computer Interfaces." After convening this baseline workshop, a WTEC panel of U.S. experts visited seventeen sites in Europe and ten facilities in China and Japan involved in BCI research.

MAJOR TRENDS IN BCI RESEARCH

The WTEC panel identified several major trends that both characterize the present, and can be projected into the future, of Brain-Computer Interface Research in North America, Europe, and Asia. First, BCI research throughout the world is extensive, with the magnitude of that research clearly on the rise. BCI research is an unmistakable growth area—which because of the inherently interdisciplinary nature of BCIs, means growth in the interface between multiple key scientific areas, including biomedical engineering, neuroscience, computer science, electrical and computer engineering, materials science and nanotechnology, and neurology and neurosurgery. Thus, the panel sees future growth in BCIs as having a widespread influence in shaping the landscape of scientific research in general and radically altering the boundaries of interdisciplinary research in particular.

Second, BCI research is rapidly approaching a level of first-generation “medical practice”—clinical trials of invasive BCI technologies and significant home use of noninvasive, electroencephalography (EEG-based) BCIs. Because the threshold for substantial use of BCIs for medical applications is rapidly approaching, the panel predicts that BCIs soon will markedly influence the medical device industry. As a corollary, the panel sees that BCI research will rapidly accelerate in nonmedical arenas of commerce as well, particularly in the gaming, automotive, and robotics industries. Thus, the industrial influence of BCIs is certain to increase in the near future.

Third, the WTEC panel found that the focus of BCI research throughout the world was decidedly uneven, with invasive BCIs almost exclusively centered in North America, noninvasive BCI systems evolving primarily from European and Asian efforts, and the integration of BCIs and robotics systems championed by Asian research programs. Thus, the panel felt that there were abundant and fertile opportunities for worldwide collaborations that would allow the existing specializations in different regions of the globe to interact in a synergistic and productive manner. In this summary, we elaborate on these and other conclusions from the WTEC panel’s study of Brain-Computer Interfaces (BCI) in North America, Europe, and Asia.

MAGNITUDE OF BCI RESEARCH

The magnitude of research and development of BCIs throughout the world will grow substantially, if not dramatically, in the next decades. There are multiple forces that are driving and will continue to drive this trend. One of the most fundamental forces accelerating BCI research is the continued advance in the science, engineering, and technology required for the realistic achievement of BCIs. The growth in neuroscience continues to be explosive, with new frontiers being reached every year in understanding principles of the central nervous system (CNS) structure and function and—importantly for BCI design—systems-level organization of the nervous system. Rapid advances in biomedical engineering and computer science are producing the methodologies required for predictive models of neural function that can interact with the brain in real time. The continuing achievements in microelectronics that allow ever-greater circuitry miniaturization together with increased speed and computational capacity are providing the next-generation hardware platforms for BCIs. This growing knowledge base and technological capability is creating the "bedrock" essential for developing BCI systems and powering ongoing advances in neural prostheses.

The strong recent and current investment in BCI research throughout the world virtually guarantees a continued high growth rate. BCI and brain-controlled robotics programs have been one of the hallmarks of the European Union's Sixth Framework Program (2002–2006) for Research and Technological Development. The large size and scope of these multidisciplinary, multinational, multilaboratory programs have been remarkable, with support levels far exceeding most BCI programs in the United States. Even if the scale of 7th Framework programs is reduced, the momentum of BCI research initiated by EU 6th Framework programs will not dampen for some time. Likewise, the panel was impressed by the formidable investment being made by China in biological sciences and engineering in general, and by the investment in BCI and BCI-related research in particular. Japanese universities and institutions also are unmistakably increasing their commitment to and investment in BCI research.

INVASIVE VERSUS NONINVASIVE BCI RESEARCH

It became clear to the panel during its study that there is a marked contrast in the worldwide distribution of "invasive" and "noninvasive" BCI research. Invasive systems interact with the brain directly, i.e., with electrodes that penetrate the brain or lay on the surface of the brain, while noninvasive systems interact with the brain indirectly by transmissions through the skull, e.g., electroencephalography (EEG), functional magnetic resonance imaging (fMRI), and magnetic sensor systems. The vast majority of invasive BCI research is currently being conducted in the United States. Virtually all BCI research in Europe is noninvasive, attributable in large part to constraints and intimidations imposed by animal rights organizations. BCI research in China appears to be almost exclusively noninvasive, though this reflects the relatively early stage of development of BCI research in that country. The massive modernization by China of its research programs in fundamental neuroscience and BCIs hopefully is leading to the emergence of a first-rate invasive BCI program. The panel felt that there is a strong need to maintain a worldwide balance between invasive and noninvasive approaches to BCI research and technology if the field of neural prostheses is to remain vigorous and viable. The panel was particularly impressed by the commitment in Europe and Japan to devote the substantial resources needed to explore the possibility of fMRI and magnetoencephalography (MEG) sensor technologies as the basis of noninvasive BCIs, despite the high cost of such technologies and the uncertain time span or probability of miniaturization to the appropriate scale for routine patient use.

NEED FOR MEDICAL BCI

One of the other forces driving the current acceleration in BCI research is societal demand for solutions to the problem of repairing the nervous system. An unassailable reality is that when the brain and spinal cord become damaged or diseased, they do not repair themselves. With the increasing size of the world population and particularly its increasing age, the number of future patients with such diagnoses as Parkinsonism and other tremor-related disorders and dementias including Alzheimer's disease, epilepsy, accident-induced spinal cord injuries, and peripheral neuropathies resulting from diabetes is likely to be staggering. The panel found that BCI researchers uniformly considered future health-related needs for BCIs to be a strongly motivating factor, with that motivation particularly great in populous countries like China.

In recognition of the current and future potential market for BCIs, the medical device industry has begun to accelerate development and market integration of BCI-related medical products. In the United States and Europe, evidence of medical industry collaborations with respect to BCI devices and systems is seen in an increasing number of startups and joint partnerships. As the bridge from research prototype to medical device strengthens, solutions are emerging to the specialized design requirements imposed by the CNS: sensor designs, mathematical models and their hardware implementations, and brain interface materials are increasingly becoming "biomimetic" and "neuromorphic" in nature. In addition, there are also power requirements and biocompatibility issues that are unique to the CNS.

SCOPE OF BCI RESEARCH: NONMEDICAL BCI

The need for medical applications of BCI research, i.e., repair of the nervous system, will remain the core driving force for BCIs at least in the near future. The panel also found evidence, however, that BCI research will increasingly widen to include nonmedical applications. This transition is already in progress in many European and Japanese BCI laboratories. Fundamental principles of BCIs were seen to generalize readily to brain control of video gaming and virtual reality environments. Intriguing extensions of BCIs to automotive industry problems were found in the form of measuring driver cognitive load. Multiple research programs included a focus on BCI-related principles for robotics control and comprehensive programs for integrating BCIs into everyday life to link the human sensorium more completely and interactively into the environment.

TRANSLATION/COMMERCIALIZATION OF BCI

The extent to which industry in Europe and Japan has embraced BCI-related research goals and the development of requisite technologies for BCIs is impressive. This high degree of industry commitment was perhaps most evidenced in Germany by institutional entities having the specific missions of actively promoting academic-industrial research interactions, garnering support for BCI research from industry sources, and transitioning the resulting BCI and BCI-related systems to industry for commercialization. Such entities house advanced technologies and equipment made available to startups with limited resources; research collaborations and partnerships could result in spinoffs that accelerate the entry of new BCIs and BCI technologies into the marketplace.

The EU 6th Framework research programs strongly encourage and to some degree require industrial involvement. Corporations involved in commercialization of BCI systems and/or BCI-related products are essentially able to participate in EU-sponsored research (with some restrictions) as a "collaborator" along with any other university or institute unit and are eligible to receive funds to conduct their respective component of the overall research project. Equally impressive was the degree to which BCI-related research issues were integrated into the agendas of major Japanese research institutes and corporations and the extent of government support of those private, and sometimes profit-making, entities. In general, the panel saw creative and highly flexible academic-industry collaborations that promoted the transition from laboratory-based to commercialized BCIs.

OPPORTUNITIES FOR WORLDWIDE COLLABORATIVE RESEARCH

Because of the rich, interdisciplinary nature of BCI-related research, the panel was able to readily identify multiple opportunities for worldwide collaborations. Foremost among these is a comprehensive effort to achieve a better understanding of the relation between noninvasive and invasive measures of cortical activity—EEG/MEG, local field potentials, and (population) single-unit activity. This issue was identified at multiple sites visited by the panel as one that is both fundamental to neuroscience and useful in the further development of BCIs. This problem also is complementary to the relative strengths of BCI research on the three continents.

Second, there is a plethora of new mathematical modeling and signal analysis methods being developed throughout the multiple countries involved in BCI research. Systematic evaluation of these methodologies and collaborative efforts to achieve synergy and avoid duplication would be beneficial to the forward movement of BCIs.

Third, there remain multiple electrode technologies used in North America, Europe, and Asia. Given the time required to develop and implement new electrode approaches and their associated electronics and signal processing protocols, dissemination of technological innovation and collaboration with respect to needed next-generation methods, e.g., “dry” EEG electrodes, could accelerate BCI research and development progress. Needed collaborations with respect to BCI-related microelectronics also were acknowledged. Several multinational collaborations and technology-sharing efforts that can attest to the beneficial effects of collaboration on BCI research include

- The joint DARPA Revolutionizing Prosthetics program (U.S.) and the robotics research program at the Polo Sant’Anna Valdera (Italy)
- U.S.-European use of the Watson Center BCI2000 system
- Multi Channel Systems and g.tec technologies.

The technologies developed within these collaborative programs are now used throughout the world in BCI research.

STUDY HIGHLIGHTS: BCI R&D IN NORTH AMERICA AND EUROPE

Science of BCIs

- The majority of BCI science in NA (North America) involves “invasive” technologies, i.e., recordings from arrays of electrodes implanted into the brain.
- The majority of BCI science in Europe involves “noninvasive” technologies, i.e., recordings from arrays of electrodes mounted onto the surface of the skull.
- Other fundamental differences between U.S. and European BCI efforts:
  - European efforts are more often integrated within a larger research scope of developing “hybrid bionic systems.”
  - European BCI systems involve a wider range of EEG-based applications.
  - The panel saw many opportunities for synergy and collaboration with European BCI investigators.
  - Overall, the panel felt that, in terms of quality and sophistication, European BCI efforts are highly competitive with those of the United States.

Interdisciplinary/Programmatic Structure for BCI Research

- Programs are defined on a decade-long time scale.
- High risk is “comfortably” inherent in programmatic definitions.
- Fundamental science is considered an equal to practical outcomes.

- In general, the panel found a strong European commitment to long-term, visionary, high-risk, interdisciplinary research, in other words, the foundation required for successful development of BCIs.
- U.S. counterparts include DARPA initiatives, NSF ERC programs, and NINDS Neural Prosthetics.
- The scale of multi-investigator projects possible under EU programs exceeds that found in the United States; multidisciplinary teams necessary for BCI research are more readily created in the EU system.

Funding for BCI Research

- Consistent with the large, multidisciplinary BCI teams found in Europe, the scale of European BCI research funding is substantial.
- Only NSF Engineering Research Centers (e.g., Biomimetic Microelectronic Systems Center at USC) and the largest DARPA programs (e.g., Revolutionizing Prosthetics) compete with EU programs.
- In part, this reflects the consistent investment by European countries in fundamental science and technology, in addition to investing in the engineering and applications aspects of BCI:
  - Tübingen, Germany: research-dedicated fMRI and MEG systems for non-invasive BCI
  - Freiburg, Germany: large-scale research program in nonlinear dynamics of brain function
  - Lausanne, Switzerland: world's most advanced electrophysiological and modeling analysis of cortical circuitry.

Translation/Commercialization of BCI Research

- The European system has created specific mechanisms and institutions for cooperative activity between academia and industry; there is a high level of transitioning BCI research.
- The European system is more effective than U.S. systems in integrating Industrial and academic efforts; there is substantial support from industry for BCI research.

Extension of BCI Research to Patient Populations

- There are several compelling examples of integrated research, development, and clinical applications in both Europe and the United States:

  - University of Aalborg, University of Tübingen, La Sapienza University
  - Wadsworth Center, Case Western Reserve University.
- Collaborations between the United States and Europe on "best practices" in clinical applications of BCIs would be beneficial.

Educational/Training Programs in BCI

- Surprisingly little attention is paid to developing formal, BCI-specific training programs at the undergraduate, graduate, or postdoctoral levels.
- The United States clearly has more comprehensive, well-developed educational/ training programs in BCI, with greater sensitivity to recruiting underrepresented minorities.
- New programs for interdisciplinary training are under development in Europe at Aalborg University and Scuola Superiore Sant'Anna.

STUDY HIGHLIGHTS: BCI R&D IN ASIA

China

Overall Scope and Magnitude of BCI Research in China

- Although BCI research in China only started within the last ten years, it is already substantial in its scope and impressive in its accomplishments.
- BCI algorithm development already leads the field.
- Current BCI research is focused on low-cost, low-technology solutions—a reflection of socioeconomic demand, i.e., large population and relatively low economic status.
- Extension to clinical settings and commercialization of BCIs are barely begun.
- Future BCI research will incorporate "systems-level" solutions evolving from fundamental, invasive studies of brain function.

Future Growth of BCI Research in China

- Growth rate is now high and will remain high into the future.
- BCI research will benefit from broad, large-scale investment in biological/ medical sciences, engineering/microelectronics, and mathematics/computer sciences.
- Evidence exists for targeted, high-priority investment in BCI/biomedical engineering.
- New facilities of world-class caliber for BCI/biomedical engineering:

  - Tsinghua University: new biomedical engineering building/facilities
  - East China Normal University: new state-of-the-art multisite electrophysiological facilities; new genetic mouse-breeding facilities
  - Shanghai Jiao-Tong University: new campus; new multidisciplinary facilities for biomedical engineering, microelectronics, computing

- Strong, high-level academic/government support exists.
- Associations between different disciplines, critical for the development of BCIs, are already forming.
- Strong commitments to education and large student/faculty population exist.
- Invasive BCI programs are just now emerging, but commitment is clear and investment has begun.

Relations with Industry/Commercialization

- BCI research is in its beginning stages in China, but it is too early for significant industrial involvement or commercialization.
- Nevertheless, there are multiple patents, and researchers are conscious of commercialization.

Funding and Funding Mechanisms

- The primary funding source for BCI research in China is the government.
- Funding entities include the Chinese Ministry of Science and Technology, “NNSF China” (National Natural Science Foundation of China), and the China High-Tech Research and Development Program.

Training Programs and Educational Mechanisms

- Little attention is now paid to developing BCI-specific training programs at any level: undergraduate, graduate, or postdoctoral.
- Because of the early stage of development of BCI programs in China, efforts are focused on forming foundational departments and programs (e.g., biomedical engineering); as a consequence, traditional disciplines have precedence.

Japan

Overall Scope and Magnitude of BCI Research in Japan

- BCI research in Japan should be evaluated within a context very different than that of China; critical factors for Japan are: