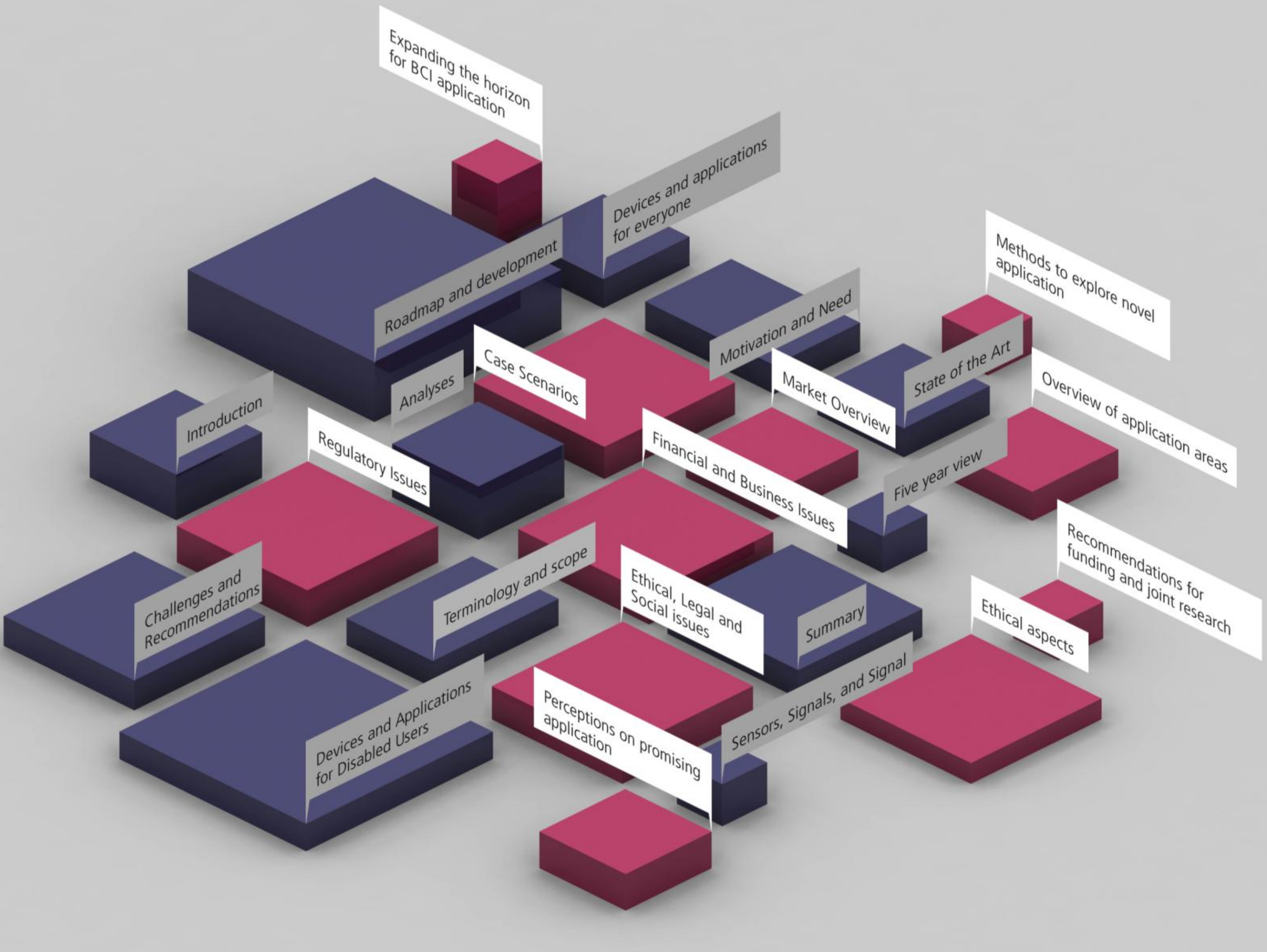
Future BNCI:

A Roadmap for Future Directions in Brain / Neuronal Computer Interaction



future bnci

This roadmap was developed by the Future BNCI Project and colleagues within the H3 INFSO Cluster, part of the Information and Communication Technologies (ICT) theme of the Seventh Framework of the European Commission.

There are nine other established projects in this H3 cluster:

Three other projects (ABC, BackHome, and Way) are just beginning now, and do not have logos. This document does not necessarily represent the views of any entity, including any specific project nor any funding sources. No entity can be held responsible for any misuse of any information contained herein.

Table of Contents

List of Figures

List of Tables

Executive Summary

Brain-computer interface (BCI) systems are improving in various ways. Key trends include improved sensors, software that is more usable, natural, and context aware, hybridization with other communication systems (including brain/neuronal computer interfaces or BNCIs), new applications such as motor recovery and entertainment, testing and validation with target users in home settings, and using BCI technology for basic scientific and diagnostic research. These and other developments are making BCIs increasingly practical for conventional users (persons with severe motor disabilities) as well as numerous emerging groups. BCIs are gaining more and more attention in academia, business, the assistive technology community, the media, and the public at large.

However, despite this progress, BCIs remain quite limited in realworld settings. BCIs are slow and unreliable, particularly over extended periods with target users. BCIs require expert assistance in many ways; a typical end user today needs help to identify, buy, setup, configure, maintain, repair and upgrade the BCI. Most BCIs still use gel-based sensors that also require expert help to set up and clean. User-centered design is underappreciated, with BCIs meeting the goals and abilities of the designer rather than user. Integration with other assistive technologies, different BNCI systems, other head-mounted devices, and usable interfaces is just beginning.

Many infrastructural factors also limit BCI development and adoption. Most people either do not know about BCIs, or have unrealistic views about how they work or might help. There is inadequate communication among different user groups, caregivers, relevant medical professionals, and researchers in academic, industrial, and other sectors. Our recent survey showed that most of the BCI community wants improved standards, reporting guidelines, certifications, ethical procedures, terms, and other canon. Resources to facilitate BCI development remain too limited and complicated.

Amidst these challenges, expectations among technology experts, funding sources, and the public at large are high – perhaps unrealistically high. Therefore, the next five years should be both dynamic and critical for BCI research and development. Hence, an effective and focused effort is necessary to address key challenges and help ensure that BNCI development can progress quickly and effectively.

This roadmap reviews the state of the art in BCIs and related systems, identifies major challenges and trends, analyzes case scenarios reflecting different users and needs, presents major BNCI research efforts and surveys, summarizes financial and ethical issues, and presents recommendations for joint research ventures combining academic, commercial, and other sectors. Scientific and technical recommendations generally include supporting the trends described above. Both invasive and noninvasive BCI systems could provide different solutions for different users, and could address distinct scientific and diagnostic challenges. Infrastructural recommendations focus largely on encouraging improved interaction, dissemination and support, such as fostering a BCI Society and publicly available web-based resources. Online resources to facilitate development, such as introductory information, telemonitoring tools, software platforms, data, documentation, problem solving guides, friendly support tools, and databases of references and events could all help BCIs transition from a nascent and fairly unknown technology into a mainstream research and development endeavor.

Introduction

Motivation and Need

Why develop BCIs, or a roadmap about them? Both of these questions can be addressed in terms of the growing gap between the potential benefits of BCIs and the actual benefits they provide. There are many indications that **the state-of-the-art is advancing quickly**, and that BCIs and related technologies are gaining attention worldwide from many groups, including academics, government funding entities, companies, various groups of healthy and disabled users, and the public at large. However, there remains considerable challenge in developing BCIs into **practical realworld tools** that fulfill the needs, desires, and expectations of **each user**. The people who need BCIs most – persons who have severe disabilities that leave them unable to effectively communicate through other means – are usually not getting them. This is especially problematic because the need for practical BCIs is growing, due largely to the increase in the mean age and the potentially greater benefits that BCIs could provide for both conventional and new user groups. That is, as BCIs become more powerful and flexible, the loss resulting from inadequate exploitation increases.

On an individual level, the lost opportunity can be severe – and is also, unfortunately, the status quo today. Many people with “locked-in syndrome” cannot exercise command and control in any way. This can lead to extreme dependence and social exclusion, in addition to the obvious frustration and discomfort from this situation. Similarly, the demands on carers, doctors, and support personnel entail considerable personal and financial costs.

Hence, there is a clear need to develop different aspects of BCI and BNCI systems, including scientific and technical challenges as well as infrastructural and support issues. This roadmap, and the FBNCI project, are needed to identify, analyze, disseminate, and address the various challenges in the near future, as well as recommended solutions. These efforts should reduce the fragmentation, confusion, misdirected funding, and wasted time that can occur with any rapidly advancing technology.

Terminology and Scope

What is a BCI or BNCI?

The canonical definition of a “BCI” is fairly strict (Wolpaw et al., 2002; Pfurtscheller et al., 2010). The latter article[1] states that:

Hybrid BCIs, like any BCI, must fulfill four criteria to function as BCI:

1. Direct: The system must rely on activity recorded directly from the brain.

---

[1] This article was published in an open access journal, and the entire text is available for free. It is accessible from the “New Directions” subtab of future-bnci.org.

2. Intentional control: At least one recordable brain signal, which can be intentionally modulated, must provide input to the BCI (electrical potentials, magnetic fields or hemodynamic changes).

3. Real time processing: The signal processing must occur online and yield a communication or control signal.

4. Feedback: The user must obtain feedback about the success or failure of his/her efforts to communicate or control.

A BNCI differs only in the first criterion; signals may also reflect direct measures of other nervous system activity, such as eye movement (EOG), muscle activity (EMG), or heart rate (HR). Hence, devices such as cochlear implants or deep brain stimulators are definitely not BCIs and not discussed in this roadmap.

The definitions of these terms have both evolved significantly since the beginning of this project only two years ago. The term "BNCI" was introduced not long before then by the European Commission, and ongoing efforts to find any definition of the acronym or feedback from the term's creator have not been successful. Also, various efforts have emerged over the last two years to broaden the definition of a BCI, such as with passive, emotional, and affective BCIs. To address different expectations, this roadmap discusses **both** classically defined BCIs and many related systems that, even if not BCIs, are relevant to BCI development. For example, passive BCIs, BCI systems for rehabilitation, neuromarketing, and BCI applications for scientific research are all addressed.

A BCI may be invasive or noninvasive. This roadmap focuses primarily on noninvasive BCIs, since these devices are more prevalent and have much broader potential appeal, but discuss different invasive systems too.

Expanding the BCI definition

Some groups have used terms such as "passive BCI", "affective BCI", "emotive BCI", or "mental state monitor" to describe devices that directly measure brain activity, and often provide real-time feedback, but do not require intentional mental activity for each message of command (Müller et al., 2008; Garcia Molina et al., 2009; Mühl et al., 2009; Nijholt et al., 2011; Zander and Kothe, 2011). Another high-profile new definition of a BCI (Wolpaw and Wolpaw, 2012) greatly expands the definition from the most heavily cited article in the BCI literature (Wolpaw et al., 2002).

> "If a BCI does not provide feedback there is no 'interface' and the device or system is simply a monitor."

Expanding the BCI definition requires consensus not only that the term must be changed, but also what exactly is (and is not) a newly defined BCI. The conventional and new definitions generally differ on whether passive monitoring tools are BCIs. The above definitions also generally conflict with each other on issues such as whether realtime interaction or enhancing human-computer interaction is required. There is less debate about whether a BCI is a device that reads directly from the brain. These issues were explored in our Asilomar survey (Nijboer et al., 2011a, 2011b, 2011c), which asked conference attendees what they thought about the terms and definitions used for BCIs. One respondent from the first of these articles commented that "If a BCI does not provide feedback there is no 'interface' and the device or system is simply a monitor".

Developing **common terms and definitions** is a major challenge, and FBNCI recommends strong support for these and other infrastructural improvements. While our project has been active in disseminating terms and encouraging a BCI Society that could develop and maintain a BCI infrastructure, more work is needed (Allison, 2011; Müller-Putz et al., 2011; Nijboer et al., 2011; Allison et al., 2012).

Other terms interpreted differently

There is general accord on many terms within the BCI literature, such as "synchronous", "no-control state", or "feedback." However, in addition to the exact definition of a BCI, some other terms have different definitions in the literature[2]. Examples include:

Illiteracy: A 2007 book chapter introduced the term "BCI illiteracy" to refer to the problem that some users cannot use some BCIs (Kübler and Müller, 2007). Some people dislike this term because it is unclear or implies that illiteracy reflects a failing of the end user. Other terms include "proficiency" or "deficiency" (Allison and Neuper, 2010; Blankertz et al., 2010).

Invasiveness: This refers to whether or not surgery is needed to implant the sensors necessary to read brain or other signals. The terms "invasive" and "noninvasive" are most often used, but other terms such as "intracranial" and "implanted" have also been used.

Rehabilitation: BNCIs and related systems might be used for rehabilitation of stroke, autism, epilepsy, or other disorders. The goal is not to provide communication or control, but produce permanent or at least lasting changes. Other terms include "neuromodulation", "therapy", or "neurotherapy". Similar technologies might appeal to healthy users, who are not seeking rehabilitation but improved sleep, relaxation, or memory.

Hybrid: A hybrid BCI was initially defined as a device that combines a BCI with another means of sending information (Millan et al., 2010; Pfurtscheller et al., 2010; Allison et al., 2012). This is the definition used here. However, other work defines a hybrid BCI more broadly.

Exogenous and endogenous: BCIs may rely on brain signals directly elicited by outside events such as P300 and SSVEP, or internally generated signals such as ERD changes from motor imagery. These have also been called reactive and active (Zander and Kothe, 2011).

Users: There is some debate about the propriety of referring to some persons as "patients", "disabled persons", or other terms that may be offensive. This terminological issue goes well beyond this roadmap. The term "client" is a more neutral term that also connotes that users are paying customers with unique needs and desires.

An initial effort was made to standardize all terms within this roadmap. However, this elicited some objections from different contributors, and may obscure some subtleties intended by the authors.

---

[2] The glossary contains additional terms and definitions.

Moreover, the roadmap keeps highlighting the importance of learning from different disciplines, and hence slight terminological differences are potentially didactic. For example, the material written by U Twente uses the word “client”, which is more common in HCI and assistive technology (AT), an area of focus for that institute.

Terminological relevance

“Who cares, really”?

Readers might by now recognize that discussions about terminology occupy an increasing amount of time and effort at conferences, and were not trivial in the development of this roadmap. Indeed, 79% of respondents in our 2010 Asilomar survey thought that a standard BCI definition should be established within five years. However, some dissenting opinions were strong. In that survey, someone raised a question that also arose during efforts to work toward common terms during workshops and other events (Nijboer et al., 2011a). “Not to be incendiary,” the respondent wrote, “but who cares, really”?

From many perspectives, this is a valid question. End users care most about whether a product meets their needs at an acceptable price. The label may be unimportant. BCIs and BCI-like systems will still develop in tandem, heavily influencing each other, regardless of what they are called.

In other cases, though, **terms and definitions do matter**. Any document that aims to discuss general BCI issues, such as a review article, roadmap, or textbook, needs to establish which devices are and aren’t relevant. Similarly, grant documents, including call texts and guidelines for reviewers, need to unequivocally establish whether a possible proposal fits within the call. Reporters, students, and others who want to produce a paper or story about a new device need to know what it is, possibly amidst false claims from manufacturers or researchers. This challenge is exacerbated by numerous instances of bad reporting (Racine et al., 2010). Companies, insurers, and regulatory entities may also need to establish whether a device should heed any regulations or guidelines for BCIs. Thus, terminological issues can matter to many groups for many reasons.

Scope

This roadmap focuses mainly on the next five to seven years, with occasional discussion of more distant futures. In addition to discussing technologies themselves, the roadmap addressed some related topics, such as commercial development, joint research efforts, standards, guidelines, case scenarios, media and perception, and other matters.

Roadmap and Development

Roadmap structure

This roadmap begins with a one page Executive Summary, followed by this Introduction. As noted above, many articles identify four components of a BCI: signal acquisition, signal processing, output, and an interface that governs the interactions between different components and the user. This roadmap includes three major “mini-roadmaps” on a specific aspect of BCIs, with an introduction, state of the art summary, analyses of “challenges” followed by “solutions and trends”, a five year view, and a concluding text box that summarizes challenges and recommendations. The first mini-roadmap addresses sensors, signals, and signal processing, corresponding to the first two elements of a BCI, which essentially involve getting a control signal. The second section addresses the output (devices and applications) and interfaces for disabled users. The third section addresses devices, applications, and interfaces for general consumers.

The following section, part VI, presents Case Scenarios that help describe how different people use different BCIs. The next four sections discuss financial and business issues, review surveys that ask different stakeholders and users about BCIs, summarize relevant research projects, and address ethical issues. Section XI contains our funding recommendations, and section XII contains our summaries and conclusions.

This roadmap also contains supplemental video materials[3]. The representation video presents a major BCI conference in Utrecht in May 2011. The FBNCI project also interviewed many stakeholders about major issues in BCI research, which were based on this roadmap. Hence, the interviews supplement many of the points made in this roadmap, and provide personal elaboration from many of the people who are most active and well-known within the research community.

“Quick and easy” roadmap guide

Most people will not have the time to read this entire roadmap. Hence, most sections end with a text box summarizing major issues in that section. “Executive Summary” and several pages of “Summary” are one-page overviews. The interviews available on our website provide an alternate way of learning stakeholders’ views, and other video materials provide introductory explanations and show some of the newest BCI systems and events.

Roadmap development process

This roadmap, like the FBNCI project, officially began in January 2010. For the first few months, we worked on developing the infrastructure for our project and roadmap, including hiring people, developing the Advisory Board, and creating the website. Until June 2010, our main focus was on researching the state of the art and major issues, both through literature research and stakeholder discussions. By September 2010, we had a framework and some initial text ready for discussion at our FBNCI conference near Graz. We then focused increasingly on an iterative process of developing different roadmap sections, discussing them with the Advisory Board and other stakeholders (often at a workshop), and revising our materials.

Workshops were a major component of roadmap development. Our 2010 conference featured about 40 attendees who were divided into four workshops, each of which focused on a different roadmap section. In 2011, FBNCI hosted several workshops attached to other major conferences or events. FBNCI held workshops in Utrecht in May, Barcelona in June and November, Memphis in October, and Alicante in November. These workshops each focused on different issues corresponding to different

---

[3] The Utrecht video is accessible from the Future BNCI website at future-bnci.org by clicking on “Videos” under “About BCIs”. The “Stakeholder Interviews” tab under “Roadmap” contains interviews.

roadmap sections. For example, the Utrecht workshop included small group discussions with 3-4 people per group focused on different case scenarios.

Figure 1: The left panel presents most attendees of the 2010 conference near Graz. The right panel shows some of the attendees listening to a presentation (left to right: Melanie Ware, Michel Ilzkovitz, Michael Tangermann, Aureli Soria-Frisch, Diane Whitmer, and Clemens Brunner).

Small group discussions were one of many techniques employed during the workshops. Typically, the small groups developed a summary to discuss with the plenary attendees to solicit further feedback. Workshops also included general discussion periods, focused writing or discussion targeted toward specific points or issues, short presentations, review and discussion of existing roadmap text and issues, and question-and-answer sessions.

In addition to these FBNCI workshops focused on the roadmap, many other events provided opportunities to improve the roadmap. At the Brussels ICT Exposition in September 2010, FBNCI hosted a “BNCI village” group of exhibits as well as a discussion forum. FBNCI hosted or facilitated several evening workshops with major conferences, such as the Asilomar conference in May 2010, the TOBI workshop in December 2010, and the Society for Neuroscience conferences in November 2010 and 2011. Teleconferences, emails, telephone calls, and direct personal contacts also provided more information and opinions that were incorporated in this roadmap.

Roadmap responsibilities

Before the FBNCI project began, the partners discussed general responsibilities for different sections. For example, the partner that manufactures sensors, Starlab, was an obvious choice for developing the roadmap section involving sensors. We further fine-tuned the section responsibilities after the project began, but did not deviate from our general plan. The roadmap outline, with the partner primarily responsible for each section, is shown below.

I. Executive Summary (Graz University of Technology)
II. Introduction (Graz University of Technology)
III. Sensors, Signals, and Signal Processing (Starlab)
IV. Devices, Applications, and Interfaces for Disabled Users (Ecole Polytechnique Federale de Lausanne)
V. Devices, Applications, and Interfaces for Everyone (University of Twente)
VI. Case scenarios (University of Twente)
VII. Financial and Business Issues (Starlab, Graz University of Technology)

VIII. Surveys of Stakeholders (Graz University of Technology)
IX. Summaries of Relevant Projects (Graz University of Technology)
X. Ethics (University of Twente)
XI. Recommendations for Funding and Joint Agendas (Graz University of Technology)
XII. Summary and Conclusions (Graz University of Technology)
XIII. Contributors (Graz University of Technology)
XIV. Glossary (Graz University of Technology)
XV. References (Graz University of Technology)
XVI. Appendix I: Invasive and non-invasive technologies (Graz University of Technology)
XVII. Appendix II: Sample funding mechanisms (Ecole Polytechnique Federale de Lausanne)
XVIII. Appendix III: Follow-up plan (Graz University of Technology)

While each section had a clear leader, we also relied on each other for contributions and feedback. All workshops were led by the relevant section leader, but were attended by at least one FBNCI team member from another institution. A lot of material was moved between sections, and coordinating different contributions was nontrivial. In our last Barcelona workshop, each partner was assigned two other sections to read, and two partners provided comments on the entire document.

Our project and team

This roadmap was developed as part of the Future BNCI project, which is funded by the Seventh Framework of the European Commission (Project number ICT-248320). FBNCI ran from January 2010 through December 2011. Future BNCI was a Coordination and Support Action, and thus aimed to help bolster interaction among other BNCI research efforts and support them. In addition to efforts directly related to our H3 BNCI research cluster, such as facilitating dissemination and scheduling joint events or teleconferences, FBNCI was also responsible for indirect support, such as developing web resources and a book.

Future BNCI was led by a consortium of four institutions: Graz University of Technology (TU Graz or just TUG), University of Twente (UT), Ecole Polytechnique Federale de Lausanne (EPFL), and Starlab. We developed this roadmap in collaboration with our Advisory Board and numerous experts in our research cluster and elsewhere[4].

Advisory Board

The Advisory Board provided feedback about the roadmap, updated us on the most recent developments, kept us in contact with the best stakeholders, and participated in events such as our workshops. Because BCI research involves so many different disciplines, sectors, regions, and interests, any Advisory Board had to include a range of people. The Advisory Board features people from different sectors (academia, industry, government, and nonprofit); disciplines (including Psychology, Engineering, and Medicine); regions (including different areas within and outside of Europe); and interests (such as invasive and non-invasive BCIs, patients and healthy users, and different BCI approaches).

---

[4] Please see “Contributors” for a list of FBNCI team members, the Advisory Board, and other contributors.

The H3 project cluster

Future BNCI is part of a cluster of thirteen projects that are all funded by the EC and focus on BCI and BNCI research. Future BNCI is focused on helping BNCI research and the BNCI community, including our cluster partners. The other projects in our cluster focus primarily on new scientific research and technological development, such as conducting new experiments, developing new hardware or software, and testing new systems with patients and other users[5].

Figure 2: The logo representing the H3 BNCI research cluster.

Additional roadmap contributors

This roadmap was developed over two years, with extensive interactions with a variety of people. People contributed in many different ways, from commenting on which problems are important, to being interviewed, to writing a subsection. In addition to the many people and institutions listed above who helped to develop this roadmap, was also wish to thank[6]:

1) All the participants in our conference and our workshops.

2) Everyone who completed one of our surveys.

3) Labmates and others who helped with practice versions of surveys, case scenarios, and other work.

4) All administrative support staff at our host institutions.

5) Anna Sanmarti, who very kindly donated her time to help with our video projects.

6) Corona Zschusschen and Cecilia Puglesi, who developed logos and graphics used in this roadmap.

7) All of the interviewees and other persons who were presented in our video materials.

8) Our colleagues at the European Commission who funded and supervised the Future BNCI project.

State of the Art Summary

Brain-computer interface (BCI) systems allow communication without movement. BCIs may be invasive or non-invasive. Invasive BCIs require surgery to implant the necessary sensors, whereas non-invasive BCIs do not. Over 80% of BCIs are non-invasive systems that measure the electroencephalogram (EEG), which reflects the electrical activity associated with mental tasks

---

[5] Please see the Project Summaries for more details about cluster projects, including FBNCI.

[6] Please see Contributors for a summary of contributors.

(Mason et al., 2007). Some groups are trying to broaden the definition of BCI. A few years ago, the European Commission (EC) introduced the term "Brain-Neuronal Computer Interaction", or BNCI. This term includes BCIs as well as devices that monitor other physiological signals (not directly recorded from the brain), such as devices that measure eye or muscle activity. BNCIs also don't require intentional control, but do still require realtime feedback.

Progress in each of the four components

Any BCI has four components: signal acquisition (getting information from the brain); signal processing (translating information to messages or commands); devices and applications (such as a speller or robotic device); and an application interface (or operating environment) that determines how these components interact with each other and the user (see Figure 3). BNCIs also have these four components, but the signal may be acquired from other sources.

Any BCI has four components: signal acquisition; signal processing; devices and applications; and an interface or operating system.

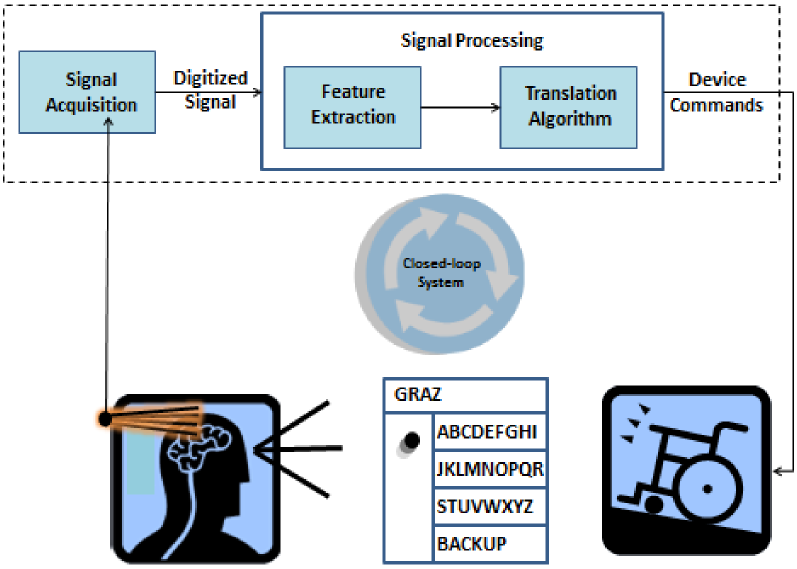


Figure 3: The components of any BCI system (from Allison, 2011).

Rapid progress is being made in all four components. New **sensors** are being developed that do not require electrode gel, which reduces preparation time and hassle and makes BCIs more accessible to new users. Dry sensors over the forehead can acquire not only brain signals, but also other relevant signals such as EOG and facial EMG. Companies like Quasar, Emotiv and NeuroSky have heavily advertised dry electrode systems for gaming and other goals. The ENOBIO dry electrode system developed by Starlab is currently available, and Starlab is working on numerous improvements. Twente Medical Systems (TMSi) has a different type of practical electrode that relies on water instead of gel. Other means of detecting brain activity such as functional Magnetic Resonance Imaging (fMRI) and Near Infrared Spectroscopy (NIRS) are also being explored within the BCI research community, although fMRI and NIRS have yet to provide any real benefit over EEG and are overrated for most BCI applications. Improved sensors for invasive BCIs could provide a better picture of brain activity in many ways while reducing the cost, time, and the inconvenience of surgery. Furthermore, many invasive BCIs have shown they can provide reliable control years after implantation, which helps to address concerns about long-term reliability.

"Hybrid" BCIs combine a BCI with another means of sending information, such as another BCI or BNCI, another assistive technology, or conventional interface like a keyboard or mouse. The additional communication system could improve bandwidth, confirm selections, turn the primary channel on or off, provide a backup if the user is fatigued, or yield other benefits. Hybrid BCI research is beginning to explore BCIs as multimodal interfaces in which users can interact, in an intuitive and natural way, using BCIs as one of the communication channels. **"Passive" BNCI systems** could augment our interactions with computers and other devices by assessing alertness, anticipation, image recognition, perceived error, or other mental states based on activity from the brain, eyes, muscles, heart, or other sources.

New **signal processing** approaches have reduced training time for some BCI approaches and improved accuracy and reliability. Progress is also apparent in BNCI signals that are not acquired directly from the brain, both alone and in combination with EEG activity. Although the prospect of combining different signal types has been validated, many resulting challenges in signal fusion remain unexplored, due largely to inadequate communication and networking among relevant stakeholders in both the sensor and signal processing communities.

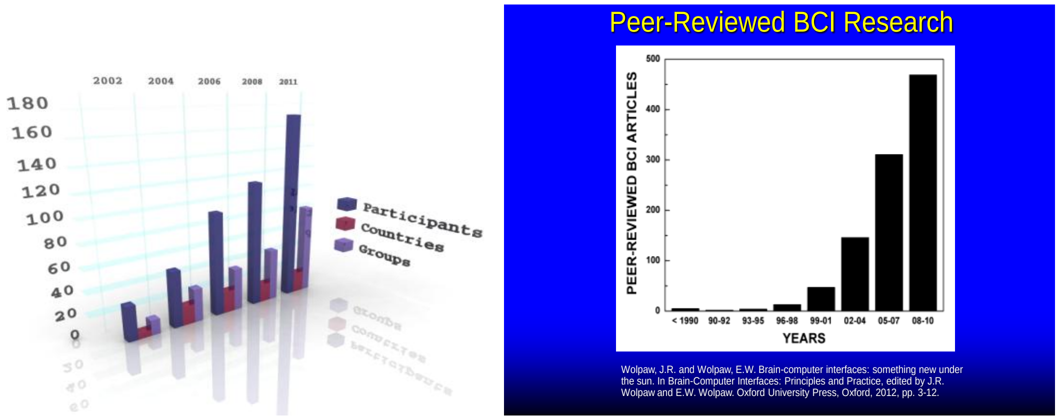
Many new BCI **devices and applications** have recently been validated, such as control of smart homes or other virtual environments, games, prosthetic devices such as artificial limbs, wheelchairs, and other robotic devices. A whole new category of BCI applications is being developed: devices for rehabilitation of disorders, rather than simple communication and control. These and other emerging applications adumbrate dramatic changes in user groups. Instead of being devices that only help severely disabled users and the occasional curious technophile, BCIs could benefit a wide variety of disabled and even healthy users.

New and well-designed **application interfaces** also show promise. Recent work has validated BCIs as a communication channel using advanced virtual environments, which reduce training time while improving accuracy, performance, and user satisfaction. While research in Human Computer Interaction (HCI) has definitely shown that well designed, user centred interfaces yield many benefits, many fundamental design and validation principles in HCI and assistive technology are still ignored in the BCI community. To integrate BCIs in the HCI framework, designers must also consider fundamental interface issues such as whether a BCI is synchronous or asynchronous, how to handle the "No Control State" in which the user does not wish to convey information, and both how and when to present feedback.

User-centered design is critical, and testing with healthy users may be inadequate. Healthy users and designers may have trouble appreciating issues unique to a severely disabled user. Consider a patient with ALS (Lou Gehrig's disease), who cannot move or blink, and may have spasms, neuropsychiatric disorders, and very different goals, abilities, and expectations. Tasks such as mounting a cap and later washing the hair, which may seem trivial for healthy persons, can be much more burdensome for disabled persons and their caretakers.

Increasing attention to BCI research

BCI research is in transition from a field in its infancy to a **full-fledged, mainstream research endeavour**. This emerging success is apparent in both academic and commercial progress, as well as EC decisions and the popular media. In the academic community, progress can be measured by the dramatic rise in peer-reviewed publications, attendance at BCI conferences and other events, and the number of active BCI research labs. Figure 4 shows the increase in BCI conferences. The number of peer-reviewed BCI publications has also increased significantly in the last decade, with the number of publications more than tripling since 2001 (Schalk, 2008).



Wolpaw, J.R. and Wolpaw, E.W. Brain-computer interfaces: something new under the sun. In Brain-Computer Interfaces: Principles and Practice, edited by J.R. Wolpaw and E.W. Wolpaw. Oxford University Press, Oxford, 2012, pp. 3-12.

Figure 4: Two indices of increasing BCI research. The left panel presents attendance at the five Graz International BCI Workshops, which were held in 2002, 2004, 2006, 2008, and 2011. The right panel shows peer-reviewed BCI publications. We thank Prof. Jonathan Wolpaw for permission to use the figure in the right panel, which will appear in the introductory chapter of his upcoming book from Oxford University Press (Wolpaw and Wolpaw, 2012).

Several sources also indicate that commercial interest in BNCI research is increasing. Within the business community, there has been a major increase in non-invasive BCI sales. According to an email from Dr. Thomas Sullivan from NeuroSky in March 2011, "We do say publicly that we have shipped over 1 million integrated circuits that process EEG signals. This is not just in our own headsets, but in the headsets of our partners like Mattel." A Wired magazine article also includes the estimate of one million units, with sales of five million projected by the end of 2011[7]. The aforementioned dry sensors have led to simple games based on head-mounted sensors that did not exist a few years ago. Users might levitate a rock or car by focusing attention on a target object and trying to relax. Other manufacturers of BCI products for both laboratories and end users are thriving. Dr. Günther Edlinger from Guger Technologies reports that g.tec had an increase in annual sales of BCI equipment of about 35% per annum since 2005. Starlab's ENOBIO system was launched in late 2009. Seventy-five percent of all ENOBIO sales have been for BCI applications. Two high-profile American companies devoted to invasive BCIs have been less successful. One such company, Cyberkinetics, ceased operations in 2009, although they had some excellent people, solid publications, and impressive BCIs. Many small to medium companies such as TMSi, Starlab, and Quasar have focused heavily on developing improved sensors for BCI systems over the past few years. Huge companies like Philips have some projects involving BCIs and similar systems.

---

[7] http://www.wired.co.uk/magazine/archive/2011/07/start/mind-controller

Enthusiasm for BCI research is also apparent through funding decisions by the EC and national funding entities. The EC spent about €38 million on ten projects based on BCIs and related systems during its Seventh Framework Funding Programme (FP7), and three more are expected to begin soon. One example of an FP7 funded project is Future BNCI, led by the author, which focuses on analyzing and facilitating BCI and BNCI research. Another is the BrainAble project, which is developing a suite of improved BNCI tools for a variety of applications and heavily emphasizes testing and development for severely disabled users in real-world settings. The Dutch government provided €24 million for the BrainGain project, and some other national governments in Europe and elsewhere (primarily the US and Asia) are funding BCI projects. The United States has focused much more heavily on invasive research than the European Union recently, resulting in several impressive recent American papers on invasive BCIs. These figures only reflect projects that focus primarily on BCIs and BNCIs. Many other funded projects focus primarily on other efforts, such as robotic wheelchairs, but do include some BCI or BNCI work, such as providing one of several mechanisms to control a robotic wheelchair system.

Finally, BCIs are suddenly gaining widespread attention in the popular media. Popular printed publications have featured cover stories about BCI research recently, including Scientific American, Scientific American Mind, Discover, Popular Science, and Wired. Members of the Future BNCI project have presented BCI research twice each on CNN, Fox, and 3SAT, as well as the Discovery Channel, WDR, and other networks. Other major networks like ABC, NBC, CBS, NPR, and BBC News have also presented work highlighting BCI research. BCIs have also been plot elements in many mainstream movies and TV shows, such as all five televised Star Trek series, House, Fringe, Surrogates, and the Matrix and X-Men series.

Analytical framework

One of the early challenges encountered when evaluating future directions is identifying all of the factors that might influence someone's decision to buy or use a BNCI. As with any consumer device, price and performance are important, but performance involves far more considerations than simply information throughput (Schalk, 2008). Similarly, the price of a BNCI system in terms of financial cost may be insignificant compared to the cost of wasted time; each session of conventional BCI use can require as much as an hour of preparation and cleanup. Furthermore, BNCI development could be disrupted by numerous related disciplines. For example, a breakthrough in electronics or manufacturing technology could alter the BNCI landscape dramatically.

The figure below presents an analytical framework for BNCI systems (Allison, 2010). The "key factors" summarize the numerous factors that affect BNCI adoption. Many of these factors are often overlooked, and could represent underappreciated potential roadblocks or opportunities. For example, a new BCI that delivers particularly high information throughput might seem appealing – but what if a competing product requires less distraction and can be ready to use within minutes without any expert help?

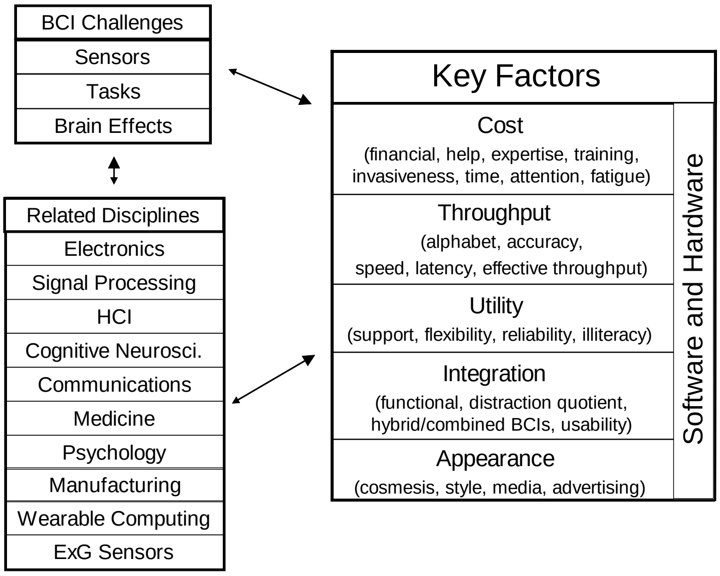


Figure 5: An analytical framework for identifying factors in BCI adoption (from Allison, 2010).

Success stories

While success within academic, commercial, and public sectors is important, one of the key indicators of success is helping persons with severe disabilities. Since BCI research, until recently, focused mainly on these users, some success should be expected. On the other hand, this is a very difficult task, and success should be defined accordingly. Here, we present three examples of successful BCI users, along with some brief discussion of the relevant lessons. Please note that the first two persons have chosen to publicly disclose their names.

Dr. Scott Mackler is a professional neuroscientist who runs a neuroscience lab in New York. Several years ago, he was diagnosed with ALS. He could use an eye tracker as an assistive technology, but it became increasingly tiring as his disease progressed. In 2008, he began using a P300 BCI provided by the Wadsworth Center. He has since relied heavily on his BCI for communication, stating that “I couldn’t run my lab without BCI. I do molecular neuroscience research and my grant pays three people. I’m writing this with my EEG courtesy of the Wadsworth Center Brain-Computer Interface Research Program.” This quote and other supporting information have been published (Allison, 2009; Sellers et al., 2010), and Dr. Mackler and other BCI users were featured in a story in the prestigious news program 60 Minutes[8].

> “I couldn’t run my lab without BCI…. I’m writing this with my EEG courtesy of the Wadsworth Center Brain-Computer Interface Research Program.”

---

[8] http://www.cbsnews.com/stories/2008/10/31/60minutes/main4560940.shtml

"It's the first time I've reached out to anybody in over seven years," Mr. Hemmes said. "I wanted to touch Katie. I never got to do that before."

Tim Hemmes lost control of his arms and legs after a motorcycle accident. A group of researchers from the University of Pittsburgh implanted an ECoG based BCI that allowed Mr. Hemmes to control a prosthetic hand. With some training, Mr. Hemmes learned to move the arm in all directions and hit targets at nearly 100% accuracy. "It's the first time I've reached out to anybody in over seven years," Mr. Hemmes said. "I wanted to touch Katie. I never got to do that before." The research team plans another phase with six human users[9].

"Here is my feedback to my first BrainPaint image; I am deeply moved to tears."

An artist also chose to participate in a research subject for a project through the University of Würzburg called "BrainPainting." This BCI system allows people to create new artistic images with a BCI, such as the image shown below. The artist wrote that "Here is my feedback to my first Brain Painting image; I am deeply moved to tears. I have not been able to paint for more than 5 years." Several other healthy and disabled users were able to use the BrainPainting system as well (Münssinger et al., 2010).

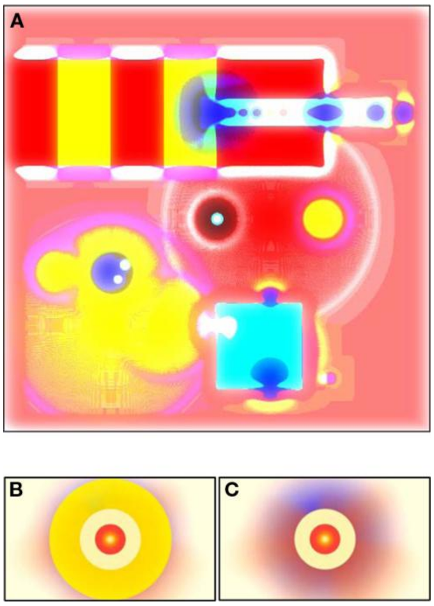


Figure 6: An example of a BrainPainting created by a BCI user (Münssinger et al., 2010)[10].

Hence, there certainly are examples of BCIs providing real benefits to real patients in realworld scenarios. Critically, though, all of these stories present users who had **ongoing support** from a local BCI research lab, using a BCI system with one application designed for nobody in particular.

[9] http://www.msnbc.msn.com/id/44843896/ns/health-mens_health/t/paralyzed-man-uses-brain-powered-robot-arm-touch/#.TvbL8Fbv18F

[10] http://www.frontiersin.org/neuroprosthetics/10.3389/fnins.2010.00182/full. Also, see "Case Scenarios".

Therefore, the main gap in BCI research is not in proving that BCIs can sometimes work, but in developing them as flexible, reliable, usable solutions that meet the needs of individual users with minimal dependence on carers or outside support.

Learning more about the State of the Art

Please see the following sources to learn more:

- The following three sections of this roadmap contain a more detailed review of progress in the different BCI components.
- The Financial and Business section reviews commercial developments.
- The Project Summaries each summarize ongoing projects within the European Commission.
- The Surveys of Stakeholders presents the different perspectives on the state of the art from different researchers and end users.
- The FBNCI website has many sources of additional information, including downloadable lectures from BCI classes, free peer-reviewed articles, and videos.

Sensors, Signals, and Signal Processing

In this section we present a short overview of the state-of-the-art of Sensors, Signals and Signal Processing, including trends in research. Taking this as a starting point we identify problems and challenges, suggest solutions and outline a five-year view for BNCI research on these topics.

State of the Art

BNCI signals from invasive sensors

Although invasive sensors and their associated signals are not the primary focus of the Future BNCI project, no SoA would be complete without a discussion of this topic. For more information the following articles provide more thorough reviews of invasive BCI research including road-mapping from an invasive BCI perspective: "Brain–machine interfaces: past, present and future" (Lebedev and Nicolelis, 2006), "Sensors for Brain-Computer Interfaces" (Hochberg and Donogue, 2006), “Bridging the Brain to the World: A Perspective on Neural Interface Systems” (Donoghue, 2008), and "Neural control of motor prostheses" (Scherberger, 2009), “Human cortical prostheses: lost in translation” (Ryu et al., 2009) provides a balancing perspective from the clinical point of view.

To summarize the field of invasive BCI research, the majority has been focused on decoding signals from the motor cortex to move a cursor or device in 2D or 3D space; these recordings have been accomplished primarily with either single and multi-unit recordings from non-human primate motor cortex, or human ECoG recordings from epilepsy patients. There are also studies on the use of local field potentials from a spatial scale between spikes and ECoG fields, and in achieving BCI control from electrodes surgically implanted in the brains of human patients.

Single and multi-units

The first demonstration of primate closed-loop control was achieved more than forty years ago when monkeys were operantly conditioned to control the firing rate of cortical neurons via biofeedback (Fetz et al., 1969). There was a significant gap in time from the first suggestion that signals recorded invasively from cortical neurons could be used to control a prosthetic device (Schmidt et al., 1980). until populations of cortical neurons in monkeys were used to move a robot arm in 3d space with closed loop control (Taylor et al., 2002) and to drive natural enough movement for a monkey to feed itself with a prosthetic arm (Velliste et al., 2008). In this time period, significant effort was devoted to characterizing and decoding the signals of the motor cortex associated with movement; it was a breakthrough to the field of neuroscience to find that the population activity of single unit motor cortex can decode the endpoint of an arm movement independent of the specific pattern of muscle activations required to arrive at that endpoint (Georgopolous et al. 1982). As the “population vector code” based on spikes became a promising possibility for the decoding of movement intention, much work was devoted to characterizing the relationships between spikes and the parameters associated with motor control, such as direction, force, and velocity. At the same time, electrode arrays for chronically recording from large numbers of neurons were developed (Nicolelis, 1995; Maynard, 1997), and a proof-of-principle that motor cortical neurons could control an external device with 1D control was carried out with a population of single units from rats (Chapin et al., 1999). Cortical single-unit and multi-unit recordings from the primate motor cortex then became the focus of research into the development of brain-controlled motor output based on invasive signals. Wessberg et al., 2000 demonstrated that populations of neurons distributed through monkey premotor, primary motor cortex, and parietal motor regions, could predict 1D and 3D arm movement trajectories. Shortly thereafter, Serruya et al., 2002 demonstrated 2D cursor control based on recordings from monkey M1 neurons, and Taylor et al., 2002 showed 3D online control. Carmena et al., 2003 demonstrated combined 2D cursor control and hand grasping force control.

One research direction in motor control BCI has been to recording from larger and larger numbers of single neurons (Nicolelis, 1995, 1997). Another has been to expand the number of discontinuous brain regions that have simultaneous implants (Nicolelis et al., 2003; Hastopoulos, 2004; Musallam et al., 2004). Hastopoulos, 2004 demonstrated that the hierarchical organization of the motor cortex can be used in simultaneous multi-region recordings for hierarchical decoding of movement selection and planning versus movement execution. The ensemble activity of the primary motor cortex more accurately predicts a specific hand movement trajectory, whereas the dorsal premotor area more accurately predicts target selection. Multi-area recordings for BCI do not necessarily have to be limited to the cortex only. Patil et al., 2004 demonstrated that ensemble thalamic recordings can be modulated based on visual feedback in terms of their responses to gripping force.

Until recently it has been an open question as to how generalizable these promising results from healthy, intact monkey brains could be to the human patients who need BCIs. The variety of neurological conditions, for which BCIs would be useful, include such diverse disorders as ALS, spinal cord injury, stroke, cerebral palsy, muscular dystrophy, and traumatic brain injury, among others. The first successful BCI in a human patient was achieved in the late 90s by Kennedy and colleagues (Kennedy and Bakay, 1998). Kennedy et al., 2000 used the outputs of motor cortex neurons in an ALS patient to control a cursor in 1D and 2D over a virtual keyboard as a communication device. In another break-through study, neuronal ensemble activity from a 96-channel microelectrode array over motor cortex was successfully used to achieve continuous 2D control over a cursor by a human tetraplegic patient who had suffered spinal cord injury (Hochberg and Donoghue, 2006). An extension of this study demonstrated that the same kinematic motor parameters (position and velocity) read out from the motor cortex of healthy, intact human cortices are present in the M1 region of tetraplegic patients even after the loss of descending motor pathways (Truccolo, 2008), suggesting that the body of BCI research from healthy primate cortex studies can be applicable to patients with paralysis. Nevertheless, a recent review (Ryu et al., 2009) admonishes the field that these proof-of-principle studies are insufficient to suggest that invasive BCIs are ready for widespread use given that there still remain bottlenecks in “system durability, system performance, and patient risks” (p.3).

Although the majority of invasive BCI research programs have focused on motor output, there is a new research direction to expand beyond motor signals, to the inclusion of “cognitive prosthetics.” Cognitive prosthetics are defined as signals that “record the cognitive state of the subject, rather than signals strictly related to motor execution or sensation” (Andersen et al., 2004). For example, Musallam et al., 2004 demonstrate that activity from neurons in the parietal reach region of the posterior parietal cortex and the dorsal premotor cortex, can decode the intention or goal of a movement, rather than the kinematic parameters of a movement, even when the movement is ultimately not executed, providing a possible short-cut to the BCIs attempt to construct a specific movement trajectory. They also demonstrated a relationship between the decoding power of the signals and the value of the reward. Cisek et al., 2004 uncovered similarly promising signals for cognitive prosthetics from the dorsal premotor cortex, possible single neuron correlates of mental rehearsal. Santhanam et al., 2006 demonstrated that the dorsal premotor (dPM) cortex can indeed provide a shortcut alternative to BCIs that are based on a decoding of the continuous movement trajectory. In this study, neural activity from dPM during the delay period of an instructed delay centre-out reach task could be used to quickly and accurately decode the target position at a rate of 6.5 bits/second, which is significantly faster than that which had been previously achieved based on spikes or from scalp EEG.

Local field potentials

Local field potential (LFP) recordings measure the summation of excitatory and inhibitory post synaptic potentials of a population of neurons (Mitzdorf, 1985) estimated to cover a recording volume on the mm^3 scale. The use of LFPs for BCI is a relatively new research direction. The amplitude of the spectra of LFP recorded from the motor cortex can be used to decode arm movement direction in a centre-out reaching task, and the best performance is achieved by a combination of different frequency ranges (Rickert et al., 2006). Researchers pursuing the use of LFP recordings for BCIs argue that LFPs represent a spatially optimal point between the fine resolution but sparse sampling of single neurons, and the widespread spatial sampling but limited specificity of EEG (Andersen et al., 2004; Pesaran et al., 2006). Indeed, a direct comparison between LFP and macro cortical surface recordings during a center-out reaching task demonstrated that, at least for this particular task paradigm, LFP signals provided a higher resolution of decoded information than ECoG (Mehring et al., 2004).

In addition to exploration for use in motor control, LFPs have also been tested for their efficacy for the development of cognitive neuroprosthetics. For example, Pesaran et al., 2002 demonstrated that two different frequency bands of the LFP recordings from the lateral interparietal (LIP) region of a monkey's posterior parietal cortex differentially decode present state eye position versus the endpoint goal of saccadic eye movements. In another study, LFPs are shown to be even more effective at predicting reaching movements than saccades (Scherberger 2005). Both of these studies suggest that for some cognitive states, the decoding of LFPs outperforms that of simultaneously recorded spikes (Pesearan et al., 2002; Schereberger, 2005). A recent study showed that a change in the LFP spectrum in the parietal reach region can be an indicator of movement onset, even in the absence of a visual cue, and can be used for closed loop control (Hwang and Andersen, 2009).

Electrocorticography (ECoG)

Electrocorticography (ECoG), like LFP recordings, measure the fields produced by populations of neurons. The only difference is the cortical volume over which these signals integrate neural activity. ECoG recordings are believed to measure fields produced by hundreds of thousands of neurons along with volume conduction effects.

As the LFP researchers argue that local fields are the ideal spatial scale in the trade-off between single units and scalp EEG, so argue the BCI researchers who use ECoG (Ryu et al., 2009). Although work as early as 1999 and 2000 suggested algorithms for ECoG-based BCI (Levine et al., 2000), the first demonstration of brain-controlled cursor movement via ECoG signals was in 2004, when Leuthardt et al., 2004 used ECoG signals from an epilepsy patient to control 1D cursor movements in offline processing and achieved 74-100% success in a closed loop binary control task. In this study, autoregressive spectral analysis was performed to determine the locations and spectral bands most predictive of movement. An alternative approach used the time domain cortical surface potentials from ECoG recordings ("local motor potentials") to control circular 2D cursor movements (Schalk et al., 2007). In this paradigm the local motor potentials produced better performance than the power spectra. The study was limited, however, in that the approach adopted was not necessarily generalizable to random cursor movements. The following year, Pisthol et al., 2008 addressed this critique in a study in which 2D arm movements to random targets were predicted from the low frequency filtered components of the ECoG signals recorded from the motor cortex.

The decrease in focality of ECoG macrowire recordings as compared to microwire LFP could be seen as either a disadvantage or as an advantage since ECoG recordings cover broader brain areas and offer greater diversity in the cortical regions from which the recording will take place and greater selection in the locations of signals. The advantages that ECoG signals have over EEG include a higher spatial and spectral resolution. Gamma band power changes occur on a finer spatial scale than alpha and beta power changes (Miller et al., 2007), likely failing to produce widespread enough coherent signals measurable from the scalp. Some of the disadvantages of ECoG are the limited control over the placement of electrodes, since ECoG-based BCI studies currently are ethically approved only for those patients who have subdurally implanted electrodes for other clinical purposes. The risks associated with brain surgery (infection, complications of anaesthesia, etc.) are obvious drawbacks to this invasive approach.

In 2011, a German startup, CorTec11, launched on the promise of practical and robust ECoG systems with improved biocompatibility for long-term implantation. Although not the first company to enter this space, their technology is novel and promising.

Also in 2011, flexible ECoG arrays (Litt et al., 2011) have been introduced that can adapt to the 3D form of the cortex providing improved spatial resolution and access to data previously unavailable with 2D surface arrays.

Invasive BCI conclusions

To summarize, the vast majority of invasive BCI research has focused on the readout from the motor cortex for the control of external devices such as cursors and robot arms through 3-d space. The generalizability of signals and algorithms from motor read-out, to higher cognitive processes remains to be seen and is an active research area. Questions that will need to be addressed in this area include:

i.) What kinds of signals would be most efficacious for cognitive prostheses?
ii.) How can the current research on cognitive prosthetics in highly trained monkeys be generalized for use in human patients?

Another interesting research direction is the use of multiple types of signals simultaneously. It could be advantageous to combine spikes and LFP recordings since they may represent different types of information: spikes represent the output of a recording area, whereas LFPs are representative of inputs and local processing. As described earlier, there are a few studies in monkeys in which spikes and LFP are recorded simultaneously (Pesaran et al., 2002; Scherberger, 2005). Both studies

---

[11] http://cortec-neuro.com/

demonstrate that there are cognitive states for which the LFP is a better decoder than spikes. There are also cases where the combination of both signals provides a better decoder than either alone (Mehring et al., 2003). There is also a study that compares the decoding power of monkey LFP to human ECoG in the same task, and finds that LFPs better predict target location in a centre-out reaching task (Mehring et al., 2004). Future directions in this area are:

1. Which spatial scales (single units, multi-units, local field potentials, or electrocorticography) are the most useful for different BCI applications? Additional studies should be performed where data are recorded via different invasive modalities simultaneously.
2. How can recordings at these different spatial scales be optimally combined? For example, new implantable multi-scale electrode montages used for epilepsy research (Worrel et al., 2008) in cognitive neuroscience (Quiroga et al., 2005) could be used for BCI research.

Multi-scale recordings are just a specific example of multimodal brain imaging, and an important future direction for BCIs will be the use of multiple complementary imaging modalities in the generation of BCIs. For example, a study published just this year demonstrates the combined use of ECoG and fMRI, wherein fMRI is used in a pre-processing step to localize functional brain regions for ECoG-based cognitive control (Vansteensel et al., 2010). The combination of LFP or ECoG with EEG, EEG with fMRI, and EEG with NIRS are just a few examples of multimodal possibilities that could provide improved BCI performance.

Finally, whereas plasticity was previously posed as a problem in the development of robust BCIs, since it is presumably an aspect of the cortical signals that required retraining of the system at the beginning of each session (Scherberger, 2009), the use of plasticity for improved BCI performance is a new and active area of investigation. For example, Ganguly and Carmena, 2009 demonstrate that after a random shuffling of weights, the decoding performance of movement BCI based on a population of spikes remains extremely high, as long as the specific ensemble of neurons from which the recording takes place remains stable. This finding has provided a degree of confidence to the notion that long-term recording from a population ensemble is possible.

BNCI signals from noninvasive sensors

This section discussed the electrical potentials that can be measured on the surface of the body. The signals that are relevant for BNCI are Electroencephalography (EEG), Electromyography (EMG) and Electrooculography (EOG).

Electroencephalography (EEG)

Electroencephalography (EEG) is the measurement of field potentials produced by populations of neurons from the surface of the scalp, and has been used extensively for clinical applications as well as studying a wide range of cognitive and perceptual processes. As explained in the introduction of this section, current dipoles produced by synchronous activity in neurons with parallel oriented fibres sum linearly to produce macroscopic fields (Nunez and Srinivasan, 2006). The localization of current sources in the brain that produce the pattern of activity measured on the scalp is known as the "inverse problem," and has a non-unique solution. This poses a problem for neuroscientists who are studying relationships between brain structure and function, but is not necessarily a problem for the application developer who would like to the use the signal with the highest predictability, irrespective of knowing where in the brain it came from. As such, EEG which is low cost and easy to use (as compared to invasive methods), has presented itself has a viable option for the development of BCIs.

The first motor imagery BCI (in the modern sense) was proposed by Wolpaw, McFarland and colleagues in 1990, who demonstrated EEG-based cursor control the following year (Wolpaw et al., 1991). The technical challenges of reading out brain intentions from such spatially diffuse signals measured outside the head is illustrated by the fact that only now, after twenty years of development, EEG signals can be used to obtain high performance control over 3D movement (McFarland et al,. 2010). An interim milestone was the achievement of EEG-based 2D cursor control in 2004 (Wolpaw and McFarland, 2004).

Since some of the earliest EEG recordings, a salient 10 Hz rhythm, now referred to as "mu," was observed in over the sensorimotor cortex and would disappear during voluntary movement. The movement-induced cessation of mu rhythm, called "mu blocking," is a robust phenomenon observed with EEG, MEG, and intracranial EEG, during movements of the tongue, hand, arm, leg, and foot (Pfurtscheller, 1981; Pfurtscheller and Neuper, 1994; Pfurtscheller et al., 1987). Like alpha oscillations, beta range oscillations also contribute spectrally to the mu rhythm (Pfurtscheller, 1981; Pfurtscheller and Neuper, 1994). The frequency domain equivalent of mu blocking is the relative decrement in alpha and beta power. The movement-induced decrements in alpha (8-12 Hz) and beta (13-25 Hz) power, referred to as "event-related desynchronization" (ERD) therefore provide robust signals for predicting movement and have been used for EEG-based BCIs.

In addition to its use for moving external effectors through space, EEG has also been used extensively for the development of communication BCIs. Stereotyped EEG signatures such as the visually evoked potential and the P300 signal (Kübler et al., 2001; Wolpaw et al., 2002; Sellers et al., 2006; Allison et al., 2007; Jin et al., 2011) provide robust signals for input to a variety of applications such as keyboard typing or the moving of a wheelchair. Visually evoked potentials are small changes in the EEG in response to visual stimuli, particularly measurable over the occipital area and most saliently elicited by flashing lights. The P300 is a positively deflected peak in the raw EEG signal that occurs approximately 300 milliseconds after the presentation of an unexpected stimulus (typically visual, auditory, or somatosensory). Slow cortical potentials, for example the bereitschaftpotential (Niedermeyer, 1999), or low frequency/DC shift that precedes movement, are another example of stereotyped EEG signals that can be used for BCIs.

Some examples of new and interesting research directions for EEG-based BCIs include the use of inverse modelling to improve signal extraction (Noirhomme et al., 2008), the combined use of EEG with fMRI, and the mixing of different stereotyped EEG signals in a single BCI (Brunner et al., 2010), a new approach known as "hybrid BCIs" that will be discussed in further detail elsewhere.

Electromyography (EMG)

As explained above, muscular cells are electrically active. Electromyography consists of recording the electrical signals associated with muscular fibers. The EMG is often used in clinics to study muscular disorders. Very thin needle electrodes can be inserted into muscle tissue, but also recordings from the skin surface can be useful, because some portion of the electrical activity produced in muscle fibers is transmitted to the body surface.

Electrooculography (EOG)

Precise control of eye movements is crucial for accurate perception of the outside world. The eyeball is an electrical dipole and its movements distort the electrical potential of neighbouring areas. Another distortion on the potential is created with the blinks, as the eyelids and other tissues surrounding the eyeball change their position, changing the electrical permeability of the space around the eye, and thus the pattern of the electrical field. The electrooculography (EOG) technique is concerned with measuring changes in electrical potential that occur when the eyes move or blinks are performed. The EOG has been useful in a wide range of applications from the rapid eye movements measured in sleep studies to the recording of visual fixations during normal perception, visual search, perceptual illusions, and in psychopathology. Studies of reading, eye movements during real and simulated car driving, radar scanning and reading instrument dials under vibrating conditions have been some of the practical tasks examined with eye movement recordings. Eye blinks are easily recorded with EOG procedures and are particularly useful in studies of eyelid conditioning, as a control for possible eye blink contamination in EEG research, and as: measures of fatigue, lapses in attention, and stress. There are also periodic eye blinks that occur throughout the waking day that serve to moisten the eyeball. Still another type of eye blink is that which occurs in response to a sudden loud stimulus and is considered to be a component of the startle reflex. The startle eye blink is muscular and is related to activity in the muscles that close the lids of the eye. Research on the eye blink component of startle has revealed interesting findings that have implications for both attentional and emotional processes.

Magnetoencephalography (MEG)

Magnetoencephalography (MEG) is the recording of the magnetic fields produced by electrical currents occurring in the brain. The acquisition of these signals is non invasive as it is performed by magnetic field sensors placed on the surface of the scalp. The first MEG recordings where done in 1968 at the University of Illinois by the physicist David Cohen using a copper coil in a shielded room to avoid the interference of external magnetic fields, including the one from the earth (Cohen, 1968). Nowadays arrays of Superconducting Quantum Interference Devices (SQUIDS) are used for sensing. Counterpoised to EEG where the mean contribution to the signal comes from extracellular volume currents, the main signal recorded with MEG devices is the one generated by synchronized intracellular axonal currents (Barth et al., 1986). About 50000 neurons with a similar orientation are required to create a signal that is detectable (Okada et al., 1983).

Functional magnetic resonance imaging (fMRI)

Functional magnetic resonance imaging (fMRI) is a non-invasive measurement of a task-induced blood oxygen level-dependent response, and has been a core methodology of cognitive neuroscience research for decades. fMRI data are traditionally analysed offline, as a “contrast image” is generated from the difference between an image from some baseline hemodynamic response and an image of hemodynamic responses in the brain during a specific task. Within the past five or so years there has been a paradigm shift in the way fMRI data are analysed, as researchers have discovered what is now referring to as the “default network”, or “resting state fMRI.” Neuroscientists have realized that there is no true baseline state of the brain, and that the patterns of brain activation during “rest” actually reveal the regions of the brain that are functionally connected when the subject is merely "thinking" or daydreaming. Resting state fMRI is analysed in the continuous, rather than trial-average domain, which may have opened the door to analyse of fMRI in a real-time mode which is what would be required for an fMRI-based BCI. Additionally, recent technological advances in the speed of data acquisition and processing have allowed for the feasibility of real-time processing of fMRI data, giving rise to the recent surge in real-time fMRI studies.

A number of studies in recent years demonstrate with real-time fMRI that subjects can achieve closed loop neuromodulation of specific brain regions. For example, (Yoo et al., 2002) use feedback from fMRI recordings to modulate the extent of activity in sensory and motor cortex. Posse et al., 2003 demonstrated a proof of principle that amygdala activation changes on a single-trial basis in response to self-induced sadness in an "open-loop" system. This was followed by a closed-loop demonstration of closed-loop neuromodulation of the anterior cingulate cortex with training (Weiskopf et al., 2003). In a later study, Caria et al., 2007 showed in a carefully controlled study that visual feedback from fMRI can be used for real-time modulation of the signals in anterior cingulate cortex. deCharms, 2005 demonstrated that real-time fMRI-based neuromodulation of the rostral ACC allowed for both healthy subjects and patients of chronic pain to control their subjective experience of pain in response to a noxious stimulus. fMRI neuromodulation for rehabilitation or functional improvement has gained considerable attention recently, as discussed in the next section.

Near-infrared spectroscopy (NIRS)

Near-infrared spectroscopy (NIRS) involves a specific band in the electromagnetic spectrum with a wavelength in the range of 780 to 2500 nm. This wavelength corresponds to the energy of molecular vibration. The selective absorption of the near-infrared energy at certain frequencies is related to specific type of molecules. When a sample of matter is exposed to near-infrared light, the spectrum of the light measured after the exposure to the sample shows a characteristic trace dependant upon the different chemical compositions of the sample. This optical method is used in a number of fields of science including physics, remote monitoring, physiology, or medicine for a variety of applications as chemical analysis or the study of the atmospheres of cool stars in astronomy, among others. It is only in the last few decades that NIRS began to be used as a medical tool for monitoring patients. The interest of BNCI in NIRS is based on the capability of this technique to obtain non-invasive measures related to the functional activity of the brain. NIRS can detect changes in the amount of oxygen content of haemoglobin. The kinetics of the oxygen concentration in the brain is related with metabolic processes that indicate major or minor energy consumption associated with neural activity. The NIRS signal can be thought as a brother of fMRI; the main advantage of the first one is that the systems are cheaper, portable and easier to use than an fMRI machine (Muehlemann et al., 2008). The main drawback is that the poor penetration of the light on the brain tissues only allows measurement of activity in cortical areas. The terms near infrared imaging (NIRI) and functional NIRS (fNIRS) are often used to refer to this technique.

Invasive BNCI sensors

Multi Electrode Arrays (MEA's)

Multi Electrode Arrays (MEA's) have been widely used in in-vitro cell cultures (non-implantable MEAs). Nowadays there is a tendency to move from in-vitro to in-vivo solutions (implantable MEAs). When used in-vivo, these sensors are often used to record Electrocorticogram (ECoG). The reason is to avoid brain damage that would occur when introducing the MEA into the deep brain. In this review we will focus on implantable MEAs (i.e. in-vivo), since those are the ones that can be used in potential BCI applications.

There are three major categories of implantable MEAs:

- *Microwire MEAs: these are usually made of stainless steel or tungsten and are useful to estimate the position of individual neurons by triangulation.*
- *Silicon-based MEAs: There are two specific models: the Michigan and Utah arrays. Michigan arrays allow a higher density of sensors for implantation as well as a higher spatial resolution than microwire MEAs. They also allow signals to be obtained along the length of the shank, rather than just at the ends of the shanks. In contrast to Michigan arrays, Utah arrays are 3-D, consisting of 100 conductive silicon needles (Maynard et al., 1997). However, in a Utah array signals are only received from the tips of each electrode, which limits the amount of information that can be obtained at one time. Furthermore, Utah arrays are manufactured with set dimensions and parameters while the Michigan array allows for more design freedom.*
- *Flexible MEAs: made with polyimide, parylene, or benzocyclobutene, provide an advantage over rigid microelectrode arrays because they provide a closer mechanical match, as the Young's modulus of silicon is much larger than that of brain tissue, contributing to shear-induced inflammation.*

Most MEAs are used for studies in animals, rather than in humans. One study shows an interesting design for an implantable microelectrode and as a proof of concept they present their results on recordings on rat brain slices (Song et al., 2005). Kipke et al., 2003 presents results of a silicon based MEA implanted in 6 living rats. 5 out of the 6 implanted MEAs were operational for 6 weeks and 4 out of 6 during more than 28 weeks. These results are optimistic regarding MEAs implants in humans. Hoogerwerf and Wise, 1994 showed a similar result with implants in guinea pig cortex. After three months in vivo, no significant tissue reaction was observed surrounding the MEAs.

Impressive work has been done by the group at Duke University, Durham, North Carolina, United States of America. Using BCI based on implantable electrodes they have shown how a Macaque monkey was able to reach and grasp using a robotic arm (Nicolelis et al., 2003).

Another interesting work describes the use of a BNCI by 5 tetraplegic subjects (Kilgore et al., 1997). By controlling the movement of their shoulder, they were able to grasp and release. It is a good example of on operative implant of a neuroprostheses but close to a muscle rather than in the brain itself.

To finalize this subsection, we would like to present a European funded project, called NeuroProbes12, to stress the relevance of the implantable electrodes in the neuroscience research field today and in the future:

NeuroProbes is a European Project aiming at developing a system platform for the scientific understanding of cerebral systems, and for the treatment of the associated diseases.

---

[12] http://naranja.umh.es/~np/index.php

“The work will enable an integrated tool that combines multiple functions to allow electrical as well as chemical sensing and stimulation of neurons. Fourteen partners, from all over Europe and both from academic and industrial worlds, form the NeuroProbes consortium. The aim of the proposed research is to develop a system platform that will allow an extremely wide series of innovative diagnostic and therapeutic measures for the treatment and for the scientific understanding of cerebral systems and associated diseases. The proposed work will enable a new integrated tool that combines multiple functions to allow electrical recording and stimulation as well as chemical sensing and stimulation. The resulting potential is expected to lead to a new era of work in the field of fundamental, scientific, as well as clinical brain research. Furthermore, the medical relevance of this work will also be demonstrated in the course of the project, specifically in the context of vision restoration of profoundly blind patients.”

Noninvasive BNCI sensors

Non-invasive sensors do not require surgical intervention to place the electrodes. In other words, the electrodes are placed outside the head. More information can be found in the summary of signals.

Biopotential/Local Field Potental transducers

A local field potential transducer is a type of hardware aimed at recording brain activity. There are two basic types: resistive contact and capacitive non-contact.

Non-polarisable metal biopotential transducers

Since these sensors are non-invasive, (i.e. surgical intervention is not required to place the sensor) and relatively cheap and easy to set up they are by far the most common sensors used nowadays in BCI designs. 83% of BCIs in Mason et al., 2007 are EEG systems, and we can assume that most of these used Ag/AgCl sensors.

Both active and passive versions of the sensors exist. There are several companies that commercialize sensors, which are very different in concept and design. For instance we have dense array EEG systems such as the ones offered by the company EGI and we also have 1 channel single electrode system such as the one offered by Neurosky.

In the research environment, several wireless systems have recently appeared, including those from g.Tec13, Neuroelectrics14 and Mindmedia15. This move to wireless systems is essential and inevitable for user friendly systems such as those that can be used at home.

[13] http://www.gtec.at

[14] http://neuroelectrics.com

[15] http://www.mindmedia.nl

Conclusions: Signals and sensors

Another line of research that could improve the ease of performing ubiquitously physiologic recordings is the development of better electrodes. Two major directions can be found in this line.

1. Dry electrodes. Some prototypes already incorporate the use of dry electrodes in unobtrusive physiologic recordings (Lin et al., 2009). Other, even more unobtrusive, technologies are appearing little by little. However, it doesn't seem reasonable to address the use of these innovative sensors until it has been thoroughly proved that, within the limiting hardware conditions –low sampling rate, few electrodes- robust results can be obtained.

2. Capacitive electrodes (see next section). The use of capacitive electrodes also promises to bring better levels of unobtrusiveness concerning hardware monitoring. The problem is that since currently the electrodes need to maintain a constant distance with the surface, the overall hardware setup is easy to apply and remove, but remains quite big. A recent example of a system for EEG monitoring using several capacitive sensors was developed (Oehler et al., 2008).

In conclusion, although current developments promise to bring new levels of usability of EEG interfaces, the main focus should go into proving that within the limitations of the hardware, the signals that can be obtained can be successfully used for biometry, and in particular in activity related scenarios. For this, specific hardware should be used if it is available, but if not then obtaining data with a general physiology sensor would be enough to adapt the data to the constraints that these portable hardware implies.

Non-contact capacitively coupled biopotential transducers

The capacitive electrodes have the enormous advantage that they do not need a direct contact with the skin. On the other hand, as the distance between the skin and the capacitive electrode has a large effect on the signal, it is complicated to place them in such a way that this distance does not change. In other word, capacitive electrodes are very sensitive to movement artifacts.

There are some more recent advances in the field of capacitive electrodes (Chi et al., 2009). This work presents a non-contact capacitive biopotential electrode with a common-mode noise suppression circuit. The sensor network utilizes a single conductive sheet to establish a common body wide reference line, eliminating the need for an explicit signal ground connection. Each electrode senses the local biopotential with a differential gain of 46dB over a 1-100Hz bandwidth. Signals are digitized directly on board with a 16-bit ADC. The coin-sized electrode consumes 285uA from a single 3.3V supply, and interfaces with a serial data bus for daisy-chain integration in body area sensor networks.

One of the most interesting developments in this field is the Electric Potential Integrated Circuit (EPIC) from the Prance group at the University of Sussex. This technology has recently been licensed by Plessey Semiconductors16 for use in medical applications such as ECG but the technology has a lot of potential for EEG also. The sensors are capable of recording biopotentials at a distance and are more robust to motion artifacts than prior art.

---

[16] http://www.plesseysemiconductors.com/epic.html

Hybrid transducers (resistive and capacitive)

The company QUASAR[17] has developed an innovative bioelectrode that uses hybrid technology: it records through normal standard resistive electrodes and at the same time it records the same signal using capacitive electrodes. The key is the electrode itself that contains several pins. These can make contact through the hair with the skin. Once the electrode is set up, the distance should remain constant, allowing the capacitive electrode, which is embedded in the electrode, to work properly.
There are two publications that describe this system (Sellers et al., 2009) and (Matthews et al., 2007).

Superconducting quantum interference device (SQUID) magnetometers

These devices are used for Magnetoencephalography (MEG). David Cohen recorded the first MEG signal back in 1968 before the invention of the SQUID (Cohen, 1986). MEG devices nowadays are based on the SQUID detectors and the signals recorded are of very good quality, i.e. comparable to EEG signals. Present-day MEG arrays are set in helmet-shaped dome that typically contain 300 sensors, covering most of the head.

This technology is non invasive, but the MEG device is very big and the sensors need to be placed in a Magnetically shielded room (MSR). The device is quite expensive and, as it has to be placed in a MSR, the cost of the use of a MEG increases. Moreover, in order to achieve high magnetic fields (up to 5 Tesla in some cases), the sensor needs to be cooled down by means of cryogenic technology. The device price is around 2 Million Euros and it is important to take into account the maintenance cost as well. These devices need to run at a very low temperature in order to produce high magnetic fields. In order to reach very low temperatures, MEG devices contain liquid helium.

In the last decade, the Prance group at the University of Sussex has been working on low noise electronic systems, with coil designs based on modern amorphous magnetic materials, to create compact induction magnetometer systems with SQUID level field sensitivity. These systems are robust, can operate at room temperature and have a large enough dynamic range to allow them to function without shielding or gradiometric balancing in most environments. While the technology has not yet been taken up by the community there is a lot of potential here for improved usability (Prance et al., 2006).

Hemodynamic transducers

Hemodynamic transducers are based on the recording of the blood flow rather than in recording the electric fields generated by the neurons. These recordings provide an insight into the brain activity because changes in blood flow and blood oxygenation (collectively known as hemodynamics) in the brain are closely linked to neural activity. This is known since 1890 (Roy and Sherrington, 1890). Several methods are used to record hemodynamic changes and all of them are non invasive. In the next sections we will review these different techniques.

Near infrared spectroscopy (NIRS)

NIRS is a much less expensive and cumbersome method than some other options, and fairly new. Functional NIRS (fNIRS) examines changes in blood haemoglobin caused by neuronal activity. Some articles have described fNIRS based BCIs (Coyle et al., 2007; Kanoh et al., 2009; Power et al., 2011). Some custom fNIRS devices have been developed and tested for BCI applications (Benaron et al., 2000; Coyle et al., 2004; Bauernfeind et al., 2008). fNIRS is also promising for scientific and medical

---

[17] http://www.quasarusa.com/hardware.html

research, such as studying brain activity that is correlated with mental artithmetic or changes in motor areas following stroke (Eliassen et al., 2008; Bauernfeind et al., 2011).

Functional Magnetic Resonance Imagery (fMRI) systems

Many BCI systems based on fMRI are done offline, i.e. no closed loop exists and no neurofeedback is done (at least in real time). Weiskopf et al., 2004 shows a BCI system that could work in real time, providing the user a neurofeedback application. Yoo et al., 2004 is also done in real time. A set of subjects is able to navigate in a 2D maze by using their thoughts.

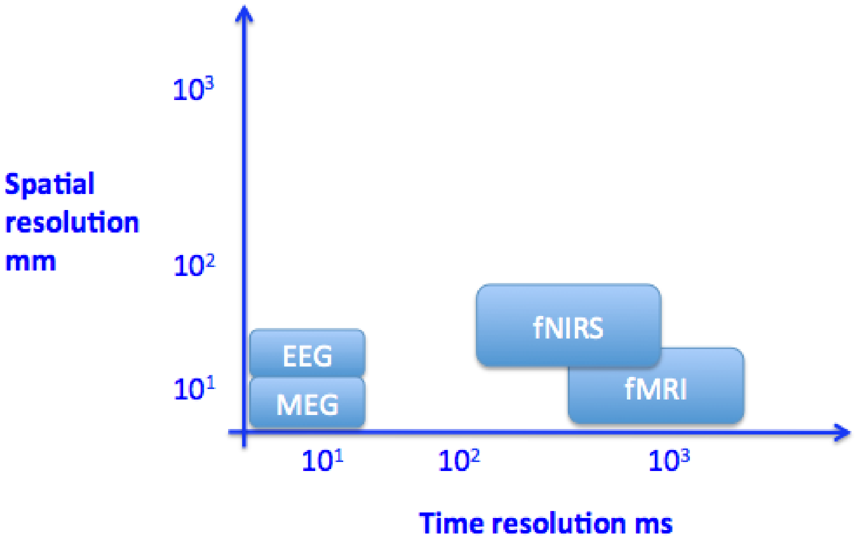


Figure 7: Spatial and temporal resolution of most common non-invasive techniques.

BNCI signal processing

Features in signal processing

The feature extraction methods regarding EEG data analysis can be separated into 2 main groups: temporal domain features and frequency domain features. Each one of these groups can be further divided in single channel type of features and synchronicity features (relations between 2 channels). Finally there are features that use more than two channels. As there are many techniques for each one of both groups, below we provide some of the main type of features used in both cases:

Single Channel Time Domain Features:

- Autoregression
- Statistical features (mean, variance, kurtosis, skewness…)
- Correlation features (autocorrelation, correlation coefficients…)
- Energy
- Entropy
- Fractal dimension

Single Channel Frequency Domain Features:

- Band Power analysis
- Wavelet related features

- Time Frequency related features
- Bump Analysis (Vialatte et al., 2009)

Synchronicity Time Domain Features:

- Mutual information
- Cross correlation
- Phase synchrony
- Synchronisation likelihood (Stam et al., 2002)

Synchronicity Frequency Domain Features:

- Coherence

Multichannel Features:

- Inverse problem resolution
- Graph theory (Complex Networks)
- Spatial Filters

For a review of features used in BCI applications, please see Lotte et al., 2007.

Computational intelligence methodologies for BNCI

Since some works in the analysed literature already undertake a general survey on BCI (Bashashati et al., 2007; Mason et al., 2007), we review further approaches based on the employment of computational intelligence (CI) techniques for Brain-Neural Computer Interfaces. Computational Intelligence, also known as Soft-Computing, is a branch of Pattern Recognition that is characterized by the combination of different complementary techniques for the implementation of real applications. In this context, CI techniques are grouped in different types of techniques, each of them with its own characteristic function (Furuhashi, 2001):

- Neurocomputing, which groups different neural network techniques.
- Fuzzy Computing, which groups fuzzy logic, fuzzy sets, and fuzzy aggregation.
- Evolutionary Computation, which is formed by Genetic Algorithms, Genetic Programming and Swarm Intelligence.
- Probabilistic Computing, which includes several statistical techniques (Duda et al., 2001).

Some authors add to this subset the research fields of Machine Learning, which in this context deals with classifier ensemble systems, and Chaos Computing, which includes some techniques based on Chaos Theory mainly employed in feature extraction.

Projection techniques for BNCI

Projection techniques used as an intermediate step between the feature extraction in a classical sense and the classification are gaining in importance in the field of BNCI. The general goal of projection is to achieve a feature representation (including or not a feature selection step) whereby the underlying data can be better discriminated. There are two types of projection techniques: unsupervised and supervised.

In this paragraph we explore unsupervised projection techniques used in BNCI. These are mostly based on the usage of independent component analysis (ICA), a technique used for separating a signal in different statistically independent components. Kachenoura et al., 2008 attempt to give an introduction to the widely used parameterization algorithms within ICA, namely SOBI, COM2, JADE, ICAR, FastICA, and INFOMAX. The application of these techniques in the BNCI field is also explained. They claim that an appropriate selection of the ICA algorithm significantly improves the BNCI performance. It is worth mentioning that most studies using ICA are based on Infomax and FastICA.

ICA is similar to the more established principal component analysis (PCA) technique. The main concept in ICA is to find out a projection matrix that separates the signals in a set (of lower cardinality than the signal set) of sources. This is done by giving the so-called unmixing matrix as an output. The components of this matrix are computed through different procedures in the aforementioned algorithms but all are based on the maximization or minimization of a fitness function characterizing the independence (in some of these functions made equal to the non-gaussianity). Not only the fitness function differentiates the algorithms, but the way it is maximized (or minimized) as well. Infomax is based on the maximization of the differential entropy, whereas FastICA maximizes the negentropy. The remaining functions maximize the so-called contrast function. It is worth mentioning that a further step differentiating these methodologies is the necessity of applying a previous standardization of the data, which is recommended in Infomax and mandatory for the rest except the ICAR.

An interesting section in the paper makes a brief survey on what is the purpose of using ICA in different types of BNCI protocols. In P300 BNCI the two goals of the ICA employment is noise filtering and signal enhancement. In Bayliss and Ballard, 1998, ICA is used in order to separate signal from eye-movement artifacts, a quite frequently employed method nowadays. The second case can be found in the seminal paper of Xu et al., 2004. This work relies on ICA to select a signal and provide a reference that maximizes the SNR in an SSVEP BCI. A further extreme reduction in the number of channels is done as well in a mu-rhythm protocol, where ICA is applied for projecting 3 channels of data into a single one. In some protocols, ICA is applied to select the signal corresponding to the frequency band of interest.

The final part of the paper analyses the performance of the different algorithms with synthetic data. The best performing algorithms are (all with very similar level) COM2, JADE, and FastICA. Infomax performance is only able to achieve similar performance with very noisy signals.

Lin et al., 2009 describes a system to detect drowsiness and distraction in drivers. Although the paper does not directly descibe a BNCI application its methodology can be of interest for such an application field. The authors systematically show the application of ICA as a preprocessing stage. Then the components are separated between signal and artifact by applying 3 different methodologies: neural network / SVM classifiers, adaptive feature selection mechanism (AFSM), and k-means. In the second case the selected features are mapped onto a drowsiness estimation through the application of a neuro-fuzzy system denoted as ICAFNN.

In spite of the works mentioned in the former paragraph, most systems use a supervised feature extraction stage. Here the most used technique is based on Common Spatial Patterns (CSP). Coyle et al., 2008 presents a 2-class EEG-based brain-computer interface (BCI), either using 2 or 60 EEG channels, which claims to be the first work in this context. Furthermore (Blankertz et al., 2008) compares the performance for BCI classification of different types of Common Spatial Pattern algorithms. The paper describes in detail different CSP filters and variants, theoretical background and implementation. It focuses particularly on single-trial classification, revealing tricks of the trade-off needed in order to achieve a powerful CSP performance. In a more recent work (Sannelli et al., 2010) the same group discusses on the importance of previously selecting EEG channels for improving the performance of CSP. Some multi-class versions of CSP have been proposed as well, such as One Versus the Rest (Wu et al. 2005).

Further supervised projection approaches, which are not based on CSP, are described in the following paragraphs. Coyle et al., 2005 presents neural networks for a BNCI application. Features in a two-class motor imagery paradigm are first extracted based on morphology of the time series and analysed with a supervised neural networks targeting class separability. Interestingly, they use two (neural networks) NNs, one per class (instead of using a multi-class approach). Lastly linear discriminant analysis (LDA) is used in the classification stage.

Coyle, 2009 proposes to use a third type of filtering for BCI processing besides the usual spatial and spectral filtering. Neural networks are employed in a prediction based preprocessing framework, referred to as neural-time-series-prediction-preprocessing (NTSPP), in an electroencephalogram (EEG)-based BNCI. NTSPP has been shown to increase feature separability by mapping the original EEG signals via time-series-prediction to a higher dimensional space. The paper implements this temporal filtering through two different approaches, a self-organizing fuzzy neural network, and a multilayer neural network trained through back-propagation. Both types of networks are trained in order to answer to particular classes in a feature space of larger dimensionality than the input one, i.e. for M channels and C classes projects into at least MxC space. After this temporal filtering, CSP is applied. Interestingly the employment of a projection space takes into account both the eigenvectors of maximal eigenvalues (as usual) but also those with minimal eigenvalues as well. The results obtained are comparable in terms of performance to these obtained at Starlab with a simpler approach.

A very recent study used a mix between Laplacian Filter and CSP (Sanelli et al., 2011). They achieve a similar performance as the one obtained using CSP, but using only 2-5 minutes of training data (compared to 20-50 minutes in the case of CSP). This study is a very good example of CI techniques applied to EEG classification.

General pattern recognition

Classification

Lotte et al., 2007 includes a very extensive review of features and classifiers for BCI. The paper focuses particularly on classification in EEG-based BCI. It briefly analyzes features, mentioning: amplitude values of EEG signals, band powers (BP), power spectral density (PSD) values, autoregressive (AR) and adaptive autoregressive (AAR) parameters, time-frequency features and inverse model-based features.

The paper discusses some theoretical aspects of classifiers such as different taxonomies. In the discussion on the curse of dimensionality the need of having 5 times so many train samples as the dimensionality of the feature vectors being classified is mentioned. This is just a rule of thumb extracted from the existing literature. We do not think this applied in all situations.

Moreover the paper justifies the application of classifier ensembles in order to reduce the variance term of the MSE, which is claimed to be particularly important in BCI data because of the variability from one acquisition set to the other. Besides this the paper makes a well-structured presentation of classifiers, distinguishing among the following groups: linear classifiers (LDA, SVM), neural networks (most focused on MLP), Bayesian (Bayesian quadratic, HMM), neighbour classifiers (KNN, Mahalanobis distance based), and classifier ensembles (different fusion strategies are discussed).

Furthermore, Lotte et al., 2007 briefly describes each of these types of classifiers. However, the description does not allow a direct implementation. The intent of trying to analyse the features of each classifier type is very interesting and targets an unsolved question in pattern recognition research. As stated by PR theorems, there is no way to assess the general superiority of one classifier over another. Therefore a classifier is better than another one just on a particular data set, which can only be assessed experimentally (Duda et al., 2001). Therefore looking at general characteristics of classifiers, as is done in the paper, is, in our opinion, the right approach for selecting one classifier over another. However, they do not go deep enough, since their analysis is not grounded on the particular features of the data set, but on high-level features such as BNCI paradigm, the synchronous/asynchronous quality, and the existence or not of comparative studies of techniques. Although they attain such a comparison in Sec. 4.2 this analysis is not grounded on measurable features of the data (except the dimensionality of the feature vectors), but on theoretical expert knowledge on BNCI data. We summarize the recommendations stated in the paper in the following.

For synchronous BNCI they report SVM, dynamic classifiers, and classifier ensembles outperforming other types of classifiers. SVM superiority is based on: robustness to outliers when being regularized (regularization is an important factor), minimization of the variance term in the error function, and robustness with respect to the curse of dimensionality. The only drawback of SVM is that they are slow, although it is possible to implement real-time BCIs with them.

The good performance of dynamic classifiers is due to its capability of capturing temporal relationships. Moreover and since they classify vectors of smaller dimensionality they are not so affected by the curse of dimensionality. The problem they have is that they classify complete time sequences (this reason is not so well understood).

Classifier ensembles are a good option because they reduce the variance term. In this context from all ensemble schemes, boosting is claimed to be excessively dependent on mislabelling data (but this does not normally occur, although the contrary is claimed in the paper).

In the case of asynchronous BNCI, dynamic classifiers lose their superiority. No tests are known using SVM or ensembles of this type of BNCI (so good opportunity for advancing the SoA). Interestingly enough they finally claim the necessity on counting with prototyping toolkits for BNCI. They recommend BCI2000.

Classifier ensembles for BNCI

One classification paradigm currently very popular is that of classifier ensembles or multi-classifier systems. This paradigm originated within the Machine Learning community that has flowed into other research areas. In this kind of system different classifiers are applied to a data set and then the results are fused through an operator. Some works that take into account the application of this paradigm in BCI applications can be found in the following paragraphs and the literature (Lotte et al., 2007). This work reflects the main advantage of using this type of approach in BCI. The employment of a classifier ensemble decreases the variance of the classification error. Since the variability of signals is rather large in BNCI systems, i.e. the main component of the error function is that of the variance; such a feature is of enormous interest.

The first approach we found in this context is this related to the BCI competition III by Shangkai Gao and colleagues (Wu et al., 2005). Although we have not found any paper in the literature describing the ensemble approach, we have analysed its structure (Cester et al., 2009). They make use of three different classifiers (LDA, fuzzy C-means, and SVM) in a bagging (Duda et al., 2001) structure. The fusion operator is the average. Performance is only acceptable when dealing with trial classification and not on a sample basis (as it would be desirable for a BCI system). Hammon et al., 2008 presents a further ensemble classifier approach for BCI. Up to 8 different types of feature extraction procedures are used. The features, which are extracted in all cases for each channel, they use are the following: 3 autoregressive coefficients of an a 3rd order approximation; power estimates in 5 spectral bands based on a filter bank; EEG signals after artifact-removal and downsampling to deliver a 10 sample sequences; a wavelet decomposition of 3 levels based on a symlet function downsampled to deliver 10 sample sequences; and 3 different feature sets based on ICA parameterized through the FastICA algorithm. Hence, a classifier stage is applied on the 8 extracted feature sets. Interestingly, they apply a multinomial logistic classification to these data sets, where the regularization parameter has been previously optimized through cross-fold validation. So we have eight classifiers, one per feature set, which are hence combined. Averaging is used as a fusion operator for the overall so-called meta-classifier. The described framework is adapted to each of the users.

We lastly comment on two recently presented frameworks. Fazli et al., 2009 tune the classifiers to subject-specific training data in a database with 45 subjects. In this case, subject-specific temporal and spatial filters form the ensemble. They claim such a system is able of real-time BCI use without any prior calibration (aka training). A slightly different approach is presented in White et al., 2010, where simulated neuron spike signals are used in a BNCI system. The work aims to use these signals for controlling a robotic arm. This data go through 3 different so-called neural decoders that map the spike signals into motor control signals. The result of these 3 neural decoders then goes through a decision fusion stage, which is implemented either with a Kalman filter or a Multilayer Perceptron. This is a slightly different approach than the other classifier ensemble approaches described herein, both from the used type of signals and the methodological point of view, but we mention it here for the sake of completeness.

CI applied to BNCI

Different classification techniques have been used in the BCI application field. They are described in the following paragraphs.

Qin et al., 2007 makes use of Support Vector Machines (SVM) for classifying data from BCI competitions into two applications for non-invasive cursor control and invasive motor imagery. They claim the resulting system, which is qualified as semi-supervised, can reduce the need for training data. This feature characterizes spatial filtering techniques.

A further work we briefly mention is in Herman et al., 2008, the performance of different spectral features, namely power spectral density (PSD) techniques, atomic decompositions, time-frequency (t-f) energy distributions, continuous and discrete wavelet approaches, for motor-imagery classification are analysed in terms of classification accuracy (CA). Different classifiers (LDA, its regularized version, and SVM with linear and Gaussian kernels) performance is analysed. CA of all classifiers is in the interval 70-74% interval.

The most complete review of classifiers for BCI applications can be found in Lotte et al., 2007. Extensive lists of different approaches can be found in this paper grouped by BCI paradigm. We review this paper in a separate section.

Analyses

Challenges

During the development of this roadmap many researchers and stakeholders provided input on the topics that concern them in BNCI research. This involved written reports, interviews, workshops and conference sessions. The following is, we hope, a fair and representative synthesis of these contributions.

The problems and challenges identified are:

Ill-defined user segmentation: As the scope of BCI application development widens we are seeing more user groups with their own sets of requirements, needs and motivations. In an effort to address this issue we have grouped users into just two categories: standard users (healthy subjects, casual gamers, disabled patients with other options) and highly motivated users (disabled patients with few alternatives, extreme gamers, and/or technophiles). Any discussion on requirements and design must take the particular user into account.

Lack of user centred design: Many BCI systems are built in labs and tested with healthy subjects. These are not realistic conditions and the approach does not lend itself to user acceptance or technology transfer in general. In order to improve user acceptance in the real world, the design of BCI systems (as with any consumer device) should be user-centred from the beginning.

Poor industrial design: As BCIs penetrate the healthy user market; they are already becoming more cosmetically appealing and user friendly. However, this remains a major challenge for assistive technology solutions where these aspects receive less attention.

Intrusive sensors: All available sensors for BCI were reviewed and their strengths and weaknesses identified. Not surprisingly, dry easy to use EEG systems are still considered the most desirable and/or likely source of an easy to use BCI sensor platform. More generally, non-invasive, nonintrusive systems are still not a reality and much remains to be done.

Performance and robustness: Problems include persistently low classification performance (<100%), inadequate robustness (across days, across different field environments and situations, across users.

New paradigms: Hybrid-BCI, Self paced BCI and Co-learning (Man and Machine) approaches are emerging as interesting themes. While providing new directions to explore such approaches also pose new problems in terms of new skill sets and lack of experience in the wider BCI community. Advances in applied neuroscience have also been discussed such as brain stimulation techniques (tCS and TMS) and their potential influence in BCI research. This line of research brings with it as many questions as it does opportunities.

Invasive vs. Non-invasive: This theme has been discussed for many years with a clear geographical divergence. Invasive work is far more widespread in the US, while non-invasive is more widespread in the EU. This was also noted in the 2007 WTEC report, showing that this is a longstanding trend. Hence, this geographic split between invasive and non-invasive research efforts is well entrenched.

Design and usability cannot be separated from any discussion of sensors and signal processing.

Clearly these problems and challenges are not all related to sensors, signals and signal processing but we feel that equally clearly a discussion of these technical issues cannot be separated from user and design aspects.

Solutions

The trend has been towards user centred design with a broad approach to problem solving. This takes the focus off the sensors and signal processing techniques in some cases and puts it squarely on the shoulders of the application developer. The tendency is now not to develop a 100% reliable BCI but to develop a 100% reliable application. Approaches include context awareness and hybrid systems that use multiple modes in order to improve robustness and accuracy.

See BrainAble[18] for an example of context aware systems or TOBI[19] for an example of multimodal systems.

In some research projects, BCI has been relegated to but one of many simple interaction modes. BCI must compete with other more established systems such as switches, eye tracking and newer ones such as sip/puff when being evaluated in a user centred design. This can mean that BCI is not chosen as the primary communication channel. See ASTERICS[20] or Brain[21] for examples of this approach.

This, however, is not the whole story as many research groups continue to push the limits of what can be done in terms of EEG feature extraction and classification, which addresses some of the underlying problems that has led to the trend described above; poor classification performance and poor robustness.

Other groups are pushing the limits of what can be done in terms of sensors. Including non-contact electric field sensors and room temperature induction magnetometer systems that rival SQUIDS and improved biocompatibility for ECoG arrays.

In terms of solutions we believe that this leads to a two-tier approach:

[18] http://www.brainable.org/en/Pages/Home.aspx

[19] http://www.tobi-project.org/

[20] http://www.asterics.eu/

[21] http://www.brain-project.org/

Short term: Focus on user-centred design and intelligent systems to maximise current SoA.

Mid term: Continued basic research on sensors, signals and signal processing.

User-centred design: The manufacturers of BCI systems should have user needs and user feedback as a top priority while designing BCI systems. This is a crucial point independent of sensors or signal processing and will often drive the choice and the number of sensors needed to achieve the desired result.

Easy to use systems & improved industrial design: This point is very much related with the preceding one. In order to reach a wider market the system should be wearable, easy and fast to set-up, comfortable, unobtrusive and wireless. Companies such as Neuroelectrics[22] and Neurofocus[23] are developing easy to use, wireless, wearable systems for research applications and Emotiv[24] and Neurosky[25] have recently released commercial wireless and easy to use EEG systems aimed at application developers and research. By following and taking advantage of this trend researchers can benefit greatly.

New paradigms: The BCI community should continue to embrace new paradigms and opportunities provided by new research. While BCI is a well-developed field researchers should not become complacent or resigned to current technical limitations in terms of sensor technology or classification performance.

Five Year View

The following is a synthesis of the views of those that contributed to the roadmap. We have tried to represent all points of view fairly and comprehensively. There are clearly recurring themes in terms of both problems and opportunities. While recognising some serious limitations in current BCI SoA the community is very optimistic.

This section serves as the conclusion to this part of the roadmap. We hope that it will influence future research and research funding decisions in an area that is, we feel, on the verge of mainstream social impact.

The following themes are likely to play a role in the evolution of BNCI research and application development over the next 5 years.

Smart Systems

[22] http://neuroelectrics.com/

[23] http://www.neurofocus.com/

[24] http://emotiv.com

[25] http://www.neurosky.com/

A Smart Systems approach shall become more and more important while becoming ubiquitous in all fields of technology. By this we mean that context awareness and intelligent multimodal systems shall play a significant role in the deployment of BCI beyond the lab (Millan et al., 2010; Allison et al., 2012. We expect that this shall be the case in many fields of technology during the next 5 years. Starlab is currently involved in the EU Technology Platform for Smart Systems Integration[26] (EPoSS) and in promoting BCI technology to this group has received very positive feedback in terms of applicability and suitability.

Through work carried out in another CSA HC2 27 we see a proliferation of Smart Systems and Pervasive Computing on the horizon. The much talked about "internet of things". More data means more context.

Dry sensor technologies

Many companies have or are about to release dry electrode solutions for BCI applications and EEG in general. In most, if not all, cases these systems are not based on advances in material science but are simply progressive improvement in low noise and low power components coupled with clever design allowing relatively stable capture of EEG without gel or conductive paste.

We expect that all manufacturers will release a dry system within the next 5 years with varying but adequate performance. A key issue will be industrial design and usability, rather than technology, as the playing field levels.

However, this is not to say that technological advances will not disrupt the field.

We foresee advances in three technology fields relevant to dry sensors:

- Capacitive sensors
- Magnetic sensors
- Ultrasound sensors

Capacitive Sensors: The EPIC sensor developed by the University of Sussex and licensed to Plessey Semiconductors (England). They are purely capacitive, dry, reusable, can be used over hair or clothes and are immune to the environmental and motion artifacts that typically plague such sensors. Currently they measure reliably in the mV range, which while sufficient for ECG is not yet sufficient for EEG.

Magnetic Sensors: Some progress is being made in high temperature SQUIDs used in magnetoencephalography (MEG), which may yet lead to a more user friendly device suitable for BCI.

Ultrasound sensors: Researcher at Heriot-Watt are developing miniaturised ultrasound sensors with integrated electronics that may pave the way for wearable US based BCI headsets. Recent work described a BCI based on transcranial Doppler ultrasound (Myrden et al., 2011).

Low cost systems

We have seen the emergence of consumer level BCI devices such as Emotiv and Neurosky. These systems are being widely used for unusual and novel applications as well as a platform for

---

[26] http://www.smart-systems-integration.org/public

[27] http://hcsquared.eu/home

hobbyists/hackers/makers. This trend will continue as the low cost encourages an extended development community that self supports. It is not clear if this business model can support hardware improvement to the point where they compete with mid-range research systems (Enobio and gTec) in terms of performance but it is not impossible.

A new tendency that has appeared in recent years regarding general hardware development is the so-called open source hardware movement. Since pieces of hardware are often expensive, open source hardware projects provide all the needed information on how to build a hardware yourself (do-it-yourself) in a cheap manner. This is the case of the OpenEEG[28] project.

They provide all the instructions needed to build your own EEG acquisition hardware. The price of the components is around 300 Euros.

Neuromodulation
Neurofeedback has been unpopular in recent years due to associations with pseudoscience. However, in many studies Neurofeedback has shown promising results for applications in skill learning performance and treatment of ADHD among others. With a possible “rebranding” as Neuromodulation we will likely see greater uptake of these techniques in the coming years.

New techniques
Recent work has demonstrated the use of Electrical Impedance Tomography as a technique for brain activation detection. Although not a new technique per se, its use in BCI has gained some momentum due to recent technology developments. This recent work has provided for the first time systems portable enough for this to be considered a viable BCI technology.

Physically closing the loop: Brain stimulation
In some senses this is the opposite of BCI, we are inputting information to the brain rather than extracting it but we believe this research offers up some interesting possibilities in terms of closed-loop systems with feedback. Techniques that are potentially wearable and therefore suitable for BCI include Transcranial Current Stimulation (both direct and alternating) and Ultra Sound.

Signal processing
In terms of signal processing it is more difficult to predict where we will find success. We know that work in applied neuroscience may provide possibilities but, for example, a new feature for control seems unlikely. What may be more likely are improvements in performance using co-learning systems (personalised classifiers that constantly update for their user). User state classification using connectivity maps, inverse solutions (tomography), inter-channel coherence and information content such as Kolmogorov complexity is a growing field often associated with affective BCI and its potential applications. This also ties into context awareness and the smart systems approach as a way to improve classification results.

A new signal processing approach has been proposed recently: Common Spatial Patterns Patches (CSPP). It can be considered as a compromise between Common Spatial Patterns (CSP) filters and Laplacian filters. This method outperforms both former techniques even when very limited calibration data is available, i.e. around 2 minutes of data, about 10 times less than CSP. This is a

[28] http://openeeg.sourceforge.net/doc/index.html

good example showing that improving the calibration time by using computational intelligence increases the willingness to use a BCI system. This customer driven innovation is a very important future direction for the BCI community, as stated in previous sections.

Summary

Challenges & Recommendations

To summarise, we highlight the following challenges and associated recommendations for future research and development.

Challenges:

- Ill-defined user segmentation – target users are not always clearly defined
- Lack of user centred design – user centred design is not widely applied
- Poor industrial design – related to the previous two challenges the design of any systems is often poor
- Intrusive sensors – all currently used systems are intrusive by consumer goods standards
- Performance and robustness – classification rates without assistance are below 100% and vary across users and scenarios

Recommendations:

BNCI is considered by some to be a mature technology that has entered the application development phase. While this is true in the sense that powerful systems are being developed using existing technology we believe that much remains to be done at a fundamental level. We therefore make the following recommendations:

- Fundamental research on sensors for non-contact, non-invasive measurement, mainly with non-EEG sensing
- Fundamental research on sensors for biocompatible, long-term invasive measurement
- Fundamental research on advanced signal processing techniques for improved performance and robustness
- Continued application of user-centred design, smart system design and multi-modal system design in order to maximise performance, utility, ease of use and robustness

New researchers entering the field should not accept the current SoA in sensors or signal processing before moving to the next phase of application development.

Devices and Applications for Disabled Users

A significant number of individuals across the globe are suffering from various motor disabilities resulting from nervous system impairments such as Amyotrophic Lateral Sclerosis (ALS), Stroke and Spinal Cord Injury (SCI). ALS is an idiopathic, fatal neurodegenerative disease of the human motor system. Recent epidemiological studies revealed that the evidence of ALS in Europe alone is 2.16 per 100.000 person-years (Mattew et al., 2011, Logroscino et al., 2011). A report from early this year by the American Heart Association (AHA) provided a stunning estimate that nearly 7.000.000 Americans above 20 have had stroke (Véronique et al., 2011). Overall stroke prevalence is estimated to be of 3.0%, with each year 795.000 people experiencing a new or recurrent stroke. This means, in United States alone every 40 seconds someone has a stroke. Paraplegia is the impairment in motor or sensory function of the lower extremities. Depending on the level and extent of spinal damage, people with paraplegia may experience some, or complete loss of sensation in the affected limbs. Quadriplegia, also known as tetraplegia, is the paralysis caused by illness or injury to a person, which result in total or partial loss of all their limbs and torso motor or sensory functions. The impairment is most often associated with sensation and motor control. However, the cognitive abilities may be intact. Estimates from 2002 show that nearly 250.000 Americans have spinal cord injury, of which 52% are paraplegic and 47% are quadriplegic. Approximately 11.000 new injuries occur each year.

> "Let us keep looking in spite of everything. Let us keep searching. It is indeed the best method of finding, and perhaps thanks to our efforts, the verdict we will give such a patient tomorrow will not be the same we must give this man today."

The symptoms and progress of ALS have been known for about a century, yet much has to be done to prevent and to improve the quality of life of people suffering from them. As Jean-Martin Charcot (1825–1893) who first described ALS, motivates: "Let us keep looking in spite of everything. Let us keep searching. It is indeed the best method of finding, and perhaps thanks to our efforts, the verdict we will give such a patient tomorrow will not be the same we must give this man today." In most cases, depending on the level of disability, these individuals are currently either assisted by a family member, nurse or use assistive technology (AT) devices. These ATs may improve mobility using robotic devices and communication capabilities using software tools. These tools most often rely either on residual muscular activity or eye blinks and eye movements.

In recent years, new research has brought the field of electroencephalographic (EEG)-based Brain-Computer Interfacing (BCI) out of its infancy and into a phase of relative maturity through many demonstrated prototypes such as brain-controlled wheelchairs, keyboards, and computer games. With this proof-of-concept phase in the past, the time is now ripe to focus on the development of practical BCI technologies that can be brought out of the lab and into real-world applications. In particular, we must focus on the prospect of improving the lives of countless disabled individuals through a combination of BCI technology with existing assistive technologies (AT).

In pursuit of more practical BCIs for use outside of the laboratories, in this mini-roadmap, we identify four application areas where these disabled individuals could greatly benefit from advancements in BCI technology, namely, “Communication & Control”, “Motor Substitution”, “Entertainment”, and “Motor Recovery”. We first review the current state of the art and possible future developments, while discussing the main research issues in these four areas. In particular, we expect the most progress in the development of technologies such as hybrid BCI architectures, user-machine adaptation algorithms, the exploitation of users’ mental states for BCI reliability and confidence measures, the incorporation of principles in human-computer interaction (HCI) to improve BCI usability, and the development of novel BCI technology including better EEG devices (Millán et al., 2010). Secondly, to promote the development of BCI technology towards its end users, discussions were coordinated among several stakeholders during the FBNCI workshop held in Laβnitzhöhe, Austria (near Graz) in 2010. These discussions were focused on problems and challenges associated with BNCI devices and applications as well as their preferred solutions. Finally, we identify the five-year view with special emphasis on developments that may address the needs of disabled users. We also provide the key recommendations that would lead to advancement of BNCI technology in general with a particular emphasis on disabled users.

State of the Art

Recently, we have been witnessing a flourishing interest in developing BNCI technologies that decode mental intentions from the user's brain and bodily signals in order to control devices (Millán et al., 2010; Allison et al., 2007; Pfurtscheller et al., 2010; Müller-Putz et al., 2011; Leeb et al., 2011). Typical applications of this technology are communication aids such as spelling devices (Birbaumer et al., 1999; Millán, 2003; Obermaier, 2003) and prosthesis and mobility aids such as wheelchairs (Galán et al., 2008). These interfaces are originally intended as assistive devices for challenged individuals who lost control over their limbs (such as patients with ALS, stroke, tetraplegia and paraplegia) in order to improve their communication, mobility and independence (Millán et al., 2010). It is interesting to note that this technology has also the potential of improving capabilities of healthy individuals by direct brain interaction (such as for space applications, where the environment is inherently hostile and dangerous for astronauts who could greatly benefit from direct mental tele-operation of external semi-automatic manipulators (Negueruela et al., 2011), and for entertainment applications like multimedia gaming (Millán, 2003 and Nijholt, 2009) and serious games.

The main focus of this mini roadmap is on the directions for further research and development on the design of devices and applications that address the needs of disabled users. Hence, in the following paragraphs we provide a brief state of the art of BNCI devices in various application areas that could greatly benefit to improve quality of life of these users. These areas have been recently reviewed in by Millán et al. (2011), and are ‘Communication & Control’, ‘Motor Rehabilitation and Recovery’, ‘Motor Substitution’, ‘Entertainment and Gaming’, and ‘Mental State Monitoring’. More recently, hybrid-BCIs along with shared control techniques have emerged. We also discuss the new idea of a synergetic combination of BNCIs with non-EEG signal based interfaces, i.e., hybrid-BCIs (hBCIs). Such an integration may improve the reliability of the interface as well as its usability, hence it would be a promising solution for bringing BNCI technologies to users (Müller-Putz et al., 2011, Millán et al., 2011). Below we provide a brief review of each of these application areas.

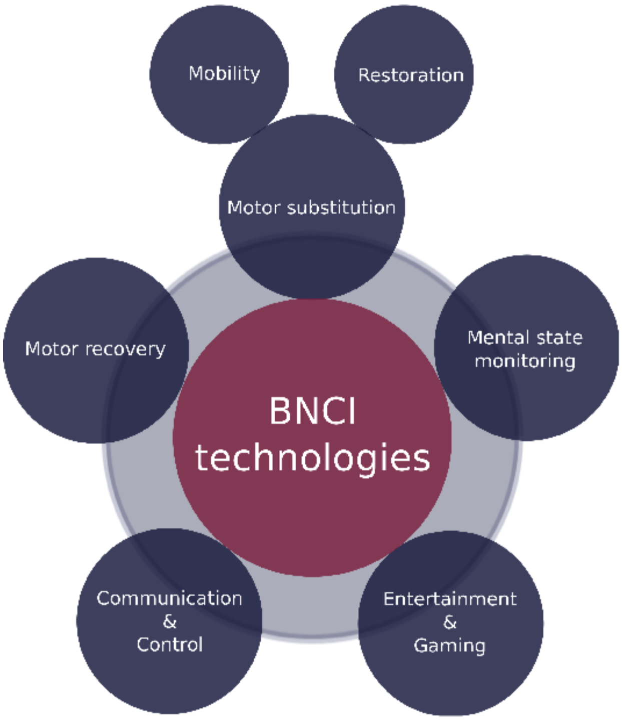


Figure 8: Application areas of BNCI technologies for disabled individuals (e.g. such as those suffering from ALS, stroke, quadriplegia and paraplegia etc.).

Figure 8 shows how BNCI technologies can be exploited as tools for functional recovery in general, and for motor recovery in particular. This technology, together with current rehabilitation methods (e.g. portable virtual reality based tools), could be used for accelerating the rehabilitation process. Another much anticipated application is the restoration of motor function. This can be achieved by using neuro-prosthetic devices (e.g., a robotic neuroprosthetic device to restore the reach and grasp functions of upper limbs). Mobility of these individuals can be enhanced by appropriate use of mobile robotic devices (e.g., brain actuated wheelchairs that could mobilize users and tele-presence robots that could help to socialize with family members). The use of BNCI technologies may sometimes be demanding. Access to the user's mental states (such as fatigue, stress and emotions) could be beneficial for enhancing the interaction with BNCI coupled devices. Finally, the entertainment and gaming application areas based on BNCI technology could reduce the dependence on the caregiver (see Millán et al., 2011).

Communication and control

A BCI could help users communicate with devices and other people.

In ALS patients, communication difficulties usually result from progressive dysarthria, while language functions remain largely intact. When this status progresses, augmentative and alternative communication (AAC) systems that can substantially improve the quality life are needed (Andersen et al., 2005). For ventilated patients, eye-pointing and eye gaze based high-tech assistive technologies have been proven to be useful. Similarly, a BCI could help users communicate with devices and other people. Professor Birbaumer established the first communication with a locked-in patient in the 90s (Birbaumer, 1999). Later, several studies aimed to show the feasibility and to compare the performances with healthy subjects using either slow cortical potentials (Kübler, 2004) or cognitive evoked potentials like P300 (Piccione, 2006) or motor imagery (MI) (Kübler, 2005). Later research has further shown that persons, even despite severe disabilities, may interact with computers by only using their brain—in the extreme case using the brain channel as a single switch, just like a hand mouse. Research on establishing communication functions were mostly focused on writing (spelling) applications and surfing (browsing) the Internet.

Several spelling devices based on the voluntary modulation of brain rhythms have been demonstrated. These systems can operate synchronously (Parra et al., 2003, Birbaumer et al., 1999) or asynchronously (Millán 2003, Millán et al., 2004, Müller & Blankertz, 2006, Scherer et al., 2004, Williamson et al., 2009, Perdikis et al., 2010). Mostly binary choices of the BCI were used to select letters, e.g. in a procedure where the alphabet was iteratively split into halves (binary tree). The big disadvantage of all these systems is that the writing speed is very slow. Particularly relevant is the spelling system called Hex-O-Spell (Williamson et al., 2009), which illustrates how a normal BCI can be significantly improved by state-of-the-art human-computer interaction principles, although the text entry system is still controlled only by one or two input signals (based on motor imagery). The principle of structuring the character locations based on an underlying language model speeds up the writing process.

Other kinds of BCI spelling devices, especially those mostly used by disabled people, are based on the detection of potentials that are evoked by external stimuli. The most prominent is the approach that elicits a P300 component (Farwell and Donchin, 1988). In this approach, all characters are presented in a matrix. The symbol on which the user focuses her/his attention can be predicted from the brain potentials that are evoked by random flashing of rows and columns. Similar P300-based spelling devices have extensively been investigated and developed since then (e.g., Allison and Pineda, 2003; Sellers et al., 2006, Nijboer et al., 2006, Silvoni et al., 2009, Piccione et al., 2006). Additionally, steady-state visual evoked potentials (SSVEPs) can be used for virtual keyboards. Either each character of the alphabet or each number on a number pad is stimulated with its own frequency and can be selected directly (Gao, 2003), or additional stimulation boxes (like arrows) are placed aside the keyboard and are used for navigating left/right/up/down and selecting the letter (Valbuena et al., 2008).

In the coming years we anticipate more varieties of brain actuated AT products designed specifically for disabled user groups.

The first application to access the Internet via the BCI was a very simple solution, by displaying web pages for a fixed amount of time ('Descartes' by Karim et al., 2006), but later browsers allowed a more flexible selection of links ('Nessi' by Bensch et al., 2007). The challenge of selecting a large amount of links with only a limited amount of BCI commands (mostly two) can be overcome by applying scanning techniques, which allow a sequential switching or auto-switching between them. Even functions like zoom in/out, scroll up/down, go back/forward can be added in the user interface and selected by the BCI via a hierarchical approach (Perdikis et al., 2010). Nevertheless, users reported that the correct selection can be quite demanding (Leeb et al., 2011b). More recently, different groups have developed Internet browsers based on P300 potentials. In the first one, all possible links are tagged with characters, and a normal character P300 matrix (6x6 matrix) was used on a separate screen for selection (Mugler et al., 2008). In a more recent approach, an active overlay was placed over the web site that elicited the P300 by directly highlighting the links. Hence, switching between the stimulation device and the browsing screen was not necessary (Riccio et al., 2011).

After nearly 20 years of research a first commercial BCI system for typing was released recently, called IntendiX® (g.tec medical engineering, Schiedelberg, Austria). The system relies on VEP/P300 potentials to use for patients with motor disabilities. In the coming years, we anticipate more varieties of brain actuated AT products designed specifically for disabled user groups.

There is a practice-gap between the training needed and received.

Motor rehabilitation and recovery

People who sustained a stroke are often left with residual motor impairments that limit the ability to engage in meaningful occupations such as self-care, work and leisure (Nilsen et al, 2010). Consequently, occupational therapists working with such individuals use procedures that aim at optimizing motor behavior to restore the occupational performance. These treatments included repeated task related constrained movements over a few hours every week demanding active engagement of patients. Although after stroke, these patients appear to benefit from substantial time spent in practice, they may not be getting enough of it. Thus, there is a practice-gap between the training needed and received. This inactive period may account for reduced sensorimotor capacity. This practice-gap can be reduced by mentally exercising goal-oriented actions in addition to the physical practice or singuarly when physical practice is not possible.

Recent work by Nilsen et al. (2010) reviewed approximately 25 years of literature on motor rehabilitation of stroke patients. They determined whether mental practice is an effective intervention strategy to remediate impairments and improve upper-limb function after stroke. Their results suggested that mental practice when combined with physical practice improves upper-limb recovery. This may be due to the commonalities in the neural substrates involved in imagined and executed movements. They also suggested taking precautions on generalization issues of this strategy and further research warranting who will benefit from training and the most effective protocols etc.

The effectiveness of these protocols could be enhanced by direct feedback of the activity of sensory-motor areas, during occupational therapy that involve mental practice or physical practice or both. The BCIs that use sensory motor rhythms are the best candidates for such purposes. Moreover, the BCI feedback may help to reduce maladaptation of the brain areas as compared to simple motor imagery alone.

The use of BCI protocols to promote recovery of motor function by encouraging and guiding plasticity phenomena occurring after stroke (or more generally after brain injury) has been proposed recently (Jeannerod et al., 2001, Nilsen et al. 2010). Discussion is currently underway over several factors including: the extent to which patients have detectable brain signals that can support training strategies; which brain signal features are best suited for use in restoring motor functions and how these features can be used most effectively; and what are the most effective BCI approaches for BCIs aimed at improving motor functions (for instance, what guidance should be provided to the user to maximize training that produces beneficial changes in brain signals). Preliminary findings suggested that event-related EEG activity time-frequency maps of event-related EEG activity and their classification are proper tools to monitor motor imagery related brain activity in stroke patients and to contribute to quantify the effectiveness of motor imagery (Biasiucci et al., 2011, Silvoni et al., 2011, Pichiorri et al., 2011, Ang et al., 2011). Preliminary studies on stroke patients using BCI found that the best signals were recorded over the ipsilateral (unaffected) hemisphere (Buch et al., 2009). Finally, the idea that BCI technology can induce neuroplasticity has received remarkable support from the community based on invasive detection of brain electrical signals (Millán et al., 2010).

> “Use a BCI to get rid of it!”

The continuous monitoring of mental tasks execution based on BCI techniques could support the positive effects of standard therapies not only for the functional restoration of the patient but also for the therapists as a measure to track the sensory motor rhythms. These BCI based rehabilitation strategies could be complimented by the use of practical virtual reality techniques as well as robotics to effectively reduce the practice-gap.

As Professor Millán suggests to stroke patients, “Use a BCI to get rid of it!” That means a patient can stop using a BCI soon after she/he recovered functionally. Extensive research is still needed for filling the missing knowledge of functional recovery and retention by BCI intervention. Therapeutic studies involving a large motor disabled population with various levels of functional loss are needed. Note that the recovery process in some patients may be quicker than others. A longer time frame is needed for completion of such studies.

Motor substitution

The restoration of grasp functions in spinal cord injured patients or patients suffering from paralysis of upper extremities typically rely on Functional Electrical Stimulation (FES). In this context, the term neuroprosthesis is used for FES systems that seek to restore a weak or lost grasp function when controlled by physiological signals. Some of these neuroprostheses are based on surface electrodes for external stimulation of muscles of the hand and forearm (Ijzermann et al., 1996, Thorsen et al., 2001, Mangold et al., 2005). Others, like the Freehand® system (NeuroControl, Cleveland, US), uses implantable neuroprostheses to overcome the limitations of surface stimulation electrodes concerning selectivity and reproducibility (Keith et al, 2002), but this system is no longer available on the market.

Pioneering work by the groups in Heidelberg and Graz showed that a BCI could be combined with an FES-system with surface electrodes (Pfurtscheller et al., 2003). In this study, the restoration of lateral grasp was achieved in a spinal cord injured subject. The subject suffered from a complete motor paralysis with missing hand and finger function. The patient could trigger sequential grasp phases by imagining foot movements. After many years of using the BCI, the patient can still control the system, even during conversation with other persons. The same procedure could be repeated with another tetraplegic patient who was provided with a Freehand® system (Müller-Putz et al., 2007). All currently available FES systems for grasp restoration can only be used by patients with preserved voluntary shoulder and elbow function, which is the case in patients with an injury of the spinal cord below C5. So neuroprostheses for the restoration of forearm function (like hand, finger and elbow) require the use of residual movements not directly related to the grasping process. To overcome this restriction, a new method of controlling grasp and elbow function with a BCI was introduced recently (Müller-Putz et al., 2007). Thereby a low number of pulse-width coded brain patterns are used to control sequentially more degrees of freedom (Müller-Putz et al., 2010).

BCIs have been used to control not only grasping but also other complex tasks like writing. Millán's group used the motor imagery of hand movements to stimulate the same hand for a grasping and writing task (Tavella et al., 2010). Thereby the subjects had to split his/her attention to multitask between BCI control, reaching, and the primary handwriting task itself. In contrast with the current state of the art, an approach in which the subject was imagining a movement of the same hand that he is controlling through FES was applied. Moreover, the same group developed an adaptable passive hand orthosis, which evenly synchronizes the grasping movements and applied forces on all fingers (Leeb et al., 2010). This is necessary due to the very complex hand anatomy and current limitations in FES-technology with surface electrodes, because of which these grasp patterns cannot be smoothly executed. The orthosis support and synchronize the movement of the fingers stimulated by FES for patients with upper extremity palsy to improve everyday grasping and to make grasping more ergonomic and natural compared to the existing solutions. Furthermore, this orthosis also avoids fatigue in long-term stimulation situations, by locking the position of the fingers and switching the stimulation off (Leeb et al., 2010).

The current state of these FES based movement based restoration techniques are still evolving, which in the coming years may extend the number of restoration functions as well as to incorporate improved usability and aesthetics.

Towards control of mobility: Practical BCIs based on shared control techniques

Another area where BCI technology can support motor substitution is in assisting user's mobility. Users could move directly through brain-controlled wheelchairs or by mentally driving a telepresence mobile robot—equipped with a camera and a screen—to join relatives and friends located elsewhere and participate in their activities.

Driving a wheelchair or a robot in a natural environment demands a fine and quickly responding control signal. Unfortunately BCIs are limited by a low information transfer rate, because of the inherent properties of the EEG. Therefore the requirements and the skills don't match at all. Nonetheless, researchers have demonstrated the feasibility of mentally controlling complex robotic devices from EEG. A key factor to do so is the use of smart interaction designs, which in the field of robotics corresponds to shared control (Flemisch et al., 2003, Vanhooydonck et al., 2003, Carlson & Demiris, 2008). In the case of neuroprosthetics, Millán's group has pioneered the use of shared control that takes the continuous estimation of the operator's mental intent and provides assistance to achieve tasks (Millán et al., 2004, Galán et al., 2008, Carlson et al., 2012).

Generally in a shared autonomy framework, the BCI's outputs are combined with information about the environment (obstacles perceived by the robot's sensors) and the robot itself (position and velocities) to better estimate the user's intent. Some broader issues in human–machine interaction are discussed in Flemisch et al., 2003, where the H-Metaphor is introduced, suggesting that interaction should be more like riding a horse, with notions of "loosening the reins", allowing the system more autonomy. Shared autonomy (or shared control) is a key component of future hybrid BCI systems, as it will shape the closed-loop dynamics between the user and the brain-actuated device so tasks can be performed as easily as possible and effectively. As mentioned above, the idea is to integrate the user's mental commands with the contextual information gathered by the intelligent brain-actuated device, so as to help the user to reach the target or override the mental commands in critical situations. In other words, the actual commands sent to the device and the feedback to the user will adapt to the context and inferred goals. In such a way, shared control can make target-oriented control easier, can inhibit pointless mental commands (e.g. driving zig-zag), and can help determine meaningful motion sequences (e.g., for a neuroprostheses). A critical aspect of shared control for BCI is coherent feedback —the behavior of the robot should be intuitive to the user and the robot should unambiguously understand the user's mental commands. Otherwise, people find it difficult to form mental models of the neuroprosthetic device.

Furthermore, thanks to the principle of mutual learning, where the user and the BCI are coupled together and adapt to each other, humans learn to operate the brain-actuated device very rapidly, in a few hours normally split between a few days (Millán et al, 2008). Examples of shared control applications are neuroprostheses such as robots and wheelchairs (Millán et al., 2009, Millán et al., 2004, Galán et al., 2008, Tonin et al., 2010, Vanhooydonck et al., 2003), as well as smart virtual keyboards (Müller & Blankertz, 2006, Wills et al., 2006, Williamson et al., 2009) and other AT software with predictive capabilities. Underlying all assistive mobility scenarios, there is the issue of shared autonomy. The crucial design question for a shared control system is: who —man, machine or both— gets control over the system, when, and to what extent?

The crucial design question for a shared control system is: who —man, machine or both— gets control over the system, when, and to what extent?

Tele-presence robot controlled by individuals with motor-disabilities

Applying the above-mentioned principle of shared control allows BCI subjects to drive a mobile tele-presence platform remotely in a natural office environment. Normally this would be a complex and frustrating task, especially since the timing and speed of interaction is limited by the BCI. Furthermore, the user has to pay attention to the BCI and the tele-presence screen and also remember where the place is and where he wants to go. Many difficulties emerge when developing such systems, from the variability of an unknown remote environment to the reduced vision field through the control camera. In this scenario, shared control facilitates navigation in two ways. On the one hand, shared control takes care of the low-level details (such as obstacle detection and avoidance for safety reasons). On the other hand, it can interpret the user's intentions to reach possible targets (such as persons or objects the user wants to approach).

Although the whole field of neuroprosthetics targets disabled people with motor impairments as end-users, all successful demonstrations of brain-controlled robots or neuroprosthetics, except (Müller-Putz et al., 2005), have been actually carried out with either healthy human subjects or monkeys. In recent work, Tonin et al., 2011 report the results with two patients (suffering from myopathy and spinal cord injury) who mentally drove a tele-presence robot from their clinic more than 100 km away and compare their performances to a set of healthy users carrying out the same tasks. Remarkably, the system functioned effectively although the patients had never visited the location where the tele-presence robot was operating.

Investigations on such tele-presence robotics would lead to products that could leverage the social involvement of severely disabled patients with their family or friends directly from their bed.

Assisting mobility: BCI controlled wheelchair

> If we want to bring the wheelchair to patients, the additional equipment should not cost more than the robotic wheelchair itself.

In the case of brain-controlled robots and wheelchairs, Millán's group has pioneered the development of a shared autonomy approach within the European MAIA project. This research effort estimated the user's mental intent asynchronously and provided appropriate assistance for wheelchair navigation, which greatly improved BCI driving performance [Galán et al., 2008, Millán et al., 2009, Tonin et al., 2010]. Although asynchronous spontaneous BCIs seem to be the most natural and suitable alternative, there are a few examples of synchronous evoked BCIs for wheelchair control (Iturrate et al., 2009, Rebsamen et al., 2010). The systems are based on the P300, so the system flashes the possible predefined target destinations several times in a random order. The stimulus that elicits the largest P300 is chosen as the target. Then, the intelligent wheelchair reaches the selected target autonomously. Once there, it stops and the subject can select another destination – a process that takes around 10 seconds. The main limitation is the fact that no interaction or interruption is possible between selecting the target and reaching it. Therefore it is not possible to stop halfway down and change its mind to a new target location. In most of these BCIs, the control is based on low throughput signals; hence a shared control approach is necessary to control a complex system such as a wheelchair.

Millán's group's approach is not a P300 based BCI, but a motor-imagery based BCI. Thereby, the participants were able to send left/right steering commands to the wheelchair at their own pace. The BCI was also combined with a shared control paradigm, so that the wheelchair pro-actively slows down and turns to avoid obstacles as it approaches them. Using a computer vision algorithm such as those described in (Carlson et al., 2010, Carlson et al., 2012), they constructed a local 10 cm resolution occupancy grid (Borenstein et al., 1991), which was then used by the shared control module for local planning. They also implemented a docking mode, additionally to the obstacle avoidance. These algorithms can compensate for the low information throughput from the BCI system. Interestingly, the computer vision part of their shared control paradigm relied just on cheap webcams and was not based on an expensive laser rangefinder. Such a strategy will facilitate the development of affordable and useful assistive devices. If we want to bring the wheelchair to patients, the additional equipment should not cost more than the robotic wheelchair itself.

Mental state monitoring

Another area of recent research is in the recognition of the user's mental states (mental workload, stress level, tiredness, attention level) and cognitive processes (e.g., awareness of errors committed by the BCI) will facilitate interaction and reduce the user's cognitive effort by making the BCI assistive device react to the user. For instance, in case of high mental workload or stress level, the dynamics and complexity of the interaction will be simplified, or the system will trigger the switch to stop brain interaction and move on to muscle-based interraction. As another example, in the case of detection of excessive fatigue, the tele-presence mobile robot or wheelchair will take over complete control and move autonomously to its base station close to the user's bed. Pioneering work in this area deals with the recognition of mental states (such as mental workload described in Kohlmorgen, et al, 2007), attention levels (Hamadicharef et al., 2009) and fatigue (Trejo et al., 2005) and cognitive processes such as error-related potentials (Blankertz et al., 2003, 2010; Ferrez & Millán, 2005, 2008) and anticipation (Gangadhar et al., 2009) from EEG. In the latter case, Ferrez & Millán (2005 & 2008) have shown that errors made by the BCI can be reliably recognized and corrected, thus yielding significant improvements in performance. Recently the areas of cognitive monitoring and implicit human-computer interaction are also phrased as passive BCI's in the literature (George et al., 2010, Zander et al., 2011).

Entertainment and gaming

Entertainment applications that enable activities during leisure time, such as browsing social networks on the Internet, browsing personnel or family picture libraries and gaming would enhance the patient's mental health. This application had a lower priority in BCI research and development, compared to more functional activities such as basic communication or control tasks. Several studies explored BCIs for controlling games (Lalor et al., 2005; Nijholt et al., 2005; Millán et al., 2003; Krepki et al., 2007; Tangermann et al., 2008; Finke et al., 2009; Nijholt et al., 2009; Pineda et al., 2003) and virtual reality (VR) environments (Bayliss, 2003; Lécuyer et al., 2008; Leeb et al., 2007; Leeb et al., 2007b; Leeb et al. 2006; Lotte et al., 2010; Scherer et al., 2008, Ron-Angevin et al., 2009). Importantly, patients have mentioned entertainment as one of their needs, although it is indeed a need with a lower priority (Zickler et al., 2009). Moreover, BCI's may be used to assess the user's cognitive or emotional state in real-time and use that information to opportunely adapt human-computer interaction (Nijholt, 2009; Zander et al., 2011). A recent overview of HCI, BCI and Games can be found in (Plass-Oude et al., 2010).

Hybrid BCI (hBCI)

Despite the progress in BCI research, the level of control is still very limited compared to natural communication or existing AT products. Practical Brain-Computer Interfaces for disabled people should allow them to use all their remaining functionalities as control possibilities. Sometimes these people have residual activity of their muscles, most likely in the morning when they are not exhausted. In such a hybrid approach, where conventional AT products (operated using some residual muscular functionality) are enhanced by BCI technology, leads to what is called a hybrid BCI (hBCI).

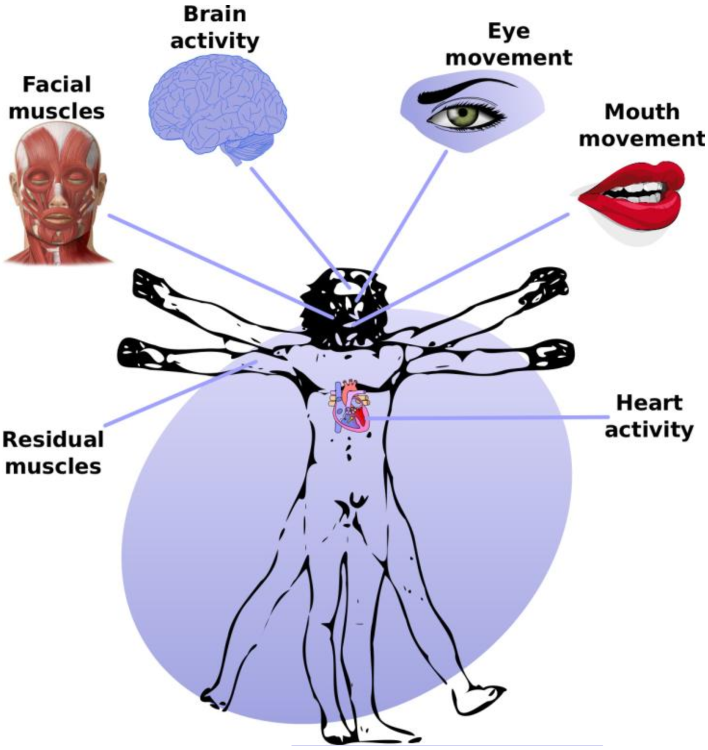


Figure 9: The concept of hybrid BCI (hBCI): One way of building the hBCI system using purely brain signals. The user's intention can be inferred from various cognitive states, which could be combined to improve the overall interaction performance. For example, a hBCI can be built with a combination of motor imagery recognition with error potential detection. Other hBCI systems can be built by combining brain activity with other physiological signals such as EMG of residual muscular activity (body muscles, facial muscles, eye muscles) from eye movements (EOG and/or eye-tracking can be used) and heart activity (i.e., using ECG).

As a general definition, a hBCI is a combination of two or more different input signals including at least one BCI channel (Millán et al, 2010, Pfurtscheller et al, 2010, Allison et al, 2010, 2012; Müller-Putz et al, 2011). Thus, it could be a combination of two BCI channels or a combination of a BCI and other biosignals (such as electromyography (EMG), etc.) or special AT input devices (e.g., joysticks, switches, etc.). There exist a few examples of hybrid BCIs. Some are based on multiple brain signals alone. One such hBCI is based upon the combination of motor imagery based BCI with error potential (ErrP) detection and correction of false mental commands (Ferrez & Millán, 2008). A second example is the combination of motor imagery with steady state visual evoked potentials (SSVEP) (Allison et al, 2010; Brunner et al, 2010, 2011). Other hBCIs combine brain and other biosignals. For instance, Scherer et al. (2007) combined a standard SSVEP BCI with an on/off switch controlled by heart rate variation. Here the focus is to give users the ability to use the BCI only when they want or need to use it. Alternatively, and following the idea of enhancing people's residual capabilities with a BCI, Leeb et al. (2011) fused EMG with EEG activity, so that the subjects could achieve a good control of their hBCI independently of their level of muscular fatigue. Finally, EEG signals could be combined with eye gaze (Danoczy et al, 2008). Pfurtscheller et al. (2010) recently reviewed preliminary attempts, and feasibility studies, to develop hBCIs combining multiple brain signals alone or with other biosignals. Millán et al. (2010) review the state of the art and challenges in combining BCI and assistive technologies.

Analyses

BNCI technology is flourishing and has the potential of spreading into society by addressing the needs of various user groups under different application scenarios ranging from AT and rehabilitation tools for disabled people to tools for augmenting capabilities of healthy users and to the entertainment sectors. In the past, several prototypes have been demonstrated by a number of groups across the globe. The number of these research groups and industrial partners (stakeholders) are increasing every year. However, due to diverse interests, the lack of standards, common platforms and validation standards is likely to dampen the development of BNCI technologies in the right direction. Furthermore, synergetic collaboration across various stakeholders working for different user groups is necessary to bring BNCI products from the lab to user's home. More specifically, this mini-roadmap is aimed at preparing recommendations for bringing this technology to the disabled user group to use in daily living conditions.

Apart from these coordination related challenges, there are other challenges associated with the reliability of BCI technology, market entry and disabled user's needs. To understand better these issues, we conducted a 3 day workshop with various stakeholders across the world from well known BCI teams and industrial partners near Graz (Laβnitzhöhe), Austria in the year 2010. During this workshop, we discussed urgent and long term problems and challenges in bringing BNCI devices to address the needs of disabled users. Several interesting issues emerged in this regard, and in the following sections, we list a few important ones along with preferred solutions. Note that these issues were discussed again with the remaining FBNCI consortium and key stakeholders to ensure general accord.

Challenges

BNCIs and ATs: The AT products (e.g. eye-tracking, mouth-mouse control etc.) are already in the market. Can BNCI products replace existing ATs? Or can BNCI technologies complement existing ATs? What would be a fair strategy that ensures sustained R&D of the young BNCI technologies to cope up with the competition from the standard ATs?

Invasive or noninvasive: The solutions based on invasive and non-invasive fall at the different sides of a risk-cost-performance triangle. While the non-invasive approaches are cheaper and easier, they suffer from the problem of reliability due to very low SNR (signal-to-noise ratio). On the other hand, invasive approaches are expensive and associated with the need of surgical procedures, which are risky but provide better SNR. Which approaches are suitable for a given user group and under what circumstances?

User groups: BNCIs have the capability of integrating into many application sectors for both disabled and healthy user groups. The corresponding user groups range from healthy individuals to patients who have suffered from stroke or other neurological conditions. What is the appropriate mapping between user groups and applications? Which combinations should be favored? Which medical applications should be immediately favored to address the needs of disabled people?

Limitations of BCI technology: Current BCIs not only suffer from low throughput, but also other usability issues, such as poor reliability, inadequate automation of BCI devices, unsupervised hardware and electrode failures, the need for expert support and the preparation time required for setting up a BNCI. Which issues have to be tackled to bring BCI applications to the standards of usability? In addition, due to lack of standards in the current R&D community and associated industries, portability of software & hardware is a big issue. How can the community ensure portability for effective development?

Reliability-Speed tradeoff: Not all the users are able to control BNCI devices. This inability was coined as ‘the BCI illiteracy’ or ‘BCI proficiency’ problem. In addition, the subjects who have a decent control show variability in the performance across sessions. What are the key factors behind this reliability-speed tradeoff?

Usability issues: Dry or wet? Reliability vs. setup time! The setup time for wet electrodes takes more than 20 minutes. It is important to note that a typical occupational therapeutic session lasts over 45 to 50 minutes (in commercial terms, ‘time is money’). In such scenarios the dry electrodes are promising for reducing the set-up time drastically. However, are the dry electrodes as reliable as the wet in respect of acquiring brain activity?

Standards and certifications: The lack of standardization across the R&D teams and associated industrial stakeholders due to their disparate interests could be detrimental for the efficient exchange of software, hardware and applications. What strategies have to be taken to ease all the stakeholders to go through this tough process?

Case scenarios for the market entry: Which is the best strategy for bringing BNCI technology into the market for sustained business that nurtures the R&D as well?

Solutions and trends

BNCIs and ATs: A direct comparison of the market potential of the young BNCI technology with more matured ATs would be harsh. Currently, BNCIs have still some constraints of low throughput, cumbersome hardware setup, software issues and preparation related challenges. The comparison of performances of the BNCI’s with ATs would be unfair, and even more, disrupt the related R & D. Therefore, BNCIs cannot and must not endeavor to replace the available AT solutions within the next several years. Furthermore, BNCIs offer an alternative and novel way to control devices and applications that can help the users complete various tasks. For example, if a patient already relies on an AT device, the BNCI could engage him/her with other additional activities such as picture browsing. The BNCI technology based rehabilitation and entertainment devices could be deployed to utilize the practice-gap for stroke patients. Yet another trendy deployment of BNCI devices is in a synergetic integration with conventional ATs (e.g. based on muscular activity), via a so called ‘hybrid-BCI’ framework.

Figure 10: Invasive or non-invasive? A correct decision for a given user depends on the trade-off among several factors and risk, cost and performance are the key ones.

Invasive or Noninvasive: Both invasive and non-invasive approaches have their own advantages and disadvantages. The adaption of one of the technologies for a given user must be based on a good balance between the needs and risks-cost-performance triangle (see Figure 10). An invasive approach could be an option when non-invasive approaches fail to address the needs of a given user. Nevertheless, we should be aware that it is still unclear what the full potential of non-invasive approaches is. Furthermore, a comparison of invasive versus non-invasive is user and task dependent. Many different potential users, such as healthy users, elderly and patients with residual motor control are not targets for invasive solutions. To have a complete assessment of both approaches' potential, the better solution would be to encourage research groups that work hand-in-hand towards addressing the needs of the users. As when the ethical perspectives improve as well as risk factors reduce, invasive BCIs may be helpful to more users.

User groups: BNCIs have the potential to enter into many application segments. However, not all segments may lead to sustained R&D of BNCI. Furthermore, a few segments have great market potential (e.g., gaming, neuro-marketing etc.) but can be disruptive, interesting only for an individual investor rather than for the whole society. Consider the example of a recent video demonstrating controlling a real car with the Emotive electrode set[29]. Although, the video claims to report a mind control technology, it is unclear to what extent the electrode-set records brain activity as compared to facial muscular activity. Yet another example is the MindFlex™ gaming toy from Mattel Inc., which claims to use the brain's power in controlling a ball. However, Prof J. D Haynes from Germany demonstrated in a TV interview that the game could be controlled even with a mannequin or a sponge[30]. Often, BNCI gaming products are toys and use very small number of electrodes, which may not necessarily rely on the brain signals alone. Hence, due to overpromise, media hype and fragile nature, the development of such products may not necessarily benefit the development of products

---

[29] http://www.youtube.com/watch?v=iDV_62QoHjY

[30] See YouTube video demonstration http://www.youtube.com/watch?v=HsmLA9PqTGM

for disabled user group. The medical products that aim to reach disabled persons in the home and hospital require more reliability, as well as standards and certification.

The development of BNCI technologies was originally intended to offer ATs for disabled users. In the past years, several research labs have demonstrated various prototypes that can offer communication and control capabilities and the potential for rehabilitation. These prototypes were restricted to the laboratory, but recently, a few groups began testing in collaboration with hospitals to better understand the needs of the disabled users. However the current state of these prototypes is premature (e.g., cumbersome hardware & software set-up, need for an expert etc.), and need some more developmental cycles to fully enter an appropriate market as well as the disabled user's daily living areas.

For these developmental cycles, a special emphasis has to be made for users with severe disabilities who could greatly benefit from BCI technologies. This means that the early involvement of patients in the design of appropriate devices and applications is critical. Furthermore, the feedback and evaluation from the early users has a strong impact on the possible future acceptance. Finally, if applicable, the industrial perspectives should be also embedded in the design. Table 1: What is the best-case scenario for the development of BCI devices/applications that could benefit patients? The scenario must consider 'which are the short term directions of research that could lead to the research and development of products for patients.'

Scenario	Currently Preferred?
Completely-locked in patients	Not preferred
Motor-rehabilitation	Preferred
Cognitive impairment	Preferred
Monitoring mental state	Preferred
Healthy elderly	Varies with application

Table 1: What is the best-case scenario for the development of BCI devices/applications that could benefit patients? The scenario must consider 'which are the short term directions of research that could lead to the research and development of products for patients.'

As a long-term goal, the BNCI devices should be capable of helping completely locked-in patients to communicate with the world. However, the challenge associated with these patients is beyond the reach of current technology, mainly due to the challenges associated with them (i.e., current BNCI devices are not 100% perfect, and due to unavailability of ground truth from these patients it would be extremely difficult for the validation). Moreover, complete locked in syndrome could lead to "extinction of thought", which would preclude any BCI use (Kübler and Birbaumer, 2008). As a short-term goal, other reachable user groups have to be considered, such as stroke patients, quadriplegia and paraplegia. The BNCI devices for motor-rehabilitation must be favored due to the availability of scientific knowledge and ground truth.

For patients with cognitive impairments (e.g. such as those in autism), BNCI technology could offer a neuro-feedback based therapy but with feedback of top-down processing such as anticipation, error processing and emotions (Pineda et al., 2008). Since the neuro-feedback market is already established and big, it would ease the market entry of BNCI and its R&D by such application areas.

Another area of recent research is in the recognition of the user's mental states (such as mental workload, stress level, tiredness attention level, etc…) and cognitive processes (e.g., awareness of errors made by a BNCI). Such monitoring will facilitate interaction and reduce the users' cognitive effort by making the BNCI assistive/rehabilitation device react to the user mental states. Development of devices with such capabilities will definitely benefit almost all user groups, including many groups of disabled users.

There had been suggestions in developing BNCI tools for brain-gym like applications for elderly (other than disabled individuals). However these tools will be similar to entertainment and toy like gaming devices for healthy user group. The needs of this user group are different from that of disabled users. Hence, the development in this direction may not fully support the disabled users.

Limitations of BCI technology: The usability of current BNCI devices is far from perfect. The technology suffers from long preparation and setup times. The electrode caps are not aesthetic enough to be worn without being the center of attention. Research must be carried out to enhance the usability of hardware and software so that the whole device will be "plug and play". The operation must cope up with the needs of a layperson who does not have any technical background. The following directions of research should be favored:

1. Development of a reliable and cosmetically appealing dry electrode set.
2. Work directly with users, consider user evaluations and user-centered design principles.
3. Development of software and hardware that is almost invisible to end-users (i.e., development of a transparent BCI).

Reliability-Speed tradeoff: BNCIs suffer low throughput due to inherent noise associated with the measurement of signals non-invasively (i.e. low SNR). However, from discussions with experienced stakeholders (working with patients) we found that the reliability is more important than speed. The current day BNCI devices are not very reliable. In addition, different groups report that some (~20%) of healthy subjects and patients could not gain proficiency in controlling a BNCI device (Guger et al., 2003, Kübler and Müller, 2007; Allison et al., 2010; Allison and Neuper, 2010; Blankertz et al., 2010; Vidaurre et al., 2010). This inability to use a BCI was called the "BCI illiteracy" or "BCI proficiency" problem. In addition, even subjects who have good control of a BCI device show variable performance over time and days. The roots of the problem could be the non-stationary nature of brain signals. New directions have to be taken in solving this issue, by exploring signal processing and machine learning techniques (e.g., adaptation, mutual learning etc).

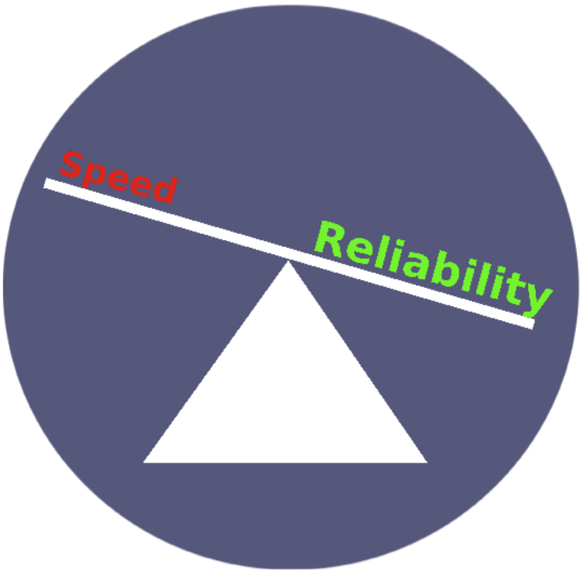


Figure 11: Depending on the applications, reliability and speed may play different roles. For example, in the case of virtual keyboard applications for typing messages, both the reliability and speed are unlikely as critical because errors do not lead to any danger. Whereas, in applications such as a prosthesis or a wheelchair, reliability but also speed are both key issues!

However, not all applications require similar needs of reliability and speed (see Figure 11). For example, a virtual keyboard for typing a message is unlikely to be very risky if the reliability is low. The speed has to be just enough for a user to be able to convey a message in a certain time limit. Language models and context can help enhance the overall typing performance even when the reliability of the BCI is low. However, applications like a prosthetic arm for self-feeding or a wheelchair require a different balance of reliability and speed, due to the associated risk. Standards could be derived based on the risk factors for each of these application scenarios. Furthermore, as discussed in the state of the art section, shared control techniques and hBCI approaches must be favored to ensure reliability.

Usability issues: Dry or wet? And reliability vs. setup time! The gel based electrode arrangement offers a decent signal quality at the cost of long setup times. Recently, a few systems from different companies (eg. gtec's “g.SAHARA”, Starlab's “Enobio”, and systems from NeuroSky and Quasar) develop dry electrodes to replace the wet electrodes, which could not only drastically decrease setup time, but also have greater aesthetic appeal. Recently, water-based electrodes were developed which do not require washing after use. However, these electrode setups need to be validated to ensure the signal quality to be similar to the gel-based electrodes. The best-case scenario would be to have dry electrodes that are as good as wet electrodes in terms of performance and signal quality as well as aesthetics and usability. Both hardware and software should be designed in such a way that a BNCI device must be mobile and should be able to connect to any conventional assistive technology devices (e.g., a powered wheelchair). The interface should be designed in such a way that a non-computer specialist (e.g., a family member or care giver) should be able to operate it easily and quickly. Furthermore, in hospital like environments these devices should be compatible with existing treatments (e.g., ventilator support).

Standards and certifications: The lack of standards across various R&D teams across the globe and associated industrial stakeholders leads to poor exchangeability of the outcomes (e.g., hardware, software and files and formats). There is a clear need for deriving standards to facilitate the rapid growth of R&D. These standards could cope up with the existing standards of ATs. For example, every BNCI product should have same interface protocol and should be able to connect to any device such as a Television (see a recent proposal by Müller-Putz et al, 2011). One such successful industrial standard is the 'Universal Serial Bus (USB)' developed in mid 90s, which lead to a communication protocol that is standard across computers and various electronic devices. We expect a similar level of standardization for biomedical devices in general and BNCI devises in particular. Standardized benchmarking tests could not only help cross-platform comparisons but also make it more difficult to misrepresent the capabilities of a BNCI system.

Case scenarios for the market entry: The BNCI industry should not have the strategy of entering big market first and filling in the remaining markets later on. As an example, consider a market such as the games industry, which has a big share. Entering such a market could bring substantial revenue to the growing consumer BNCI industry, but the development of devices for patients by such strategies is questionable. This recommendation is mainly due to the current trends in BNCI's gaming application sector. Most of these gaming devices are toys based on very small number of sensors and in the majority of the cases just on one sensor. The reason for these one-sensor solutions in gaming applications is the strategy of minimizing the risk of product failures: "If one sensor can give more or less enough information, why add more sensors and risking higher failure rates?" For non-gaming applications, and importantly for applications aimed at disabled user groups, the goals are of course different (e.g. reliability is one of the most important factors). Hence advancements in gaming like big markets may not advance the development of BNCI devices for disabled users.

On the other hand, the workshops identified that the entry point should be mature markets such as neuro-feedback, epilepsy, sleep-analysis and rehabilitation. These markets are using conventional hardware with sufficiently high number of sensors. Furthermore, some of these hardware and software systems have already attained (or are well on their way toward) successful validations and positive evaluations from both patients and therapists. Significant progress with rehabilitation could also facilitate market entry, even if there is inadequate progress with improved sensors.

Five Year View

Many new BCI devices and applications have currently gone through validation procedures, such as control of smart home or virtual environment, games, prosthetic devices such as artificial limbs, wheelchairs, and other robotic devices among different research labs in Europe. A whole new category of BCI applications is being developed: devices for rehabilitation of disorders, rather than simple communication and control. These and other emerging applications are expected to address the needs of disabled user groups and have dramatic changes in their quality of life.

Because of the progress of BNCI technology and its yet to be unveiled application potential, new devices will emerge to address the needs of other user groups (e.g., elderly, cognitively impaired such as autism and healthy users etc.). The classic user group consists of severely disabled patients:

persons who cannot communicate through other means. These users should expect modest progress in the next several years. Why? For non-invasive BCIs, relevant improvements will largely involve practical electrodes, hybridization with other systems, and improved software that makes BCIs more flexible and easier to use with less support. Invasive BCIs are likely to see significant developments that improve information transfer rate and expand the vocabulary of BNCIs.

BCIs could also aid in communication for less disabled users, and provide rehabilitation for users with other conditions such as stroke, addiction, autism, and emotional disorders. BCIs also show promise for healthy users in specific situations, for example when the conventional interfaces are unavailable, cumbersome, or do not provide the needed information. Furthermore, BCIs might supplement other interfaces to create a mixed system with greater bandwidth, more flexibility, and/or improved usability compared to each interface in isolation. Examples of such systems are video games controlled by a mixture of conventional control tools (keyboard, joystick, Wii) together with a BCI. Another example is a smart word processor that automatically detects when users think they made a mistake, or software that adapts its interface when users are tired, confused or even frustrated. Healthy people often experience 'situational disability' when their hands or voices are busy, unavailable, or inadequate (Allison, 2010, Negueruela et al, 2011). Drivers, cell phone users, gamers, surgeons, soldiers, mechanics, and many other users may want an interface that does not require their hands or voices[31].

---

[31] Please see the following section, "Devices, Applications, and Interfaces for Everyone".

Summary: Challenges and Recommendations

Major challenges include:

- How can BNCI products cope with competing and existing AT market such as eye-tracking, mouth-mouse etc.? Which strategy must BNCIs take to nurture their development? How should BNCI products enter consumer markets?
- Invasive or non-invasive BNCIs?
- What are the short term and long-term preferences in terms of user groups for sustaining R&D of BNCIs for disabled users?
- Current BNCI devices suffer from low throughput. How could we improve it? Should we aim for reliability or speed?
- How to improve usability of current BNCI prototypes for the disabled?
- BNCIs need to evolve beyond standalone systems. Which signal combination(s) is best for each user, in different situations, for specific tasks? How can context awareness and ambient intelligence best supplement BNCIs?
- How can BNCIs become simple, usable, transparent systems with minimal support?

We recommend:

- The BNCI technologies should not endeavor to replace existing ATs, but instead offer alternative and novel ways to complement them. The blooming hybrid-BCI approaches that integrate existing ATs with BNCI technologies must be favored. Furthermore, BNCI products should not be aimed at cornering big markets such as the gaming industry. But instead other existing markets such as neurofeedback, sleep analysis and epilepsy detection products should be the entry point.

- Risk, cost and performance are the three key factors behind deployment of invasive or non-invasive approaches for a user, given the nature and severity of the disability. To have a complete assessment of both approaches potential, the better solution would be to encourage research groups that work hand-in-hand towards addressing the needs of the users.

- As a short-term goal, the user groups that require motor rehabilitation and assistive devices, offer communication and control, provide cognitive enhancement and perform mental state monitoring are preferred over brain-gym applications for healthy elderly or completely locked-in. However, as a long-term goal the remaining user groups are definitely interesting.

- Most BNCI applications require more reliability than speed alone. Along with signal processing, mathematical and algorithmic approaches, the techniques such as shared control and context awareness should be favored to ensure more reliable BNCI applications.

- Invest R&D in practical sensors that could significantly reduce the setup. The hardware setup should aesthetic enough to be invisible. Furthermore, interface standards must be derived and enforced across research groups such that a novice can use a BNCI device as a “plug-and-play” product and connect to conventional hardware such as a television.

Devices and Applications for Everyone

For years, Brain-Computer Interfaces were considered emerging technologies for users with physical disabilities. Yet, while science is struggling to bring BCIs as assistive technology from the lab to the homes of users with disabilities, the market has already picked up on BCIs pulled them into society. In addition, BCIs have become more visible to computer science and the human-computer interaction (HCI) community. Start-up companies and R & D departments of large ICT companies now also try to exploit and investigate the commercial possibilities of this new technology. New companies such as Emotiv and Neurosky as well as established companies like IBM and Microsoft have become active in this field. Rather than aiming at medical applications, they look at the much bigger market of non-disabled and healthy persons. Consumer products are being offered, but until now these are mainly games, toys, and gadgets. This is not bad; the game market is a multibillion dollar market and still growing. But clearly, companies also see opportunities to introduce BCI into domestic and professional environments where an added modality to interact with an application will make the interaction more intuitive and enjoyable.

In this mini-roadmap we first present the state-or-the-art of BCI applications and devices for users without disabilities in the academic community. Second, we analyze the challenges that need to be addressed to spur development of BCIs for large user groups and, third, we provide recommendations for future research.

State-of-the-Art

BCIs for control in interactive systems

Games

Research on Brain-Computer Interfacing for games is ongoing in academia and industry. We first summarize some research efforts. Pineda and colleagues introduced a game in which subjects navigate through a first person shooter (FPS) type of game with a combination of imagined movements and keyboard commands (Pineda et al. 2003). Lalor and colleagues described an SSVEP game in which users moved a character across a tightrope with visual attention (Lalor et al. 2005). In (Martinez et al. 2007) one can find an example of another SSVEP BCI game that allowed users to move a car around a racetrack. Plass-Oude Bos and colleagues used alpha waves in the EEG for automatic adaptation of the avatar shape (bear or elf) in the well-known game World of Warcraft® (Plass-Oude Bos et al. 2010; Nijholt et al. 2009). Similarly, Scherer and colleagues developed a self-paced 3-class ERD/S approach for playing World of Warcraft® (Scherer et al., 2011). Congedo and colleagues describe a BCI-based Space Invador game (Congedo et al., 2011). A recent overview of HCI, BCI and Games can be found in (Plass-Oude Bos et al. 2010).

The industry has also developed many games for entertainment based on BCI or BNCI technologies. Companies which invest in game development are Neurosky, Emotiv, Uncle Milton, MindGames, PLX Devices, Mattel, MindTechnologies, Interactive Productline and OCZ technology (Nijboer et al., 2011; see Figure 12 for an overview). However, many of these games are probably partly controlled by electromyograophic or electro-ocular input and the scientific validity of these “BCIs” is highly questioned. Some researchers fear that negative experiences of consumers after using these products might be detrimental to the field. Nevertheless, these products have also boosted public interest in BCIs.

Figure 12: Overview of companies and some over their products for general consumers.

Virtual worlds

The increasing availability of virtual reality (VR) technology has awakened increasing interest in using BCI applications in virtual environments (VEs). BCI systems may overcome an important limitation of VEs, which is that one has to use interfaces such as mouse or keypad for e.g. navigating through a VE. Several studies have looked at using BCI-based interaction with virtual worlds (Groenegress et al., 2010; Guger et al., 2010; Leeb et al., 2007; Lotte et al., 2008, 2010; Scherer et al., 2007, 2008). However, these studies mostly focus on users with physical disabilities whilst the exploration of virtual environments could also be an interesting application for general consumers.

Creative Explorations

Creative expression is viewed by many as a purely human ability and skill. The creative process allows humans to express their identity. BCIs can be used in a unique way for creative expression. The BCI can provide a direct link between the brain, from which creativity sprouts, and a work of art. Various projects have already used BCIs for artistic expression in the direction of music, dance, sculptures and paintings.

An example of the use of BCI in sonification of brain signals is the exposition Staalhemel (Boeck, 2010) created by Christoph de Boeck. Staalhemel is an interactive installation with 80 steel segments suspended over the visitor’s head as he walks through the space. Tiny hammers tap rhythmic patterns on the steel plates, activated by the brainwaves of the visitor who wears a portable EEG scanner.

Figure 13: A disabled user creates music with brain signals. From (Miranda et al., 2011).

Another approach is the Brain-Computer Music Interface (Miranda et al., 2011), a research project at the University of Plymouth. Another one is the orchestral sonification of brain signals and dancers dancing to their own "brain music" (Hinterberger, 2007). More recently, Tim Mullen, Prof. Scott Makeig, and colleagues from UC San Diego gave a public demonstration of a BCI music system to the entire plenary session at the BCI Meeting 2010 in Asilomar.

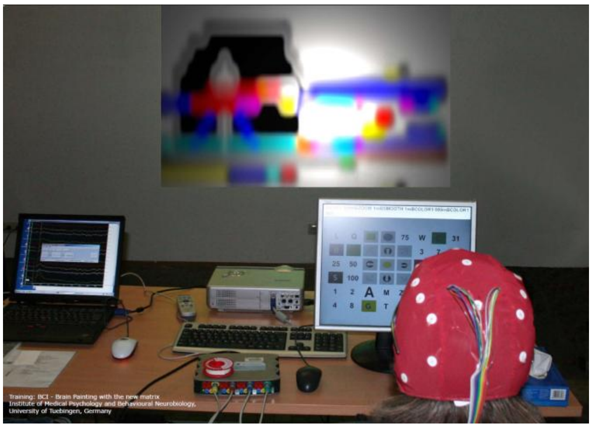


Figure 14: Brainpainting – The painting in the background is produced with a BCI.

"Today I again had butterflies in my stomach, a feeling that I have missed for so much, so much. I was so sad, I was plagued by fears of loss, I was in shock because I could not paint. For me the picture I have created is so typical for me, no other paints in my style, and despite five years of absence, I am simply an artist again; I'm back to life!"

Another aesthetic application was created in the Braindance project (Hinterberger, Braindance). In this project a dancer equipped with a wireless EEG headcap danced on and interacted with the sonification of her brain signals.

Prof. Kübler and colleagues developed the BrainPainting system, which allows abled and disabled users to paint with a BCI (Munssinger et al., 2010). One female participant, who was severely disabled due to amyotrophic lateral sclerosis, commented on what the BrainPainting system meant to her (personal communication with Prof. A. Kübler): *"Here is my feedback to my first Brain Painting image; I am deeply moved to tears. I have not been able to paint for more than 5 years. Today I again had butterflies in my stomach, a feeling that I have missed for so much, so much. I was so sad, I was plagued by fears of loss, I was in shock because I could not paint. For me the picture I have created is so typical for me, no other paints in my style, and despite five years of absence, I am simply an artist again; I'm back to life! I thank the Uni Würzburg, Harry, Adi and Prof. Kübler. I thank you with your contribution that will affect many people"*.

An fNIRS based brain painting device has been developed by Archinoetics Inc (Archinoetics Inc.). This device was used by the late artist, Peggy Chun. Other creative directions, such as sculpture and BCI, are also explored (for example, by the artists Hoesle[32]).

Figure 15: A sculpture which depicts the EEG measurement of Jörg Immendorff, a famous German painter who had amyotrophic lateral sclerosis, while he observed his own work.

To conclude, BCI applications which allow self-expression are appealing to both abled-bodied as well as disabled users. Moreover, users have equal opportunities to create art which may build a bridge between these groups. However, BCIs for creative expression are just emerging and there are many opportunities to improve interfaces and environments.

BCIs for enhancing human-computer interaction

Technology in the future must be context-aware and user-aware.

Interactive technologies are deeply intertwined in our daily lives. They help us do our work, navigate new environments, locate people in our social network, plan meetings and make informed decisions. Interfaces increasingly develop into context-aware systems. For example, your car knows whether it is raining or not and automatically switches on the window wipers for you. However, interfaces are not yet clever enough to read our mental state. Technology in the future must be context-aware and user-aware. Recent BCI research has focused on so-called passive brain-computer interfacing. A passive BCI derives its outputs from arbitrary brain activity arising without the purpose of voluntary control, for enriching human-computer interaction with implicit information on the actual user state (Zander and Kothe, 2011). Based on this definition a new form of interaction is defined as passive input (Cutrell and Tan, 2008). This is an inherently different approach then cognitive user state monitoring as the use of information provided by the passive BCI is interpreted automatically and is restricted to improving the current interaction in a defined human-machine system.

A broad spectrum of user states could hypothetically be accessed with passive BCIs, for example: latent cognitive state such as arousal (Chanel et al., 2006), fatigue (Cajochen et al., 1996), vigilance (Schmidt et al. 2009), working memory load (Grimes et al., 2008), visual/auditory/tactile/cross-modality attention focus (Kelly et al., 2005).

---

[32] http://www.retrogradist.de

Similarly, passive brain-computer interfacing could be used to enhance human-robot interaction. The more robots can learn from their users, the better they learn to show appropriate behavior.

Thus, BCIs can be used for other purposes than control. Real-time processing of user states with automatic adaption of the application to the user could significantly enhance human-computer interaction and human-robot interaction.

Brain-Computer Interfacing offers novel tools for science

The field of Brain-Computer Interfacing traditionally aims at applying neuroscience to develop neurotechnologies for (mostly) disabled users. However, throughout the development of the BCI field, new tools and algorithms have emerged which have been integrated in neuroscience research. For example, BCI methodology has been used in a study which evaluated the effect of different sleep stages by disrupting certain sleep stages of human participants (Van Der Werf et al., 2009). The sleep stages were detected “online” through BCI methods. Moreover, algorithms developed originally for BCI research are now increasingly implemented in neuroscience or artificial intelligence and vice versa.

Summary

Early BCI research focused on simply getting a BCI to work with a disabled user. More recent research has also focused more heavily on application interfaces and environments. Newer work has explored applications for healthy users and new directions with disabled users. New applications, devices, and user groups require new application interfaces and environments. There are many challenges involved with each of these new directions, as well as many challenges with existing directions. These are worth considering within the context of FBNCI as possible opportunities and/or roadblocks.

On the other hand, the recent new work has addressed some questions. For example, BCIs have been validated with games and virtual reality, which can yield substantial benefits over simpler application interfaces. BCIs have allowed creative expression such as music or painting, and could lead to new tasks for BCIs. Passive BCI interfaces could contribute to many fields well beyond BCI, such as human-computer confluence, ambient living and affective computing. The key conclusion is that BCIs can now be seen as intelligent sensors rather than only control signals.

Analyses

Challenges

The knowledge gap

While technology is advancing rapidly, fundamental knowledge on the brain is lagging behind. To develop applications and devices for general consumers, which go beyond the currently available toys and games, the field needs much more insight into the neural correlates of mental states of users then is currently available. It is often said that “neuroscience is a field which is data-rich, but theory poor”. The same saying can be applied to the field of brain-computer interfacing. The upcoming challenge is to have more theory-driven research to complement the current data-driven approach in brain-computer interfacing.

Shifting the focus on usability and user experience

At the moment BCIs are almost exclusively used in lab settings. In order for BCIs to be successful interaction paradigms the top level challenge is: Successfully migrating BCI out of the lab into the everyday and working lives of people.

User experience and usability play a prominent role in successful migration from the lab to society.

For most current and future users, BCI is *just one* of many available interaction paradigms, so users have alternatives which they can use in parallel or in a sequential manner. Hence, they can and will choose based on the usability and user experience of the provided BCIs. For instance a gamer can choose a BCI due to the novelty, increased challenge, and richer user experience, although the reliability and information transfer rate (technical issue) are much lower than for a traditional input device.

For other users, for instance locked-in patients, BCIs may be the only way to communicate. Although these users don't have a choice, still they prefer devices that are usable, look good and provide a pleasant experience. Otherwise, the assistive technology will end up in the closet, not being used (Scherer, 2000).

Thus, successful migration requires not only reliability, but also usability and pleasant user experience. Most current BCIs are not reliable at all times, inefficient, and difficult to learn and use. Thus, the challenges in usability are multifold. How can BCIs be designed to be more usable? Can usability requirements of users be made compatible with neuro-requirements of the BCI? How can we create pleasant user experiences for users with a BCI? Also, how can we measure usability and user experience of BCIs? Conventional tools of the HCI field for measuring usability and user experience are not necessarily suited for BCI applications (Van de Laar et al., 2011; Gürkök et al., 2011; Plass-Oude Bos et al., 2011). It is a challenge in itself to develop tools to measure the usability of BCI technologies. Finally, if we build technologies that incorporate BCIs, how can we make such systems safe? What BCI paradigms are easy to learn and hard to forget?

Multimodal interfaces

Using only BCI input to control a system is probably not desirable. BCI input should be an additional input modality to interact with an interface. Other input modalities could be a keyboard, speech or eye gaze. A first challenges that arises when designing such a system is data fusion. How does the system fuse information from different input modalities? A second challenge is related to the first one. How does a system differentiate between information? Speech generation interferes with EEG signals and the system might have difficulty differentiating information.

Creating a robust and universal BCI

Although we plead for a focus shift to usability rather than reliability, robustness is still a key challenge to be tackled for BCIs in daily life. BCIs should let you do the thing you want to do in a predictable way and with a known accuracy. Currently, users need weekly, if not daily, help from experts from a nearby university to continuously update algorithms and fix bugs. Systems with integrated BCI technology should work every time you use them. Also, general consumers need systems that are universal. That is, systems should preferably be transferable from user to user.

Plug & Play systems

As already mentioned in the state-of-the-art, rapid technologization of society calls for natural, intuitive interaction between users and technology. In most labs a BCI consists of a laptop, a separate computer screen, a headset and many wires in between. Also the BCI-related software is very visible and not integrated with existing software. In future we need to find ways to let the BCI components disappear and to create a natural experience for the user. Basically, the challenge is to develop a plug & play system.

One very closely related challenge is unobtrusive sensing. The attractiveness of BCI-based technologies for everyone will depend heavily on the comfort of the system. Many universities and companies are actively researching and developing dry sensors or sensors that only need water. However, if we consider the potential for BCI technologies in ambient intelligent environments, then in future the challenge arises how we can sense physiological signals from users from a distance. For example, how can we have reliable recordings of the heart beat from sensors embedded in the bed of a user with heart problems? Or, how have sensors embedded in the head support of the seat in a car to measure the workload of a driver? Thus, the real challenge in unobtrusive sensing consists of making sensors invisible, reliable and possibly even dislocated from the user.

BCI as intelligent sensors

Since current BCI technologies have such poor reliability and robustness the BCI field is more and more shifting away from the idea of using a BCI as a control input for interactive systems. Instead, BCIs are increasingly used as intelligent sensors which “read” passive signals from the nervous system and infer user states to adapt human-computer or human-robot interaction. This new application area for BCIs challenges researchers to understand how information about the user state should support HCI and human-robot interaction. What constitutes opportune support? How does the feedback of the changing HCI and human-robot interaction affect brain signals? Many research challenges need to be tackled here.

Ethical challenges

Above we have listed scientific and technological challenges, but a key factor in developing BCI products for general consumers is the acceptance of these products in society. Acceptance is directly determined by the ethical and societal issues related to the research and development of such systems. Ethical issues related to BCIs for the general public include for example safety, side-effects, privacy of mind, social stratification and communication to the media. Thus, in the coming years we are challenged to address these ethical issues.

Solutions and trends

Ambient Intelligence

Ambient intelligence, pervasive computing, ubiquitous computing and ‘disappearing interfaces’ are names that have been introduce to describe the research domains in which we assume that we live or will live in sensor-equipped environments, that sensors will be embedded, that they will have local intelligence, and that the information they collect and process can be distributed to other intelligent sensors and computing devices. Obviously, there are already sensor-equipped environments, but, as long as their design is tuned to rather specialized applications, they will certainly not achieve their full potential. In ambient intelligence environments, sensors can be used to detect and interpret human behavior and activities, to anticipate certain activities or desires in order to provide real-time support, and to allow explicit control of the environment by its inhabitants by providing feedback and appropriate actions on commands of the inhabitants. These views have led to an increase in attention for sensors in general, including sensors that allow us to issue commands, for example for games and domestic applications, through BCI devices and systems.

Human-Computer Confluence

"Human-Computer Confluence" (HCC) is a recent European research initiative which investigates how the emerging symbiotic relation between humans and computing devices can enable new forms of sensing, perception, interaction, and understanding. The main goal of HCC is to develop a disappearing interface, in other words an interface that feels so natural that you do not even notice it is there. Three main research lines can be distinguished:

- HCC Data - Perception and interaction with massive amounts of data. How can users interact with massive amount of data in future?
- HCC Transit - Smooth transition from physical to virtual/augmented reality
- HCC Sense - New forms of perception and action. What are new forms of re-experiencing oneself or experiencing being others, how can we experience environments and new senses or abstract data spaces?

Two European projects on these topics include CEEDS and VERE . Both projects also make use of Brain-Computer Interfacing technologies. Also, there is a cost and support action called HCC , in which Stephen Dunne (Starlab) is involved.

Similarly, as mentioned in the state-of-the-art, new perspectives in the field of Brain-Computer Interfacing have emerged on what BCIs are and thus how they could be applied. BCIs need not only produce voluntary self-regulated signals with the purpose of voluntary control of an interface. Rather, BCIs could extract involuntary, automatically generated brain-activity and extract information about the user's mental state with the purpose of opportunely adapting human-machine interaction to the user (Nijholt and Tan 2008; Nijboer et al. 2009; Zander et al., 2010; Zander and Kothe 2011). This new research area is referred to as passive Brain-Computer Interfacing (Zander and Kothe, 2011). Passive brain-computer interfacing closely ties in with affective computing, ambient intelligence and human-computer confluence.

Physiological measurements in HCI

Measuring cognitive load is the standard example of what interface designers are interested in (Nijholt, 2011). They need to know how an interface works for a particular user. There has always been interest in using (neuro-) physiological measurements to learn about the cognitive load associated with performing certain tasks using a particular interface. This kind of information is meant to re-think, to re-design, and to re-implement the interface in order that it should perform better for a particular user or group of users. However, in recent years many more methods have become available to measure experience. Computer vision, speech analysis, and eye tracking are among them, and this has led to a boost of interest, methods and devices, including BCI devices, that not only measure user experience for redesign and performing tasks more efficiently, but also look at 'tasks' that do not necessarily require efficiency but rather aim at providing positive experiences such as fun, game experience, relaxation, and edutainment. And, moreover, use the information that is sensed in real time to adapt the interface, the task (e.g., the game level) and the interaction modalities to the user and context.

Social media and games

People love to connect with other people. Europeans spend many hours on social media (e.g. Twitter, Facebook, Google+) and playing social games (e.g. Wordfeud). The consulting company Insites performed a study covering more than 90000 citizens from 35 countries[33]. Seventy-three percent of Europeans are a member of at least one social network (mostly Facebook, Twitter and MySpace). There are about 1 billion social media users worldwide. Video games are increasingly social and based in the internet. Some of those games are more cooperative (e.g. FarmVille on Facebook) and some more competitive (e.g. World of Warcraft, Quake). Industry quickly picked on these trends and it has shifted branding efforts more and more to social media.

Changing input channels

Closely related to the disappearing interface is the trend towards changing input channels. Users moved from using command lines input computers to using joysticks, mouse and keyboard. Currently, users are moving towards touch and strokes to input with interactive screen (e.g. smart phones, tablets). Moreover, first initiatives have shown that users can use body movements to input to a system (e.g. Kinect). A possible long-term goal might be the direct input from the brain into computer.

Five Year View

In the next 5 years, we first will have developed better theories on brain-computer interfacing and more knowledge about neural correlates of cognitive and affective states of users. Second, we will have merged the fields of human-computer interaction with brain-computer interfacing, and new tools will have been developed to measure usability and user experience of BCI technologies. Researchers will have shifted their focus to usability rather than reliability, while still aiming to make BCI’s as robust as possible. Third, BCIs will no longer be used as the sole input modality for interactive systems but as an additional input modality. Thus, we will see more multimodal interfaces that rely partly on brain signals. Fourth, we expect researchers to narrow down their foci and create more robust and universal BCI prototypes for the general public. These systems will be plug & play systems. The BCI technology will be made invisible for the user. Fifth, we will see an increase in interest to use BCIs as intelligent sensors rather than as a control signal. BCIs will be used as adaptors for human-computer and human-robot interaction. This will bring about closer cooperations between the field of brain-computer interfacing, the field of robotics and the field of ambient intelligence. Finally, ethical, legal and social issues will be more and more evident, and we will see an increase in efforts to address these issues.

---

[33] “Social media around the world 2011”, a study by Insites Consulting. Please see www.slideshare.net/stevenvanbelleghem/social-media-around-the-world-2011

Summary: Challenges and Recommendations

Our recommendations are grouped according to major challenges:

Shifting the focus on usability and user experience:

- Foster cooperation between the field of human-computer interaction and brain-computer interfacing.
- Develop tools to measure usability and user experience of BCI technologies.
- Elucidate what factors determine BCI usability and user experience.

Developing Multimodal/hybrid BCIs:

- Use BCI input in combination with other input modalities.

Creating a robust and universal BCI:

- Support benchmarking studies to determine which brain signals, sensors, algorithms and software systems are most robust.
- Create large databases of brain signals to investigate if a large dataset can lead to universal “parameters” for BCIs that would fit all users.
- Encourage additional research lines that purposefully measure brain signals in noisy, real life situations to ensure ecological validity.

Building Plug & Play systems:

- Embed BCI technology in existing interactive systems. BCIs should be invisible for the user.
- Push further than ‘just’ dry electrodes. (Neuro)physiological sensing needs to be as unobtrusive as possible.

BCIs as intelligent sensors:

- Development of BCIs as intelligent sensors to enhance human-computer interaction and human-robot interaction.
- Encourage theory-driven BCI research toward better understanding and detection of mental states of users.

Case Scenarios

Expanding the Horizon for BCI Applications

The field of Brain-Computer Interfacing has existed for decades, since the early work of pioneers such as Walter, Fetz, Vidal, Birbaumer and Lutzenberger. Yet until recently, research was almost exclusively focused on one scenario, in which a BCI could be applied for a user with physical disabilities: BCI-controlled assistive technology. Thus, BCI researchers targeted 1 user group which consisted of persons with severe physical disabilities or in the locked-in state. The goal of these researchers, mostly psychologists, neuroscientists and physicians, was to help patients.

Noble as this goal may be, a more systematic and open-minded approach is needed to exploit the full potential of Brain-Computer Interfaces. The field of Human Computer Interaction (HCI) deals with the design and development of interactive systems. Without proper design, systems may never be accepted by users. Systems need to meet the needs and requirements of users. Requirements of users need to be translated into system specifications and the design of the system involves the iterative testing of the product with end-users. Somehow it seems that the field of Brain-Computer Interfacing has skipped the whole user centered design process. “Just” bringing a BCI from the lab to a patient at home does not equal system development, and it does not mean that products are ready for the market.

Another lesson that can be learned from HCI and the field of assistive technology is that stakeholders are not referred to as “patients” but as “users” or “clients”. The concept of clients is associated with active persons who have their own wishes and demands, whereas the concept of patients is too medical and often (wrongfully) associated with characteristics such as “weak”, “incompetent to make decisions”, “helpless”. People with disabilities do not wish to be referred to as patients. They are clients and they demand good products. Thus, it is of utmost importance that BCI developers take a user-centered approach, and design and develop BCI-based systems to meet the needs of users.

Moreover, many emerging BCI users do not have physical impairments. Emerging users could include gamers, students, neuroscientists, pilots, air traffic controllers or elderly persons.

In this section we present:

1) Our methods to explore novel application areas and case scenarios for BCI

2) An overview of application areas

3) A survey on promising application areas

4) Novel case scenarios

Methods to Explore Novel Application Areas and Case Scenarios

The main principle underlying the exploration of novel application areas and the creation of new case scenarios was the iterative consultancy of many stakeholders (see Figure 16).

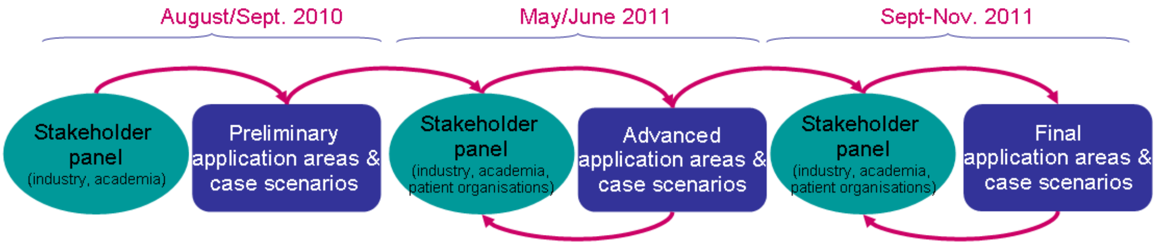


Figure 16: Iterative process of developing valid case scenarios.

Step 1: Before and during the workshop on “Application interfaces and environments” at the fBNCI conference in Graz during September 2010, a broad overview of application areas was discussed and 8 preliminary case scenarios were written with participants (N=11; see Figure 16). In addition, participants developed a technology assessment survey. The purpose of the technology assessment survey was to evaluate the case scenarios on a number of dimensions (e.g. low hanging fruit, scientific feasibility, value for society and so on). Deliverable 4.3 includes a full report of the outcome of this workshop.

Figure 17: All but one participants of the workshop “Application interfaces and environments” at the fBNCI conference in Graz in September 2010.

Step 2: At the workshop “Major issues in BCI research” organized by fBNCI project in May 2011, participants (N=15) further explored and assessed different application areas for BCI technologies. Also, we refined the case scenarios and discussed the value and content of the technology assessment questionnaire. These discussions continued during the attached Utrecht conference.

Figure 18: Participants at the workshop "Major issues in BCI research" in May 2011.

Step 3: During the last half of 2011, the application areas were finalized through e-mail, telephone conferences and face-to-face meetings with persons who previously attended the workshops. In addition, the advisory board was consulted.

Step 4: In October 2011 the most promising application areas, as perceived by the BCI researchers, were identified and further defined.

Step 5: Final case scenarios were written for the top 5 most promising areas.

Overview of Application Areas

We have identified several areas and subareas where BCI technologies can be applied (see Figure 19). Research and development of BCI technologies have come a long way in some of these areas, but some areas seem "undiscovered". The following paragraphs provide an overview of different areas.

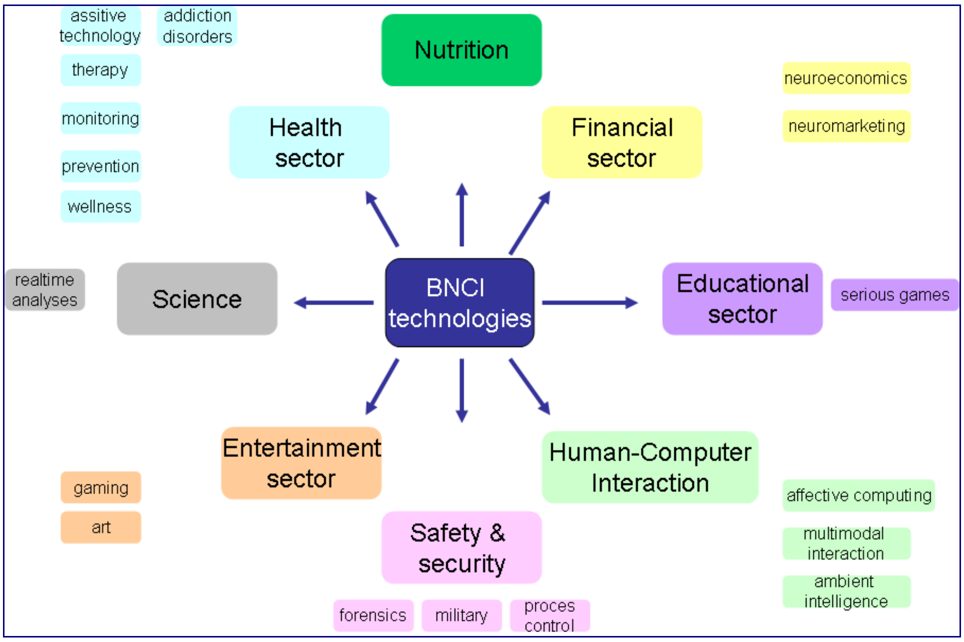


Figure 19: Overview of possible application areas for BNCI technologies.

Health

Subarea	Concept	Potential user group
addiction disorders	To detect craving in real-time and give immediate feedback to patients with addictions about their brain activity.	persons with obesity drug addicts alcohol addicts
assistive technology	To provide AT to physically disabled persons.	persons with tetra- or quadriplegia locked-in patients
therapy	To provide neurofeedback which could initiate or accelerate brain plasticity in damaged or disordered cortical networks.	ADHD autism epilepsy cortical stroke Alzheimer’s disease schizophrenia depression psychopathy
monitoring	To monitor and classify brain states in real-time.	acute trauma Alzheimer’s disease Parkinson’s disease
diagnosis	To make better diagnosis based on neurophysiological markers.	locked-in state vegetative state/coma mild cognitive impairment
prevention	To provide neurofeedback which could slow down neurodegeneration.	Alzheimer’s disease mild cognitive impairment elderly persons
wellness	To trigger more brain plasticity than normally would occur and thus, may boost mental performance or emotional well being. This is also known as cognitive	all users

	enhancement.	

Table 2: Health.

Science

Subarea	Concept	Potential user group
realtime analyses	To better understand the brain.	neuroscientists neurologists neuropsychologists

Table 3: Science.

Entertainment sector

Subarea	Concept	User group
gaming	To provide new interaction styles through active BCIs or enhance game experience through passive BCIs.	gamers
art	To provide new interaction styles in art.	artists all users

Table 4: Entertainment sector.

Safety and security

Subarea	Concept	Potential user group
forensics	To help monitor criminal knowledge or intent.	police prisons
military	To augment and monitor mental performance in soldiers.	soldiers
process control	To monitor attention levels in controllers and determine opportune moment to deliver information to the user.	air traffic controllers train controllers attention critical situations

Table 5: Safety and security.

Human Computer Interaction (HCI)

Subarea	Concept	Potential user group
multimodal interaction	To provide interfaces with an extra input modality	all pilots situational disability
affective computing	To provide interfaces with information about the user state in order to support custom-tailored human-computer interaction (also referred to as "passive BCI").	all
ambient intelligence	To provide user information to context-aware systems that seamlessly incorporate relevant information about the system, environment, and user.	architects all

Table 6: Human Computer Interaction.

Educational sector

Subarea	Concept	Potential user group
serious gaming	To provide new interaction styles in serious games, and an interactive educational system to facilitate learning and increase brain plasticity.	all

Table 7: Educational sector.

Financial sector

Subarea	Concept	Potential user group
neuroeconomics	To provide novel tools to study in how humans make financial decisions. Since classification is possible in real-time new experimental setups can be made.	scientists marketers banks
neuromarketing	To provide novel tools to study in how humans react to	all

	advertisement, products or media. Since classification is possible in real-time, new experimental setups can be made.	marketers banks

Table 8: Financial sector.

Nutrition

Subarea	Concept	Potential user group
nutrition	To provide novel tools to study in how humans process food related stimuli in the brain. Since classification is possible in real-time, realtime feedback could facilitate new experiments or therapies.	nutritional scientists food & beverages industry persons with obesity

Table 9: Nutrition.

Perceptions on Promising Application Areas

We aimed first to identify of the top 5 most often mentioned areas in the top 10. Second, we wanted to identify the five most promising application areas for BNCI technology.

Participants in previous workshops were asked to participate in a small survey. They were shown Figure 19, which consists of 19 application areas. They were then asked to choose the ten most promising areas for BNCI technology. Then, respondents were asked to rank these 10 areas. (1= most promising). Twenty-four participants completed the survey. We evaluated the rank per area weighted for the number of persons who ranked that area. That is, we multiplied the number of respondents who ranked an area with (11-rank). Figure 20 overviews of the results. The length of each bar reflects how many persons ranked this area as important.

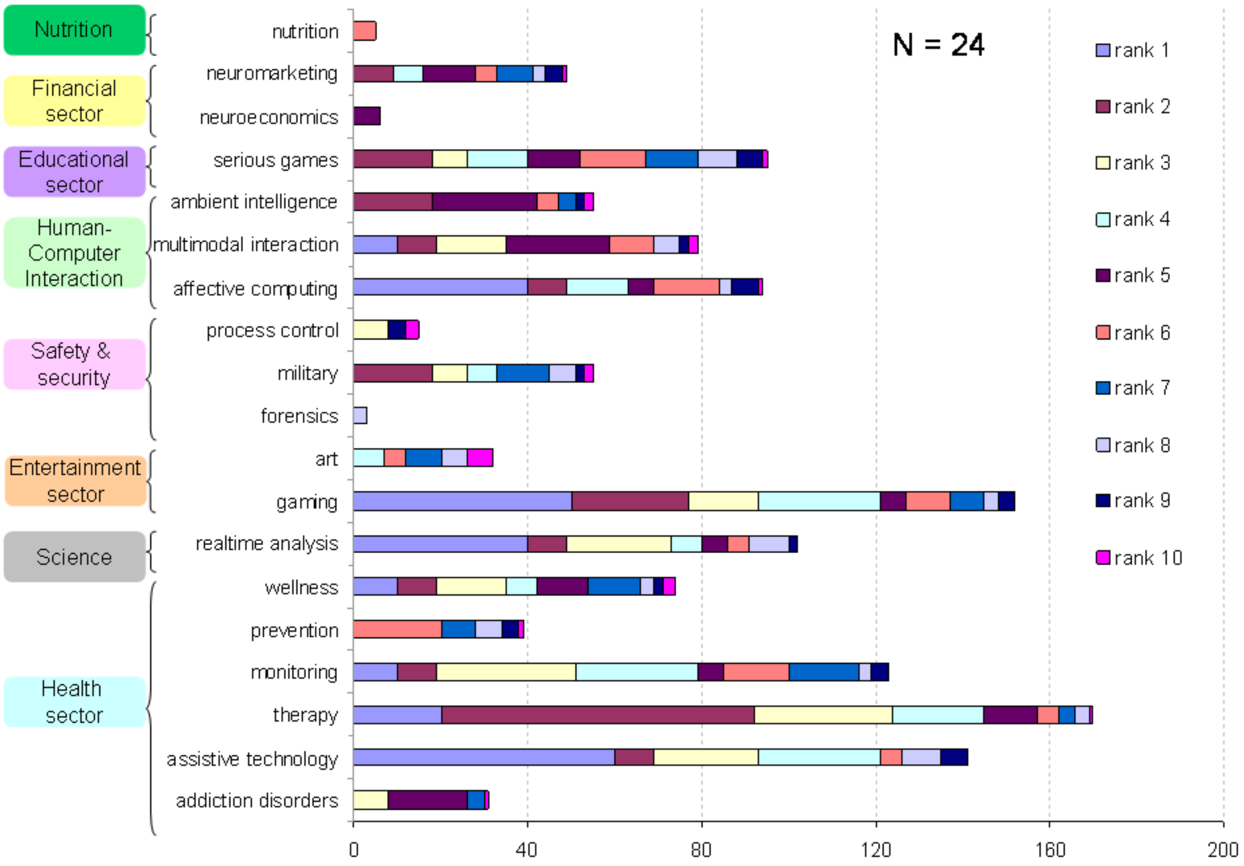


Figure 20: Overview of areas perceived as promising by the respondents.

First, the 5 most often mentioned areas are:

Top 5 most often mentioned application areas

1. BCI for therapy
2. BCI for gaming
3. BCI for assistive technology
4. BCI for monitoring
5. BCI for realtime analyses

Second, we asked what *the* most promising application area was. Which application areas are most often given a rank 1 in the survey?

Top 5 most promising application areas

1. BCI for assistive technology
2. BCI for gaming
3. BCI for real time affective computing
4. BCI for real time analysis in science
5. BCI for therapeutic purposes (neurofeedback)

Many respondents commented that some subareas seemed synonymous to them, and others noted that “promising” could be broadly defined. A few respondents gave their personal opinion on promising areas. For example: “*Toys and video games are here. I think wellness applications are the next most promising in term for consumer devices. These would be things like sleep aids (like Zeo), medication coaches, and serious games. They don´t necessarily require medical device approvals, but they could be used by people to improve their own health. Long term, I am bullish on neurofeedback therapies for ADD and autism, and diagnostics for diseases (for example measuring cognitive decline in Alzheimer´s or effectiveness of a drug on depression)*.” In the following section we present the 3 final scenarios that combine these areas.

Novel Case Scenarios

BCI-supported user interface for communication, affect expression and enhanced human-computer interaction in locked-in patients:

George is a 39-year old former lawyer. He suffered a brainstem stroke 4 years ago which left him in the locked-in state. He can still raise one eyebrow and blink his eyes when he wants, but otherwise he is completely paralyzed. He lives in a home for assisted living. Since he no longer has a steady income, he is going to start a course on writing in an online university. His objective is to write a book about issues related to intellectual property in the biomedical field, which is his speciality.

He has applied for and been granted a novel assistive technology system. The system supports multimodal interaction. That is, George can control the system using his eye gaze, his eye blinks, his eyebrow raise and his brain activity. Several comfortable, wearable and wireless sensors are placed in the vicinity of his eyes and on his scalp daily by a nurse.

The system also measures George´s affective state in the brain activity and projects his mood or affective state as ambilight attached to his computer, which is practical given that George´s face no longer expresses emotion. In daily communication, this screen helps other people in the home and elsewhere to understand him and communicate with him.

Finally, the information from his brain is used to enhance human-computer interaction. If George notices that the interface failed to do what he wants, the system automatically detects the ¨alarm¨ in his brain activity and corrects the last action. Also, the system goes in standby when it notices that George is dozing off.

Persuasive rehabilitation after stroke with a BCI game:

Mrs. De Luca is a 62 year old lady living in Rome. She suffered a stroke 3 months ago that left her arms paralyzed. She also has slurred speech and some problems concentrating. Finally, just like many stroke survivors, she has developed depressive symptoms. She initially did not want to do the daily rehabilitation requiring several hours. However, the hospital purchased a novel rehabilitation system which offers a holistic rehabilitation program to its users.

Mrs. De Luca still has to do the same physical arm training, but now it does not feel like training anymore; it is fun! Her arm is placed in a robotic device which assists her movement. She sits in front of a large computer screen and has to play a card game called “Patience”. She can flip a card by bringing her arm to the card and hovering over it. The robot arm is not only controlled by Mrs. De Luca´s attempted movement, but also by the related features in her ECoG signal. Directly after her stroke, surgeons implanted her with a temporary micro ECoG grid which wirelessly transmits to the robot arm. The game challenges Mrs. De Luca to train her arm and the damaged cortical areas. It also rewards her at opportune moments for her achievements or adapts the difficulty level of the game depending on her mental state. The engaging game, combined with support from both the robot arm and her own brain, persuades Mrs. De Luca to do her daily rehabilitation and reduces the time she needs to stay in the hospital.

BCI tools for neuroscience:

David is a postdoc at a renowned Institute for Cognitive Neuroscience. He studies the difference in attention processes between healthy persons and persons with schizophrenia. In one of his experiments, healthy subjects perform a continuous attention test where they have to attend certain stimuli (n=200) and press a button as fast as they can. David is mainly interested in the times the subject failed to respond to the stimuli. What happened in the moments before the stimuli was presented? Was the subject distracted? David is very happy he can now use new methods and tools from Brain-Computer Interfacing to analyze his data. In former days, he would have to average all trials in which the subjects failed to respond and look at the averaged ERP. Now he can investigate brain activity on a single trial basis and even real-time, while the subject is sitting in front of him.

More importantly, he can setup a flexible experimental design which adapts to the subject's brain. He can alter stimulus parameters to learn more about the unique characteristics of different brains. This could help scientists identify disorders more quickly and reliably, develop BCI-based better treatments, and improve therapy.

The development of Case Scenarios showed that:

- BNCIs are still mentioned prominently as assistive technologies.
- However, BNCIs for healthy users are overshadowing other user groups, notably gaming and affective computing.
- BNCI technology is also gaining attention for other applications such as rehabilitation and scientific research.
- As applications and user groups expand, providing the right BCI for each user gains importance. A BCI that satisfies one user may be totally inadequate to another user, depending on whether the BCI helps the user accomplish a goal.
- Challenges and opportunities also vary for different BCIs. Practical sensors may be critical for casual gaming, but less of a barrier to entry for stroke rehabilitation.

Financial and Business Issues

Market Overview

Potential users and applications - the changing landscape

Until recently, most BCI research focused on providing assistive communication for people with severe disabilities. There are many ways that persons with different disabilities or conditions might benefit from a BCI. The conventional BCI target market has been people who have severe movement disabilities that render them unable to effectively use other communication and control mechanisms. Persons with stroke, Lou Gehrig's Disease (ALS), other neurological disorders, traumatic brain injury (TBI), and some innate conditions such as cerebral palsy have used BCIs. However, due primarily to the need for expert help to use a BCI, the number of patients who actually rely on a BCI for communication is on the scale of dozens. As BCIs become cheaper and more powerful, the number of potential users in these groups may increase, and new users with mild disabilities might prefer BCIs over other assistive technologies – or in combination with them. Also, if BCIs gain acceptance for functional improvement (such as reducing the cognitive or motor deficits resulting from stroke), then the disabled user market could become much more engaged.

Figure 21 shows the effect of lowering costs on market segments (this can also be thought of as improving performance for a given cost). In general, the trend towards cheaper and better BCI technology will carry all application areas towards greater numbers of users.

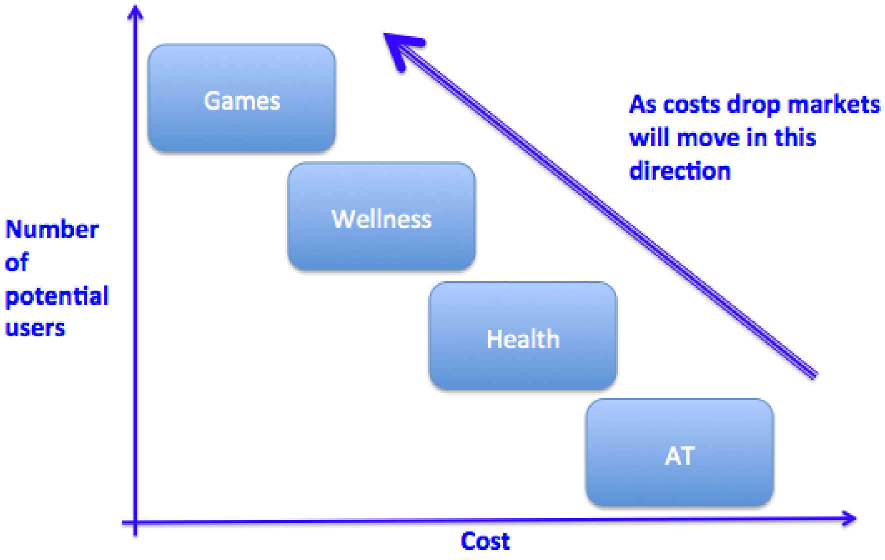


Figure 21: Impact of lowering costs.

Now, however, commercial interest in terms of investment and numbers is focused on non-assistive applications intended for healthy users. Nearly all BCIs and related systems sold are relatively inexpensive non-invasive devices. Although the number of electrodes and signal quality in such systems often precludes some conventional BCI signals, inexpensive systems can provide some usable information. On the other hand, invasive BCI systems have been less successful commercially, despite promising recent research advances.

Noninvasive BCIs and related systems

This trend towards consumer devices will drive progress in various fields, particularly related to practical electrodes and ease of use and will continue to drive down costs.

Neurosky[34] is a company that licenses BCI systems and chips for mass-market applications. They have sold over one million chips used in BCI applications, mainly toys, and predict 5 million by the end of 2011[35]. Dr. Thomas Sullivan from Neurosky elaborated[36], "We do say publicly that we have shipped over 1 million integrated circuits that process EEG signals. This is not just in our own headsets, but in the headsets of our partners like Mattel." Emotiv[37], another company in this space, markets a consumer level EEG system with an eye on the gaming and research markets. Another article puts the number of headsets sold at 10,000[38] units in late 2010. Both Neurosky and Emotiv encourage developers to produce new applications, which could foster innovation in many different ways. Both of these companies have raised over 10 million in venture capital.

Other companies producing BCI-like systems are also doing well with non-assistive technologies. Advanced Brain Monitoring, which develops tools to monitor sleep, alertness, and memory, was recently named one of the top 100 growing healthcare companies by Inc. magazine[39]. Neuromarketing companies such as Emsense[40] and Neurofocus[41] have developed or bought hardware solutions for their services. While the former company ceased operations, the latter was recently acquired by Nielsen, demonstrating a serious interest in this technology and the possibilities it offers.

Despite the trend toward BCIs and related devices as non-assistive technologies, with less expensive and demanding sensor systems, the market for conventional systems remains strong. g.tec, which produces more expensive high-end recording systems, has reported annual sales increases of about 35% per annum since 2005[42].

[34] http://www.neurosky.com/Default.aspx

[35] http://www.wired.co.uk/magazine/archive/2011/07/start/mind-controller

[36] Source: email from Dr. Sullivan from Neurosky on 29 March 2011 (reprinted here with permission)

[37] http://emotiv.com/

[38] http://www.wired.co.uk/magazine/archive/2011/07/start/mind-controller

[39] http://www.b-alert.com/news.html

[40] http://www.emsense.com/

[41] http://www.neurofocus.com/

[42] Source: quote from Dr. Günther Edlinger, co-CEO of g.tec, September 2011 (reprinted here with permission)

Invasive BCIs and related systems

On the other hand, two high-profile American companies devoted to invasive BCIs that have been less successful. One such company, Cyberkinetics, ceased operations in 2009, although they had some excellent people, solid publications, and impressive BCIs[43]. Another company, Neural Signals, has (like Cyberkinetics) encountered considerable trouble with the costs necessary for device approval. The following text is an email from the CEO of Neural Signals[44]. His reply is in ***bold italicized*** text, and is reprinted with his permission.

> 2) Which invasive BCIs are approved? Neural Signals = yes, right? Cyberkinetics sought FDA approval, but the company does not exist any more and thus has no relevant approvals, right?
>
> ***NSI's approval is suspended until we can become compliant with the new rules. This is extremely expensive. And there is no way to finance it. So we are stuck.***
>
> On 26 September 2011, another key stakeholder provided the following anonymous quote:
>
> ***Cyberkinetics received two IDEs for BrainGate. …Note that the same implanted device and associated hardware used in the BrainGate research also has 510(k) clearance, issued to Cyberkinetics/Blackrock, for use for < 30 days (known as "NeuroPort"). This is increasingly being used for epilepsy research.***

The reason there are no intracranial BCI companies is not the expense but the uncertainty of the market.

Therefore, while both invasive and noninvasive BCIs have gained attention and made progress in many ways, there is a schism in terms of commercial success. Noninvasive BCI companies are generally doing better than invasive BCI companies. Aside from obvious reasons, such as the financial costs, invasive BCIs face much greater demands for device approvals; a noninvasive Neurosky system intended for healthy users is much less problematic than an invasive device intended as a medical system. Nick Ramsey noted that "The reason there are no intracranial BCI companies is not the expense but the uncertainty of the market. The market will become clear once we know what intracranial systems can achieve. If invasive BCIs can provide robot arm control with multiple degrees of freedom, this would benefit amputees, a much larger market than locked-in users."

There are also several reputable groups currently developing a fully implantable device for commercialization, including the Braingate-II system and the University of Pittsburg (USA), Medtronic EU (Netherlands), Minatec (France), and Osaka University (Japan). Thus, while the invasive BCI industry remains nascent, it will probably grow in the near future.

---

[43] The "Links" subtab of future-bnci.org includes a section called "Popular media articles". The 60 Minutes show presents the system developed by this company along with researchers from Brown University.

[44] Source: email from Dr. Phil Kennedy dated 19 Sep 2011, reprinted with permission.

Appealing to different users

Thinking of BCI in the traditional sense as a communication and control tool, there are major challenges in penetrating the healthy user market. Conventional communication is usually cheaper, faster and easier. However, healthy people routinely experience “situational disability” in which they are temporarily unable to use other means of communication and hence might benefit from technologies used by disabled persons. Drivers, mechanics, pilots, soldiers, surgeons, gamers, and cell phone users are all examples of people in situations that limit their ability to send command and control signals through normal output pathways. Users may adopt technology that can provide a supplemental or replacement communication channel, which could be a BCI or BNCI (Allison and Graimann, 2008; Nijholt et al., 2009; Blankertz et al., 2010).

User groups vary in many ways beyond their abilities or disabilities. For example, users’ expectations and needs are also important. Some patients may depend on a BCI for all communication and control, while others just need it as an additional device to support them in their daily lives. User adoption also varies for BCIs and BNCIs. BNCI systems are more broadly defined and may appeal to more users. For example, a BCI alone may not be useful enough for a particular client, but a system that combines a BCI with an eye tracker and voice recognition system (which is a BNCI) would be useful.

A further group of users are those interested in what we call wellness. Here we have products such as the Zeo[45] where sleep quality is tracked based on the users EEG. This is not traditional BCI and is not a medical application; the devices are sold as a means of monitoring your own sleep quality so that you can try to modify your behaviour. The Quantified Self[46] movement has grown up around people who are interested in tracking their physiological data on a regular basis for its own sake and for the potential health/wellness benefits.

There has long been an interest in neurofeedback companies that sell products to facilitate concentration, relaxation, or foster other changes. These systems can work in some situations, and neurofeedback remains an active research area. Adoption has been hampered partly by poor publicity and some instances of misrepresentation or use by poorly trained staff.

This relates to a potential emerging market, involving systems that incorporate BCIs for rehabilitation of stroke or other conditions (Pfurtscheller and Neuper, 2006; Birbaumer and Cohen, 2007; Pineda et al., 2008; Grosse-Wentrup et al., 2011; Kaiser et al., 2011). These devices are similar to wellness systems in that the overall goal is to produce a lasting change within the nervous system. While this system may involve BCIs for communication, neurofeedback, passive monitoring, and/or diagnostic tools, these components all serve the overall goal of facilitating various changes. This could emerge as a major disruptive technology, but more research is needed.

---

[45] http://www.myzeo.com/sleep/

[46] http://quantifiedself.com/

Companies in the BCI market

As the market potential changes, driven by new application fields and approaches, we see a wide variety of players with very different goals entering the market. Not all are developing traditional BCI systems but the investment in consumer products will no doubt have a significant impact on technology, costs and above all usability. This will feed back into the traditional BCI community allowing ever more user friendly and useful assistive devices which in turn expands the potential user base.

Figure 22: BCI technology sectors.

Figure 22 identifies the major sectors where BNCI technologies are in use or under development. Each of these sectors has specific goals and constraints in terms of user acceptance, usability and performance. In many cases they are not interested in BCI but in the technology itself and the data it can provide.

Table 10 presents a list of companies working in each sector.

	Health & Neuroedback	AT	Education	Safety & Security	Entertainment & Performance	Research	Financial & Marketing
Advanced Brain Monitoring	✓						✓
Ambient	✓						
BitBrain Technologies	✓	✓	✓		✓	✓	
Brain Actuated Technologies	✓						
Brain Fingerprinting Technologies				✓			
BrainMaster Technologies	✓						
BrainProducts						✓	
Biosemi						✓	
Cortech Solutions						✓	
Coretec	✓						
PLX Devices					✓		
EEG info	✓						
EEG spectrum	✓						
Emotiv					✓		
Emsense							✓
g.Tec	✓	✓				✓	

	Health & Neuroeedback	AT	Education	Safety & Security	Entertainment & Performance	Research	Financial & Marketing
Interactive Productline					✓		
Interaxon	✓						
IBVA			✓		✓		
Mattel					✓		
MegaEMG						✓	
MindGames					✓		
Mind Technologies					✓		
Neural Signals	✓						
Neuroelectrics	✓					✓	
Neurofocus							✓
Neuro-insight							✓
NeuroMatters	✓					✓	✓
Neurosky					✓		
Neurovigil	✓						
No Lie MRI				✓			
OCZ (EOL)					✓		
PLX Devices					✓		

	Health & Neuroeedback	AT	Education	Safety & Security	Entertainment & Performance	Research	Financial & Marketing
Quasar	✓					✓	
Sand Research							✓
Smart Brain Technologies	✓						
Starlab	✓	✓		✓	✓	✓	
The Mind Lab							✓
TMSi		✓				✓	
Zeo	✓						

Table 10: Companies by sector.

Most of these companies have entered the market in the last five years. A subset of these companies has provided data on their origins. Of those formed in the EU, 3 out of 6 have participated in EU projects in the early stages. Many companies outside of the EU also relied heavily on government grant support.

> This is a growing area, and by far the greatest share of sales and investment falls outside of traditional BCI activities like AT.

Company	Founded	Where	EU funding
Advanced Brain Monitoring	1997	US	No
BitBrain Technologies	2010	Spain	Yes
Cortech Solutions	2001	US	No
g.Tec	1999	Austria	ND*
Mega Electronics	1983	Finland	Yes
Mindgames	2009	Iceland	No

Mindlab	2005	England	No
Neuroelectrics	2011	Spain	No
Neurosky	2004	US	No
NeuroVigil	2007	US	No
Sands Research	2008	US	No
Starlab	2000	Spain	Yes
TMSi	1999	Netherlands	Yes

Table 11: BCI company data (*ND = Data not available).

How many people are using a BCI-System in 2011?

Among patients who need BCIs to communicate, perhaps several dozen people use a BCI at home fairly regularly. This rough estimate is based on discussions with different research groups and companies with relevant patient contact. This should increase to hundreds in the next five years, due partly to efforts described in on-going and upcoming EU and other projects. At the FBNCI workshop in September 2011, Theresa Vaughan from the Wadsworth-Center introduced the first large scale (about 25 subjects) effort to get BCIs to disabled users in home and hospital settings. Another large-scale effort is being developed through groups in Michigan and Pittsburgh.

Until recently, severely disabled clients without expert support have not adopted commercial systems. Most patients who use a BCI-System today are participants of a research project. They get the systems from an institute or a university and use it during the research study. Without on-going support from both carers at home (to help with the electrode cap and software setup) and experts from a research centre (for troubleshooting and updating), home BCI use is very rare.

Practical electrodes, improved software, better support for non-experts, and more trained experts could all facilitate wider adoption.

However, this dependence on support is changing because commercial products to help patients without expert support are finally available. The new Intendix system from g.Tec has sold over 30 units. Some of these sales are for demonstration systems, but other sales were to patients. Starlab has released a wearable wireless system for BCI research but as of yet no consumer products have been released. Business are also starting to emerge that focus on end-users and service, such as BitBrain and InteraXon.

Among healthy users, the aforementioned NeuroSky statistics overshadow other numbers, with over one million units sold and a projection of 5 million for 2011. Most of these sales are not complete NeuroSky systems, but chips that were used in other BCI products, notably the Star Wars Force Trainer. This is a very simple system compared to BCI assistive technologies, and may reflect a growing trend toward cheaper, simpler BCIs, at least within healthy user groups.

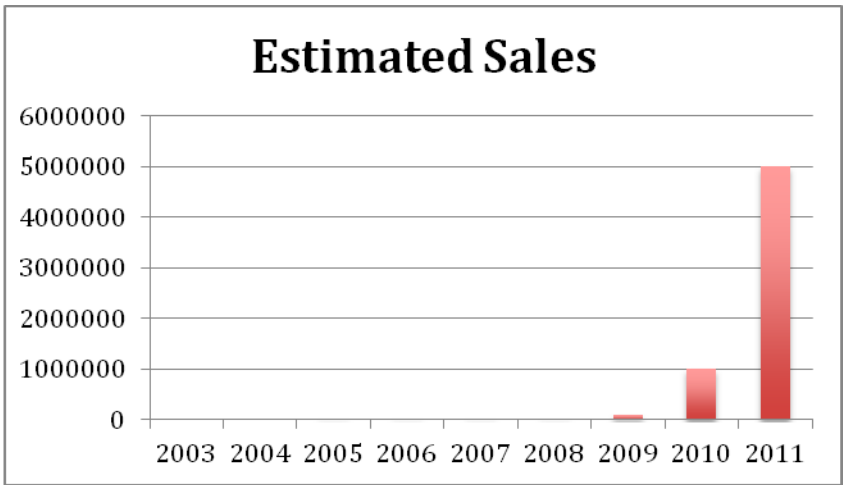


Figure 23: Estimated global sales of BCI devices.

Regulatory Issues

For any company entering the market with a BCI device a major factor will be the regulatory landscape that they find themselves in. Traditionally, BCI has been considered a “safe” technology but now that BCIs are becoming mainstream the numbers of healthy users may increase significantly. This will likely lead to a re-evaluation of the regulatory issues. In the following section we highlight some of the issues that will affect companies entering this market.

Every manufacturer decides the intended use of its product, and the intended use determines the kind of device. For the regulatory environment, a product can be graded into three groups:

1. Medical device
2. Assistive device
3. Consumer device

Currently academic BCI research is carried out in all three but with a focus on assistive devices.

Medical or nonmedical BCI?

Right now, no non-invasive BCIs are licensed as medical devices. This refers to classically defined BCIs for communication, and not (for example) neurofeedback training systems. In the United States, Neural Signals Inc. reports that “NSI's approval is suspended until we can become compliant with the new rules. This is extremely expensive.”[47] Cyberkinetics Neurotechnology Systems was an American company that launched the first multi-site pilot clinical trial of an intracortically-based BCI. Cyberkinetics made possible human use of the "Utah" implantable microelectrode array and associated recording hardware that was previously manufactured for laboratory use by Bionic Technologies. Cyberkinetics received two IDEs for its BrainGate studies, and 510(k) clearance for use of the array and other parts of the recording system for less than 30 days (known as "NeuroPort"). When Cyberkinetics ceased operations in 2009, the manufacturing division of Cyberkinetics became Blackrock Microsystems, which continues to manufacture the array, recording equipment, and

---

[47] Source: Email from Dr. Phil Kennedy, CEO of Neural Signals, Inc., 18 Sep 2011. Reprinted with permission.

associated hardware for BCI research and clinical use. For more information on Medical Device certification see: Medical device regulations global overview and guiding principles, WHO, 2003[48], EC Directive 93/42/EEC Medical Devices [49], EC Directive 90/385/EEC Active Implantable Medical Devices [50], and The future of medical devices in Europe [51]. For the most part, traditional non-medical BCIs would be classified as Assistive Devices.

According to the definition provided in ISO 9999:2011[52] “Assistive products for persons with disability - Classification and terminology”, Assistive Products are understood to be any product (including devices, equipment, instruments, technology and software) specially produced or generally available, for preventing, compensating for, monitoring, relieving or neutralizing impairments, activity limitations and participation restrictions. Assistive Technology is technology used by individuals with disabilities in order to perform functions that might otherwise be difficult or impossible. Assistive technology can include mobility devices such as walkers and wheelchairs, as well as hardware, software, and peripherals that assist people with disabilities in accessing computers or other information technologies. In 2009 a report for e-inclusion with the title “Analysing and federating the European assistive technology ICT industry"[53] was published and focused on five topics.

- Hearing aids
- Braille display
- Environmental control systems
- Software
- Communication devices

BCI is not explicitly mentioned but we are clearly dealing with applications that fall under the last 3 categories. For consumer devices such as the Neurosky based toys we are not dealing with medical or assistive devices and no certification beyond standard safety is required. Specific applications of BCI technology may indeed be classed as medical devices but for the most part this is not the case. We can conclude that the extra burden placed on companies to comply with regulatory requirements is not a key factor in the commercialisation of non-invasive BCI technology.

---

[48] www.who.int/medical_devices/publications/en/MD_Regulations.pdf

[49] http://ec.europa.eu/enterprise/policies/european-standards/documents/harmonised-standards-legislation/list-references/medical-devices/index_en.htm

[50] http://ec.europa.eu/enterprise/policies/european-standards/documents/harmonised-standards-legislation/list-references/implantable-medical-devices/index_en.htm

[51] http://www.epc.eu/prog_forum_details.php?cat_id=6&pub_id=1096&forum_id=7&prog_id=2

[52] http://www.iso.org/iso/iso_catalogue/catalogue_tc/catalogue_detail.htm?csnumber=50982

[53] http://ec.europa.eu/information_society/newsroom/cf/itemlongdetail.cfm?item_id=4897

European Union vs. United States

The European Union (EU) contains 27 member States. All of these member states of the European Union have different legal systems, regulations, procedures, traditions, infrastructures, per capita income, etc. The United States (US) contains 50 states. While the different states vary in many ways, the interstate differences in many factors are fairly minor. Many legal guidelines and regulations are established at a federal level, and there is a stronger tradition of interstate mobility and trade. Hence, in some ways, market analyses within the European Union must account for greater regional distinctions than analyses within the US.

This is non-trivial and gives significant advantage to those launching medical devices in the US. However, if for the most part we are dealing with non-medical devices, the importance of this distinction will be reduced.

Reimbursement

For any medical or assistive device a major consideration will always be the reimbursement landscape in the country of sale. As with regulatory issues this will vary country by country and in the case of the US depends on the insurance provider rather than state, and hence can vary significantly in a single geographical area.

Intellectual Property

For many start-ups one of the major obstacles to protecting IPR is simply the elevated cost of the process. The cost of outsourcing an EU patent application can be as high as €6000, which can be significant in the very early stages of a company. International patent applications, other types of IP protection, and legal maneuvering can substantially increase costs.

Support for IPR protection would be very welcome in this first phase of development.

Ethical Aspects

Ethical aspects will gain importance as we see more and more products hit the market[54]. In short, some ethical challenges related to commercial BCI devices need to be resolved soon. For example, there is inadequate research on the short and long term side effects of using some types of BCIs and related systems. Hence, there is some risk that a commercial product, such as a home gaming or wellness system, will produce negative side effects. Another concern is confidentiality. As more people use devices that monitor physiological data, technology allows researchers to learn more and more from EEG and other data, the risks associated with data theft increase (Allison, 2010). New ethical guidelines could mitigate these and other problems, which entails support for projects that develop and disseminate ethical guidelines.

---

[54] Please see “Ethics”.

Looking Forward

It is not clear if we are experiencing the start of a BCI revolution or a “bubble” around neurotechnology. We are clearly seeing mainstream interest and investment in what was previously a niche market, with a high value proposition but limited scope for growth due to the small number of potential clients for traditional BCI assistive technologies.

There have been promising developments in 2011 alone. Both Neurosky and Emotiv have received over $10 million in VC funds and Neurovigil[55] raised VC funds at a valuation of over $200 million, which is greater than both Facebook and Google together at the same stage[56]. The Nielsen group acquired NeuroFocus, a Neuromarketing company that in turn has acquired wireless EEG technology from German start-up Nouzz[57]. Neurodevices recorded revenues of $7.98 billion with 13% annual growth in 2010[58].

Likely impacts of this investment and subsequent volume production on BCI hardware and software are:

- Improved usability (including reliability and more usable software)
- Improved robustness
- Lower costs

We will also see novel applications beyond those currently under development, which in turn may lead to further improvements.

However, this assumes that these companies are successful and find their BCI-relevant killer applications. If not their impact may be short-lived. Development may also be slowed by negative publicity, misrepresentation, excess hype, and inadequately qualified staff, much like neurofeedback (Allison, 2011).

Many researchers are not convinced that current consumer technology is good enough for BCI applications and therefore doubt the scope of application development possible with such technology, while those developing it counter that their devices are “good enough” for certain applications and will lead to Low-end disruption[59]. If these companies survive, the quality of the hardware and software will no doubt improve, and costs will drop further driving development.

A significant investment has been made in European BCI technology via various EU funded projects and we are starting to see the benefit in terms of EU companies competing at international level. However, we have not yet fully capitalised on on-going research. Much more can be done in terms of support for start-ups and spin-offs at the European level.

[55] http://www.neurovigil.com/

[56] http://mobihealthnews.com/10855/neurovigil-lands-venture-funding-impressive-valuation/

[57] http://www.neurofocus.com/

[58] http://www.neuroinsights.com/

[59] http://en.wikipedia.org/wiki/Disruptive_technology

We recommend support for:

- Contact and effective interaction with VCs
- IP protection, especially for smaller SMEs
- Basic research in both invasive and non-invasive technologies
- Tech transfer, including support for startups and spinoffs
- Research beyond traditional fields of assistive technology and medical applications
- Positive media representations
- Making BCIs more independent through improved software and online support tools
- Infrastructural improvements such as benchmarking, standards, and certifications

Surveys of Stakeholders in BCI Research

What do different groups think about different issues in BCI research? This question has become increasingly complex over the last few years, as new groups have joined our research field and new issues have emerged or developed. Fortunately, some recent surveys helped answer this question.

This section of the roadmap presents some examples of recent surveys of people involved in BCI research. We first overview our video interviews, which surveyed stakeholders on major questions we explore in our roadmap. We then present other surveys that explore the needs and expectations of target user groups. Next, we summarize our survey of 145 participants of the 2010 BCI Conference in Asilomar, California. These are only some examples of surveys, and most published surveys have argued that more surveys are needed. Also, many more surveys assess related issues like assistive technology in general.

Video Surveys of Stakeholders

We have been interviewing key stakeholders in BCI research who kindly volunteered to answer some questions about their background and about major issues in BCI research. The stakeholders reflect a mix of different sectors (academia, business, medical, government, and nonprofit), disciplines (neuroscience, psychology, engineering, mathematics, etc.), projects (Brain, Tobi, BrainGain, BrainAble, Asterics, etc.), countries (Germany, Holland, Austria, Spain, USA, China, etc.), target users (different groups of patients and healthy users), and invasive and noninvasive sensor types (cone electrodes, ECoG, fMRI, fNIRS, and EEG electrodes based on gel, water, or dry contact).

These interviews have been conducted at the Utrecht, Graz, and Barcelona BCI workshops. These interviews are publicly available on the fBNCI website (linked to youtube and vimeo channels) and could be of interest to many different groups. We also developed a short video about the 2011 conference in Utrecht[60], which is on our website under “Videos”.

We did not tell the interviewees what questions would be asked. Hence, their answers are spontaneous. We asked all people the same ten questions, and sometimes added one or a few additional questions specific to each interviewee:

1. How did you get involved in BCI research?
2. What are some of your favorite memories from your BCI research career?
3. Who has influenced you most in your career, and how?
4. What would you most like to accomplish in your career?
5. What are the biggest problems and challenges in BCI research?

---

[60] http://www.bci2011.eu

6. What are the most promising trends and solutions in BCI research?
7. Do you see any major disruptive technologies – groundbreaking developments that would dramatically increase BCI use?
8. Until recently, BCI research focused heavily on severely disabled users. Which new user groups do you expect to emerge, and why would they use BCIs?
9. Do you think that invasive and noninvasive BCIs are both promising directions?
10. Do you have any other comments about BCIs, promising funding directions, or major issues?

Producing these videos would normally cost tens of thousands of euros, including flight and hotel costs, equipment rental, salaries, and various production costs. Some of these costs were borne by the FBNCI Project. However, we also wish to thank other sources of help. We are grateful to other entities and projects that contributed to travel costs: Utrecht Medical Center, g.tec, Starlab, and the BrainGain project. We also thank the two veteran filmmakers who donated their time and use of professional equipment: Ms. Anna Sanmarti, an award-winning filmmaker with a strong interest in BCIs, and Dr. Valjamae, a former postdoctoral researcher at TUG and experienced editor, director, and technical contributor. We also wish to thank all interviewees.

Figure 24: An interview conducted at the 2011 Utrecht conference. Nick Ramsey (left) prepares to answer questions from Brendan Allison (right) while Anna Sanmarti (center) checks his microphone cable.

Overview of Recent Surveys

End user surveys

Participants' concerns included "accuracy, set-up simplicity, standby mode reliability and available functions"

A recent survey asked 61 persons with ALS a variety of questions relating to BCI use (Huggins et al., 2011; see also Gruis et al., 2011)[61]. Participants indicated that their main concerns were "accuracy, set-up simplicity, standby mode reliability and available functions". Interestingly, the survey asked about desired BCI performance. Respondents indicated that they prefer a system with 90% accuracy, at 12-15 letters per minute, within 2-5 training sessions and 21-30 minutes setup time per session. There aren't any BCIs that meet all of these criteria simultaneously, particularly for home use, but such BCIs are not unrealistic in the near future. For example, a P300 BCI for home use with a dry electrode system could allow above 90% accuracy, at several letters per minute, with no training and a few minutes of setup time. However, it would only work for some users, and would still require a carer to mount the electrode apparatus. Respondents were generally open to an invasive BCI, and recovery time was a major factor in their decision.

In a follow-up study, a focus group asked 8 individuals with ALS and 9 of their caregivers to discuss factors that determined their acceptance of BCIs for use in an in-home environment. Participants were generally optimistic about BCIs as assistive technologies and highlighted some important development priorities, such as a more convenient way to sense brain signals, increased support to facilitate independence for both users and carers, improved reliability and robustness to distraction, and more usable interfaces (Blain et al., 2012).

The BRAIN project also completed surveys of end users. The resulting documents were circulated throughout the consortium, and contained useful insights. For example, when asked about preferences for home automation control, control of heating and audio/video rated very high, whereas users did not care much about controlling lights. This document is titled "Can Brain Computer Interfaces Become Practical Assistive Devices in the Community?" and may be available on request from BRAIN.

Survey respondents wanted "functionality", "possibility of independent use", and "easiness of use"

The AsTeRICS project surveyed end users to assess the needs and desires of target users. 33 subjects with motor disabilities completed a questionnaire that asked them what they would like to accomplish with assistive technologies. Results showed that the users were interested in controlling Smart Homes, "studying and learning via internet/IT-based technologies, communication

---

[61] While these articles are copyrighted, a summary is publicly available online:

http://www.umresearchgrowth.net/pmr/about/raeabstracts/Speakers%202011/Digital%20Posters/Huggins,%20J.%20-%20Poster%20for%20James%20Rae%20Day%202011.pdf with friends and family, obtaining information about the local environment and leisure activities like playing videogames or e-shopping on the internet" (Nussbaum et al., 2011).

The TOBI project has also surveyed severely disabled users through different research efforts. A recent journal article described a survey of four severely disabled persons who used a BCI and then answered questions about their experiences (Zickler et al., 2011). Zickler and colleagues conducted other surveys of severely disabled BCI end users, and presented their results at conferences in 2009 and 2010[62]. Among other results, they showed that users especially want "functionality", "possibility of independent use", and "easiness of use" in their assistive technologies.

Recently, investigators at the VA Pittsburgh Healthcare System conducted a survey of 57 military veterans with spinal cord injury regarding their priorities for restoration of function and their preferences for brain-computer interface technology (Collinger et al., in review). The majority of the participants felt that a BCI would be very helpful for controlling an FES device for arm and hand function, bladder/bowel function, or standing and walking. Fewer individuals felt that a BCI would be very helpful for controlling other technologies like a computer or wheelchair. This was in line with their top priorities for functions that, if restored, would have the greatest impact on quality of life. Non-invasiveness and being able to operate the device independently were the most important design criteria for a BCI, however more than half would consider having surgery to implant a BCI. Different user groups are likely to have unique priorities for BCI design criteria as well as for which devices they would like the BCI to interface with in order to address specific functional needs[63].

Stakeholder survey

In May-June 2010, the Wadsworth Research Center coordinated a major international BCI conference in Asilomar, California. This conference drew over 200 attendees, including many established stakeholders from around the world. The stakeholders also had different backgrounds (such as medicine, engineering, or neuroscience), different levels of experience (from students to the most senior people), and represented different sectors (including academia, business, medicine, government, and nonprofit). Hence, the conference provided an excellent opportunity to survey a broad range of people.

The Asilomar survey was such a large effort that the results have so far occupied three published papers, and the results cannot be summarized here. Instead, key points that relate to roadmap issues and recommendations are highlighted below.

Additional details of the Asilomar survey are available. The material relating to ethical issues was published in an open-access journal, and hence is available online for free (Nijboer et al., 2011a). Researchers' opinions about the marketability of BCIs are available through different mechanisms. This work was presented as a talk at the Fifth International BCI Conference in Graz in 2011 (Nijboer et al., 2011b). This presentation was videotaped and will be made available through the FBNCI website.

---

[62] http://www.tobi-project.org/publications/

[63] This paragraph was contributed by the first author of this study via email dated 16 December 2011.

An online version of the material presented is available[64]. The Asilomar survey also asked researchers' opinions about dissemination to the public media (Nijboer et al., 2011c).

End user surveys indicate that:

- Major issues include independence, simplicity/usability, reliability/accuracy/performance, and functionality.
- Desired applications include smart home control, bodily functions, communication, and entertainment. Different surveys showed different priorities.
- The majority of users, but not all, would consider using an invasive BCI.

The Asilomar survey indicated that:

- There is considerable disagreement about the definition of a BCI, although some aspects are less controversial than others.
- Respondents generally felt that invasive BCIs could offer benefits that outweigh the risks.
- Ethical issues were considered pressing, and most respondents favored BCI-specific ethical guidelines and certifications within five years.
- Respondents strongly felt that scientists should moderate their enthusiasm when talking to the media, be responsible for fact checking, and speak out against inaccuracies. However, respondents were divided over the appropriateness of speculating about long-term visions.
- The majority of respondents felt that BCIs for healthy users and as assistive technologies were on the market now or would be viable within five years, while the majority felt that BCIs for prosthetic control were more feasible beyond five years.

---

[64] http://prezi.com/nnuig5ke_aia/the-marketability-of-brain-computer-interfaces/

Project Summaries

This roadmap aims to inform and educate people about different BCI research efforts, and help develop realistic expectations about what to expect from different projects. For a policymaker considering funding a project, or a taxpayer unsure whether funds are well spent, this section provides several examples to help show how much progress is realistic for small, medium, and large projects. The projects in this section range from smaller projects to huge multinational efforts with dozens of partners and tens of millions of euros in funding.

This section is composed primarily of material provided to FBNCI by other projects. We asked many Project Coordinators to provide “1-3 page summaries of their projects, include a project overview, summary of accomplishments (except for new projects), the project website, and at least one paragraph with your recommendations for BCI funding directions.” The resulting contributions can be found in the rest of this section.

Overview of H3 Research Cluster

Future BNCI is part of the H3 Cluster of projects funded within the Information and Communication Technologies Theme by the Seventh Framework Programme in the European Commission[65]. This cluster has thirteen projects. Three of these projects (Brain, Tremor, and Tobi) began in 2008, seven others (including Future BNCI) began around Jan 2010, and three other projects (ABC, BackHome, and Way) are just beginning, with launch dates near December 2011. This section includes summaries of these projects, along with the following tables and figures that overview the activity in our cluster.

Figure 25: The logo representing the H3 BNCI research cluster.

---

[65] http://ec.europa.eu/information_society/activities/einclusion/research/bnci/fp7_cluster/index_en.htm

INFSO H3 BNCI research cluster: Project name		ASTERICS	BETTER	BRAIN	BRAINABLE	DECODER	F-BNCI	MUNDUS	TREMOR	MINDWALKER	TOBI	ABC	BACKHOME	WAY	Σparticipations	Country total	CO
Instrument		STREP	STREP	STREP	STREP	STREP	CA	STREP	STREP	STREP	IP	STREP	STREP	STREP			
Kompetenznetzwerk Informationstechnologie zur Förderung der Integration...	**AT**	C													1		1
Guger Technologies	**AT**		P		P	P							P		4		0
Technische Univ. Graz	**AT**		P		P	P	C				P	P	P		7		1
Fachhochschule Technikum Wien	**AT**	P													1		0
Technische Univ. Wien	**AT**							P							1		0
																14	
Space Applications Services N.V.	**BE**									C					1		1
Univ. Libre Bruxelles	**BE**								P	P					2		0
Univ. Liège	**BE**					P									1		0
																4	
Ecole Polytechnique Fédérale de Lausanne	**CH**						P				C				2		1
Eidgenössische Technische Hochschule Zürich	**CH**							P							1		0
HOCOMA AG	**CH**							P							1		0
QualiLife	**CH**										P				1		0
Schweizerische Unfallversicherungsanstalt; Clinique Romande de Réadapt...	**CH**										P				1		0
Scuola Univ. Prof. della Svizzera Italiana	**CH**													P	1		0
																7	
University of Cyprus	**CY**	P													1		0
																1	
INSTITUT MIKROELEKTRONICKYCH APLIKACI S.R.O. (CZ)	**CZ**	P													1		0
																1	
ANT/e-imaging	**DE**									P					1		0
FRAUNHOFER-GESELLSCHAFT ZUR FOERDERUNG ...	**DE**							P				P			2		0
Technische Univ. Berlin	**DE**							P			P				2		0
Univ. Bremen	**DE**			C											1		1
Stiftung orthopaedische Univ.kliniek Heidelberg	**DE**										P				1		0
Kreuznacher Diakonie: Beratungsstelle für Unterstützte Kommunikation	**DE**										P				1		0
Univ Tübingen	**DE**		P			P					P	P		P	5		0
Julius-Maximilian Univ. Würzburg	**DE**					C					P		P		3		1
																16	
AALBORG UNIVERSITET	**DK**		P						P						2		0
																2	
Consejo Superior de Investigaciones Científicas	**ES**		C						C			P			3		2
Fundació Privada Barcelona Digital Centre Tecnològic	**ES**				C								C	P	3		2
Fundació Privada Institut de Neurorehabilitació Guttmann	**ES**				P										1		0
FUNDACION INSTITUTO GERONTOLOGICO MATIA - INGEMA	**ES**	P													1		0
INSTITUTO DE BIOMECANICA DE VALENCIA	**ES**		P						P			C			3		1
Starlab Barcelona SL	**ES**	P					P								2		0
Technaid	**ES**		P						P			P			3		0
TELEFONICA INVESTIGACION Y DESARROLLO SA	**ES**			P											1		0
Universitat Pompeu Fabra, Institute of Audiovisual Studies	**ES**				P										1		0
PLUX	**ES**											P			1		0
																19	
ÖSSUR	**IC**		P							P				P	3		0
																3	
ASSOCIATION DU LOCKED-IN SYNDROME	**FR**					P									1		0
Université Pierre et Marie Curie	**FR**	P													1		0
																2	
AB.ACUS SRL	**IT**							P							1		0
Associazione Italiana per l'assistenza agli spastici provincia di Bologna	**IT**										P				1		0
CF CONSULTING FINANZIAMENTI UNIONE EUROPEA SRL	**IT**							P							1		0
CONGREGAZIONE DELLE SUORE INFERMIERE DELL ADDOLORATA	**IT**							P							1		0
Fondazione Santa Lucia FSL	**IT**		P			P				P	P	P			5		0
POLITECNICO DI MILANO	**IT**							C							1		1
Sculoa Superiore di Studi Santa Anna	**IT**													C	1		1
Smartex	**IT**								P						1		0
UNIVERSITA DEGLI STUDI ROMA TRE	**IT**								P						1		0
																13	
TU Delft	**NL**									P					1		0
Maastricht Univ	**NL**					P									1		0
Philips Electronics	**NL**			P											1		0
Twente Medical Systems Intl	**NL**			P											1		0
Univ. Twente	**NL**						P			P					2		0
																6	
Harpo Sp. z o.o.	**PL**	P													1		0
Univ. Warsaw	**PL**			P											1		0
																2	
Meticube Sistemas de Informação, Comunicação e Multimedia, Lda.	**PT**				P										1		0
																1	
MASA POPOVIC PR - UNA SISTEMI	**SB**								P						1		0
																1	
Umea Universitet	**SE**													P	1		0
																1	
UNIVERZA V MARIBORU	**SL**								P						1		0
																1	
AbilityNet	**UK**				P										1		0
MEDICAL RESEARCH COUNCIL	**UK**					P									1		0
Cedar Foundation	**UK**			P									P		2		0
Sensory Software Ltd	**UK**	P													1		0
Univ. Glasgow	**UK**										P				1		0
Univ. Ulster	**UK**			P											1		0
Telehealth Solutions	**UK**												P		1		0
	mean:															**8**	
Number individual beneficiaries	7	9	9	7	7	9	4	9	9	7	12	8	6	6	**102**		13
Number of MS/FP7 assoc. countries	**17**													total no.of beneficiaries:			**65**
Max EC funding (rounded, in M€)		2.65	3.25	2.67	2.3	2.8	0.5	3.35	2.49	2.75	**9.05**	2.45	3.11	2.25	**39.62**		
INFSO H3 BNCI research cluster: Project name		**ASTERICS**	**BETTER**	**BRAIN**	**BRAINABLE**	**DECODER**	**F-BNCI**	**MUNDUS**	**TREMOR**	**MINDWALKER**	**TOBI**	**ABC**	**BACKHOME**	**WAY**	**Σparticip**	**MS total**	**CO**

Table 12: Funding in the INFSO H3 BNCI Research Cluster.

Project name	*BCI signal (EEG)*		*BNCI and other signals (non-EEG)*	
	used already	*intend to use*	*used already*	*intend to use*
Asterics	motor imagery	P300, SSVEP	Acceleration, webcam, EMG, EOG, assistive devices	
ABC	---	N/A	---	EMG, eye tracker, GSR
BackHome	---	P300, SSVEP, MI	---	EOG, ECG, EMG
Better	ERD/S, MRCPs		EMG, fNIRS, force, velocity	gaze tracking
Brain	SSVEP, ERD/S	abandoned P300	eye tracker	
Brainable	P300, MI	SSVEP		EMG, EOG, eye tracker, WiiRemote
Decoder	P300, ERD, SSEP, SSVEP	---		
F-BNCI	---	---	---	---
Mindwalker	MI, SSVEP		EMG	Inertia
Mundus	P300,MI	---	eye tracker, not simultaneously with EEG	
TOBI	MI, P300		EMG, assistive devices (buttons, joysticks)	
Tremor	MI		hdEMG, inertial sensors	iEMG
Way	---	N/A	---	EEG, EOG, or EMG

Table 13: The EEG (blue background) and non-EEG signals (red background) within the projects in the H3 cluster, subdivided according to signals that have already been used, and signals that will be used. FBNCI is a support action and thus does not develop new scientific or technical outcomes. Since ABC, BackHome, and Way are just beginning, these projects have not used any signals yet and for some no information was available (N/A).

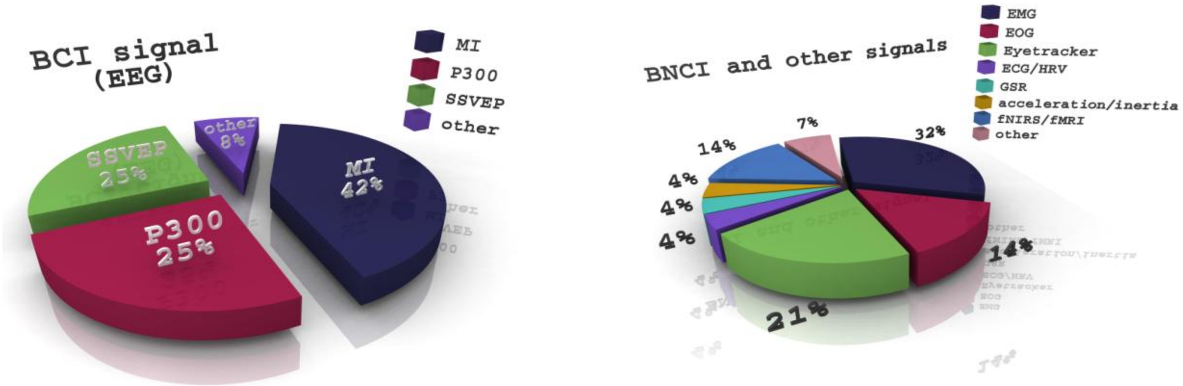


Figure 26: The left panel summarizes the distribution of EEG signals within the projects in the H3 cluster, and the right panel presents other signals.

Project name	Number	Project duration	Website
ASTERICS	247730	January 2010 - December 2012	www.asterics.eu/index.php?id=2
BETTER	247935	February 2010 - January 2013	www.iai.csic.es/better/
BRAIN	224156	September 2008 - December 2011	www.brain-project.org/
BRAINABLE	247447	January 2010 - December 2012	www.brainable.org
DECODER	247919	February 2010 - January 2013	www.decoderproject.eu
FBNCI	248320	January 2010 - December 2011	future-bnci.org
MINDWALKER	247959	January 2010 - December 2012	https://mindwalker-project.eu/
MUNDUS	248326	March 2010 - February 2013	http://www.mundus-project.eu/
TOBI	224631	November 2008 - January 2013	http://www.tobi-project.org/
TREMOR	224051	September 2008 - April 2010	http://www.iai.csic.es/tremor/

Table 14: Summary information about the ten established projects in our cluster. The three new projects (ABC, BackHome, and Way) have just begun and do not have websites yet.

H3 Research Cluster Project Summaries

Future BNCI is part of the H3 Cluster of projects funded within the Information and Communication Technologies Theme by the Seventh Framework Programme in the European Commission. This cluster has thirteen projects. Three of these projects (Brain, Tremor, and Tobi) began in 2008, seven others (including Future BNCI) began around Jan 2010, and three other projects (ABC, BackHome, and Way) are just beginning, with launch dates near December 2011.

ABC

The ABC project just began in November 2011, shortly before this roadmap was completed. The project does not yet have a logo, website, or major accomplishments. This section reprints the official project summary for the European Commission.

ABC aims at increasing human capabilities by means of Brain/Neural Computer Interfaces (BNCI). The project will develop applications addressed primarily to persons with Dyskinetic Cerebral Palsy (DCP). Due to the particular conditions associated with DCP, BNCI-based systems present a huge potential for improving the quality life and promoting independent living for this target group. In particular, the project outcomes will specifically focus on the augmentation of the capabilities related to communication, learning, social participation and control of devices. The ABC system will be composed of four independent modules based on the latest advancements in BNCI signal processing, Affective Computing, Augmented Communication and Biosignal Monitoring. The reference European research institutions in each field will lead the R&D work. DCP end-users and care professionals will be involved in R&D tasks from design to validation. To involve effectively persons with DCP into the design process, new user-centred design methods will be developed. The project will deliver a functional prototype of the ABC system validated and working in out-of-lab contexts. Two industrial SMEs will also be involved throughout the project in order to facilitate the transition from prototypes to commercial products and shorten the time-to-market of the ABC system. The modular structure of the ABC system and the independence of its components will extend its exploitation potential beyond the initial DCP niche. Different combinations of the modules could be integrated into other assistive product niches such as for people with multiple sclerosis or quadriplegia. Moreover, the ABC modules (both combined or stand-alone) have the potential to become part of mainstream applications benefitting from the augmentation of human capabilities, such as gaming, e-learning, work safety or driving assistance among others.

AsTeRICS

Assistive **Te**chnology **R**apid **I**ntegration and **C**onstruction **S**et

More than **2.6 million people in Europe** have **problems with their upper limbs** and therefore many of them depend on Assistive Technologies (AT). As the potential of the individual user is very specific, adaptive ICT-based solutions are needed to let this population group participate in modern society. Such solutions are rarely available on today's market.

AsTeRICS will provide a **flexible** and **affordable construction set** for realising **user driven AT** by combining emerging sensor techniques like Brain-Computer Interfaces and computer visual perception with basic actuators. People with reduced motor capabilities will get a flexible and adaptable technology which enables them to access the Human-Machine-Interfaces (HMI) of the standard desktop but also of embedded systems like mobile phones or smart home devices.

AsTeRICS will implement a set of **building blocks for the realisation of AT**:

- **Sensors** which allow the individual to exploit any controllable body or mind activity for interacting with human machine interfaces (HMI).
- **Actuators** for interfacing with standard IT, embedded systems and the environment
- An **Embedded Computing Platform** that can be configured to combine sensors and actuators to tailored AT-solutions which support the full potential of an individual user.

The core of the software suite will be provided as **Open Source**. The complete system will be affordable for many people who cannot benefit from leading edge supportive tools today. The following figure outlines the concept of the AsTeRICS construction set, which consists of several modules and a software suite for configuration of the overall system:

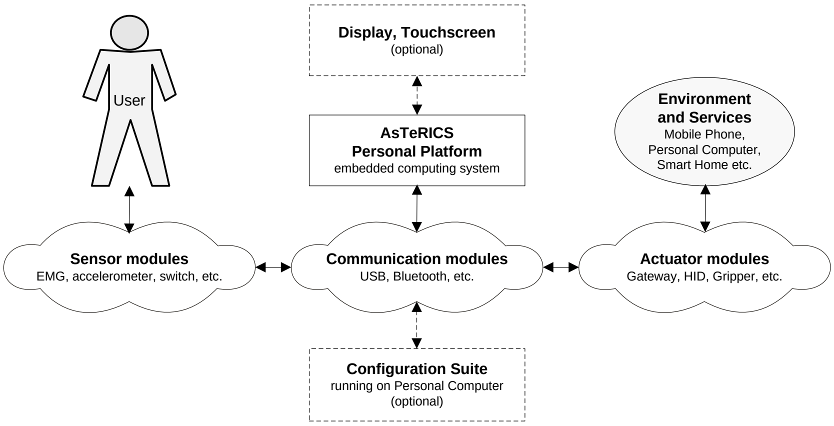


Figure 27: The AsTeRICS construction set.

AsTeRICS revolutionises the concept of AT: AT today mostly focuses on a certain task or situation. Due to the growing importance of the PC, AT has been oriented towards standard Human-Computer (HCI) or desktop interfaces. AsTeRICS respects the strong need for flexible, adaptable AT functionalities accompanying people with disabilities away from the desktop, enabling them to interact with a diverse and fast changing set of deeply embedded devices.

Major Accomplishments: Work in the first 6 months of the project was largely focussed on user involvement and system architecture and specification. A user survey was performed with primary as well as secondary users and experts. Data were analysed and technical requirements were derived from the results.

A further source of input for the system requirements was a thorough state-of-the-art analysis and of course an analysis of basic technologies that are of best use to achieve the project's goals and help as many end users as possible.

In project month 6 the system specification and architecture for the first prototype were finalised and soft- and hardware development work were started. The topic of IPR-issues has also been considered before starting actual development work. The second half of the first and the first half of the second project period were dominated by technical development on the hard- as well as on the software side.

On the hardware side the AsTeRICS hardware platform prototype 1 was developed as well as a general purpose input/output module and an analogue-to-digital/digital-to-analogue converter module. The firmware for the latter two has been finalised in project month 12 and 7 pieces of both have been manufactured for the prototype-1 tests. In the remaining months of the Prototype 1 period a core expansion interface module has been developed, manufactured and integrated with the chosen embedded PC into the functional Personal Platform. Additionally accelerometer and IMU sensors and an HID actuator were designed. The strategy for the development of the Smart Vision Module has been refined. Furthermore a pneumatic Gripper on a mouth-stick has been developed and tested.

On the software side the AsTeRICS Runtime Environment (ARE), the AsTeRICS API (ASAPI), the AsTeRICS Configuration Suite (ACS) and the AsTeRICS BNCI Evaluation Suite have been developed, tested, refined and integrated. Models can be created on the configuration suite, transferred to the runtime environment by using the ASAPI and furthermore can be started, paused, continued and stopped on the runtime environment. It is also possible to store different models on the ARE to easily select them later. First steps towards the easy configuration of certain parameters directly on the ARE have been made. Furthermore an interface to certain 3rd-party software has been developed ("Native-ASAPI") and the OSKA on-screen keyboard (by Sensory-Software) has been successfully integrated to work with AsTeRICS and serve as a key user-interface.

After the integration of all system parts, the first prototype of AsTeRICS was finalised. Together with several sensors and actuators (some of which were also developed in the context of the project) the prototype has been thoroughly tested – many models have been put together for this purpose. In June 2011 the prototype 1 user tests were started in Austria and Poland. Tests in these two countries, as well as in Spain, continued until the end of July 2011. The results from these tests have now been used to steer prototype 2 design decisions.

Many of the actuators that have been interfaced to the AsTeRICS system could be very interesting for the BNCI community, e.g. to apply existing BNCI control channels in system showcases, demonstrators and - most important - useful applications for end-users. These actuators include local and remote cursor and keyboard control, the KNX home automation gateway, an individually configurable Infrared Remote, custom actuators like the pneumatic gripper, the Abotic Door Opener system and other generic actuators which can be interfaced via relays or open collector outputs. All these features can be integrated into existing BNCI systems very easily by making a plugin or using a communication channel to the ARE.

Challenges and recommendations: The development of AsTeRICS exemplifies a perfect playground for testing BNCI technologies out of the lab, which constitutes one of the most important future goals for the further development of this application field, because of the intrinsic project nature. Hence BNCI technologies can be developed on its own but also in combination with assistive technologies. But additionally, the resulting systems are tested by a wide group of users with disabilities both in computer-centric and general daily scenarios. As a result of these tests we can issue the following recommendations for BNCI future funding.

Our funding recommendations are grouped around different types of targets:

- Sensors, signals, and algorithms:
    - Currently the variability of BNCI performance among different subjects is very large. This means BNCI algorithms have to be trained and personalized for each subject to show a feasible performance, which anyway is not come close to 100%. So, in our opinion, there is a great need to overcome such variability through the development of new algorithms particularly targeting this problem.
    - The most reliable methodologies for the analysis of evoked potentials are based on averaging, which makes the system slow and often impractical. Therefore algorithms based on single trial classification should be further developed.
    - There is a general need for extending the number of degrees of freedom in BNCI modalities. Focusing on the case of motor imagery, the algorithms perform at a reasonable level only if the number of modalities is reduced off-line to select the best signals for each subject. One way of using four freedom degrees is based on extensive training but normal users are so discouraged by initial bad results that they do not try again. So data analysis algorithms for motor imagery should be improved and/or new modalities should be sought.

  - Almost all BNCI modalities work on a detected/non-detected basis, which are able only to generate binary output signals. Therefore new modalities able to generate real-valued signals should be explored and furthered developed.
  - Affective computing and the integration of user state in BNCI systems should be further developed in order to improve the user friendliness of existent BNCI systems. Methodologies for data analysis and performance evaluation are at a very early stage of research in these fields.
- BNCI systems:
  - There is a lack of systematic and overall accepted performance evaluation procedures and measures for the simplest algorithms working with EMG, and EOG. The field needs standardized performance measures, which vary a lot among research groups, and of taking real-world scenario aspects into consideration, e.g. sensitivity, variability with respect to subject state.
  - Nowadays there is no systematic view on how to develop BNCI hybrid systems. This applies both to computing frameworks and the related technologies. As a consequence these fields should be further developed.
- BNCI technologies and tools:
  - Few works have been focused on the technological background on how to include algorithms of increasing complexity for its recall in real-time applications as most assistive technologies do. So computational intelligence and machine learning methodologies have to be revisited from this point of view.
  - BNCI tools written in real-time and embeddable programming languages are rare. If they exist, they are too general frameworks that hinder their integration in particular applications. Hence modular tools that can easily be integrated in more general applications as the ones being developed for assistive technologies should be developed in the future.
  - It is worth pointing out the need to support the further development of BNCI recording hardware. In this context dry electrodes for BNCI are still an important future milestone. This should be followed by the creation of frameworks that allow seamless integration of HW and SW algorithms - and their interconnection with modules for HCI (customizable mouse / keyboard emulation) and environmental control systems, e.g. AsTeRICS platform.
- One of the main problems for BNCI engineers within the project works and assistive technologies community is the lack of knowledge both from most technical staff and almost all end users of BNCI technologies. Hence, in our opinion dissemination among other technological fields has to be improved in order for a wider community to be aware of BNCI research capabilities and achievements.

BackHome

Brain-neural computer interfaces on track to home – Development of a practical generation of BNCI for independent home use.

Motivation and Need: The long term goal of rehabilitation for the individual with an acquired brain injury is resettlement back in the community away from institutional care. The ideal scenario is that the person will return to their previous home and life roles; however it may be necessary for supported housing options to be considered. Ideally, in the early phase post-discharge additional home care is provided to support the individual and their family. However, this is not always the case and if provided it is often not long enough to achieve the maximum possible independence. The transition to the home is often very difficult and traumatic. The family must take care of persons with functional diversity, often with help from paid carers. There is little or no support for transitional rehabilitation systems, tele-monitoring or tools to keep in touch with key people. Often, the communication and control solutions that patients have learned to rely on do not work, and nobody can help them. We have encountered many cases where communication and interaction were hardly possible simply because AT were not provided or not optimally adapted.

Therefore, there is a clear need to identify and address specific problems relating to **bringing BNCIs out of the lab and into the home**. BackHome develops around opportunities from other FP7 grants, which have performed relevant BNCI developments and elucidated patients' needs through surveys and field experience[66]. This means that we do not need to focus on developing entirely new BCI systems, but can focus on making existing systems more flexible and usable. Other projects outside of our cluster have also surveyed users to assess their needs (e.g., Huggins et al., 2011). This work has further confirmed that patients do not need BCIs that are dramatically faster or more powerful. Existing BNCI systems can provide many useful functions. Instead, what users want are BNCIs that work, reliably, at home, without extensive support. Based on these surveys, and our experience, we determined that the patients' main needs are practical electrodes and better software support.

Project overview: The main goal of BackHome is to advance existing BNCI systems into a more practical solution for home use. BackHome will address this goal through (1) software and hardware development, (2) applied research for defining outcome measures and (3) basic research into BNCI-elicited brain plasticity that may foster maintenance and restoration of cognitive and physical functioning. BackHome will lay the foundations for a more efficient BNCI in a community setting. In addition, more commercially competitive products are proposed. To attain these goals, the primary focus will be on practical electrodes, telemonitoring and software support, and easy-to-use applications to facilitate activities of daily living and entertainment and thus, improve social integration and quality of life.

---

[66] See "Surveys of Stakeholders".

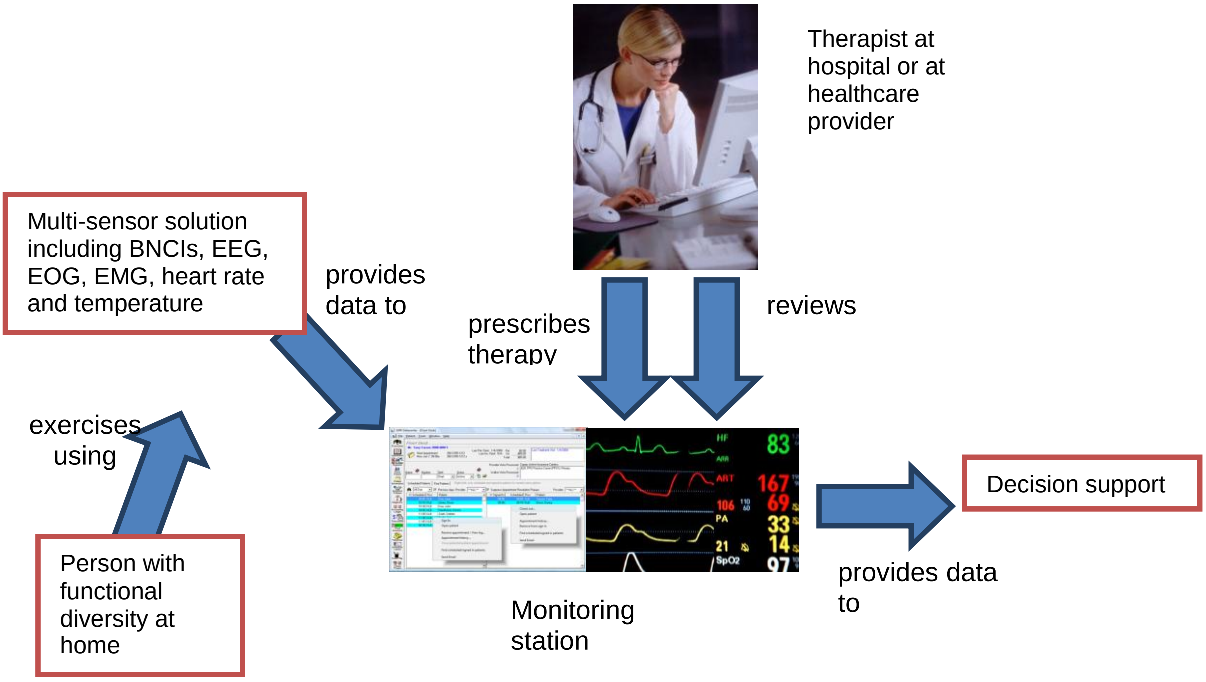


Figure 28: A schematic overview of the BackHome system that will be developed.

The main goal of advancing existing brain-neural computer interface (BNCI) systems into a more practical solution for home use can be expressed as several general objectives:

G.1. To study the transition from the hospital to the home, focusing on how people use BNCIs in both settings

G.2. To learn how different BNCIs and other assistive technologies work together

G.3. To learn how different BNCIs and other assistive technologies can help clinicians, people with functional diversity and family in the transition from the hospital to the home

G.4. To reduce the cost and hassle of the transition from the hospital to the home by developing improved products and disseminating information for different developers and users.

G.5. To produce applied results, developing:
i) a new and better integrated practical electrode system
ii) friendlier and more flexible BNCI software
iii) better telemonitoring and home support tools
iv) a better support infrastructure

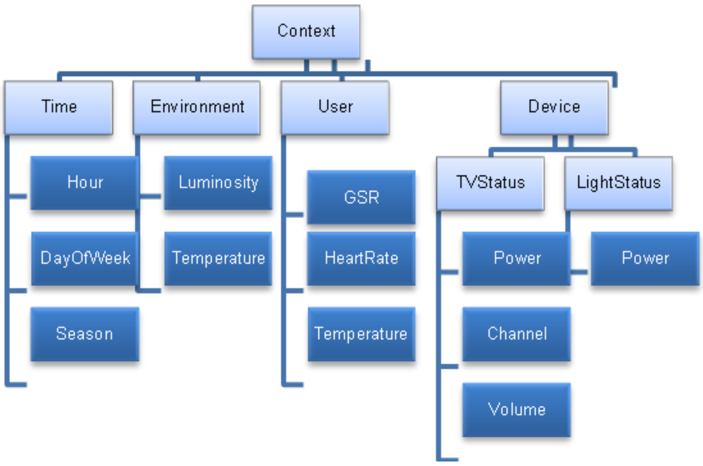


Figure 29: BackHome will use information about the environment, user, device state, etc to improve its context awareness. This will facilitate more natural, intelligent interaction with each user.

Major accomplishments: The BackHome project will begin in January 2012, shortly after this roadmap is published. BackHome will soon develop a project website. For more information, please contact the Project Coordinator, Felip Miralles.

ROADMAP RECOMMENDATIONS

In addition to our recommendations for BrainAble, we recommend:

1) **Practical electrodes:** Sensors that do not require gel could dramatically improve comfort and setup time, and reduce the burden on carers.

2) **BCIs with existing devices:** BCIs should be able to seamlessly communicate with other devices, using Universal Remote Control, Universal Smart Home, and other technologies.

3) **Passive monitoring:** Using information about cognitive and emotive state, such as whether a user is fatigued or confused, to improve overall interaction.

4) **Automated configuraton tools:** Users need automatic software that identifies the best parameters for each user and configures a BCI to individual needs without hassle.

5) **Improved telemonitoring and telesupport tools:** It should be easier to interact with users in their homes, diagnose problems, and provide support.

6) **Increased engagement with end users:** BackHome will feature Open Houses and other events to connect with target users, carers, and medical personnel.

BETTER

Brain-Neural Computer Interaction for Evaluation and Testing of Physical Therapies in Stroke Rehabilitation of Gait Disorders.

Motivation: Most promising interventions to restore walking function are based on robotic systems that intend to restore function by focusing on actions at the periphery of the body (a Bottom-Up approach). By imposing gait-like movements, such robotic devices are thought to provide many of the afferent cues critical to retraining locomotion. There is no consensus in relation to the functional benefits of these approaches.

Figure 30: Scenarios of application of BETTER therapies.

BNCI-based tools to assist physical therapies delivered at two rehabilitation stages: Joint mobilization (with wearable exoskeletons) and gait training (with body weight support with robotic assistance).

BETTER proposes a multimodal BNCI whose main goal is to explore the representations in the cortex, characterize the user involvement and modify the training.

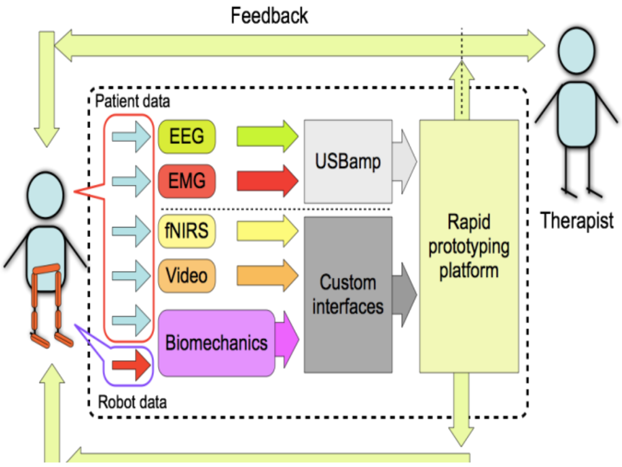


Figure 31: BNCI system concept 1.

BETTER develops new rehabilitation therapies with tools that provide functions under a novel *Top-Down approach*: The robotic physical stimulation -at the periphery- can be delivered as a function of targeted *neural activation patterns* (related to user involvement) that can be estimated with a novel BNCI system. This intervention should help reorganize the cortex. Such Top-Down therapeutic treatment should *encourage plasticity* of the affected structures to improve motor function.

BETTER therapies are designed and developed for existing and new robotic rehabilitation devices. The BETTER BNCI, integrated with such robots, integrates multimodal information from electroencephalogram (EEG), electromyogram (EMG), functional near-infrared spectroscopy (fNIRS), and mechanical information (from inertial mechanical units, IMUs) to assess the patient's cortical patterns, motor recovery, compliance, and effort.

Case scenario 1: During joint mobilization, novel feedback features (based on EMG, EEG and fNIRs are researched and developed to support the therapy and increase recovery. The patient is able to adapt and improve the quality of the locomotor pattern during training joint movement

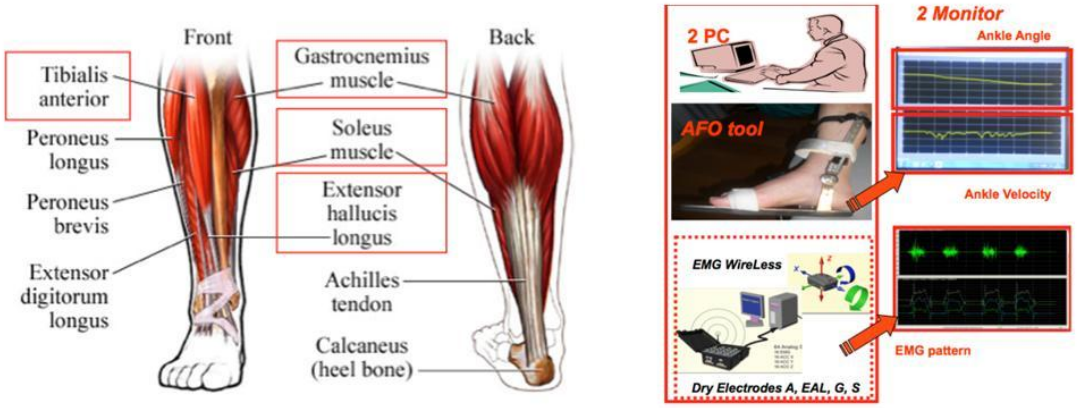


Figure 32: **Case scenario 1: BETTER NCI for joint mobilization with ambulatory exoskeleton.**

Case scenario 2: During gait training, novel feedback is generated (estimated from EMG, EEG and IMU signals) to drive the robotic intervention, assess compliance and improve patient performance and involvement.

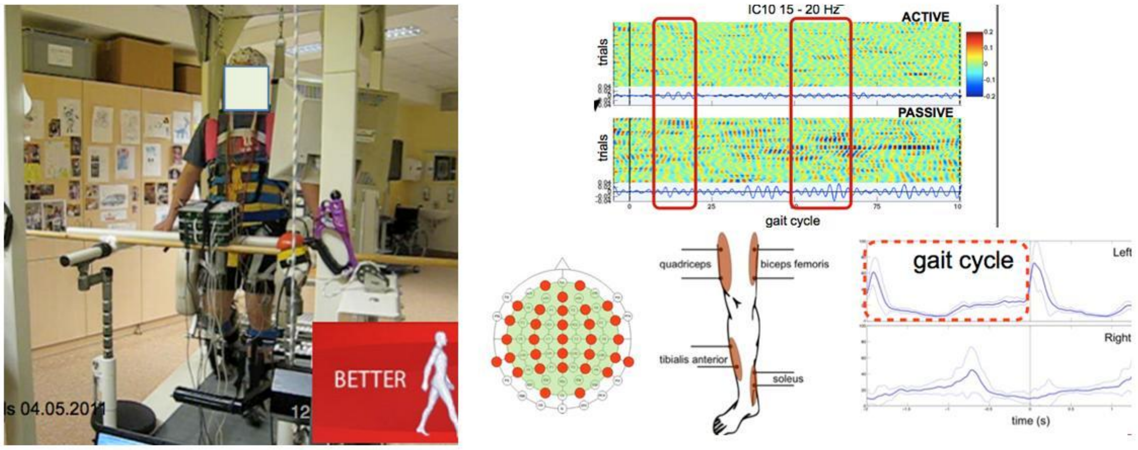


Figure 33: Case scenario 2: BETTER BNCI for gait training with non-ambulatory exoskeleton.

Major accomplishments: At the halfway point in the duration of project, a first prototype of the functional BNCI system to be used in the BETTER project has been developed. The first prototype of the functional BNCI system has a passive role, in the sense that it provides information to both the patient and the therapist, but it does not provide direct control over the robotic trainer. In turn, it will provide new signals for immediate or periodic adaptation of the therapy. Based on the first findings of testing with stroke patients, the outputs of the BNCI system will be used to activate or modulate the robotic trainers.

1 The system provides a means to assess compliance through a multimodal BNCI. The proposed BNCI combines CNS and PNS data with biomechanical data.
2 It will make it possible to investigate whether adding lower limb tasks to robotics devices improves restoration of lower limb function.
3 BETTER is generating tools for objective evaluation of the BNCI-based physical rehabilitation therapy and its usability and acceptability.

The current functions of the BETTER BNCI prototype include: monitoring cortical reorganization, detection of movement intention, detection of post-movement beta rebound, assessment of muscle activation and assessment of compliance. Additional functions are under research and development, such as detection of involuntary movement with EEG/EMG and assessment of compliance with novel video-based measurement systems.

A non-ambulatory robotic gait trainer has been integrated with the first BNCI prototype and enables a number of studies with control subjects. Scientific papers on the foundations of the therapy and neurophysiology of human walking have been published and are under development to disseminate the knowledge that BETTER brings to the community.

A novel exoskeleton prototype for ambulatory (unrestricted movement) therapy, to train uniarticular and biarticular movements has been prototyped and is under integration and functional testing of partial components.

From the current experience in BETTER we envisage a number of directions for FP8:

- Further use and adaptation of the novel BNCI tools that enable breakthroughs in the motor control field.

- Specific tools for assisting training concrete patient groups should be delivered as spin-off results of multimodal BNCIs.

- Clustering with projects and researchers in the field of biomechanics is crucial for the success of BNCIs applied for motor recovery. A strong biomechanical background should support initiatives to integrate current and novel movement analysis tools in novel activities.

- Promoting infrastructure and project instruments that enable large scale clinical evaluation to produce sound evidences and benchmarking is crucial for the long-term sustainability of the different BNCI research efforts.

BRAIN

BRAIN (BCIs with Rapid Automated Interfaces for Nonexperts) develops BCIs into practical assistive and ICT tools to enhance inclusion for a range of different disabled users.

BRAIN improves BCI reliability, flexibility, usability, and accessibility while minimizing dependence on outside help. These improvements entail upgrades to all four components of a BCI system - signal acquisition, operating protocol, signal translation, and application. BRAIN has developed hardware and software components of a new practical BCI system through four scientific and technical objectives: convenient setup, individualised BCI, application suite, and evaluation.

Convenient setup: BCI setup normally requires about 20 minutes. After each session, at least 20 minutes are needed to wash the cap and the person's hair. An expert must precisely position the electrodes, scrape the person's head, apply electrode gel, measure electrode impedance, and identify bad or misplaced electrodes. BRAIN's goal was to develop a lightweight, inexpensive and straightforward EEG acquisition system that can be easily mounted on the head without expert supervision, reducing both setup and cleanup time to only several seconds, and greatly improving accessibility and usability. To this end, BRAIN upgraded two aspects of the system needed to acquire data from the user: electrodes and the measuring system. The EEG sensor approach that has been developed is a new **water** based EEG **sensor** system that makes preparation much faster and easier, eliminating the need for unpleasant conductive gel or expert help. The water electrodes function for at least eight hours if regular tap water is applied. Unlike conventional electrodes, the new water system does not require abrading the skin, applying electrode gel, washing the cap, or shampooing the hair. The water electrode system has been integrated into an easy to use **head wrap** (see Figure 34). Improved amplifier hardware from TMSi, including a new wireless high-impedance **amplifier** to allow effective operation despite noise, completes the BRAIN acquisition system.

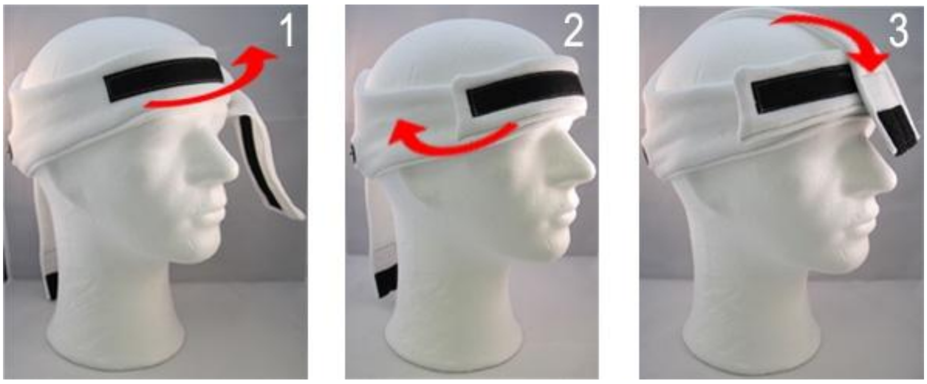


Figure 34: SSVEP head wrap.

Individualized BCI: To maximize BCI information throughput for each subject without assistance, BRAIN has developed automatic tools that identify the best BCI parameters for each subject and customise the BCI accordingly. Two BCI approaches were explored within BRAIN: SSVEP and ERD/ERS. For **ERD/ERS**, a new mathematical approach and software were developed to determine best individual frequency ranges, relevant electrode sites, spatial filters and relevant features to train a multinomial logistic regression classifier for the detection of different motor imagery classes (e.g., right hand, left hand, and feet). Our findings during software evaluation runs revealed the relatively small share of (neuro)psychological factors (e.g. power of imagination, degree of attention, type of operant conditioning) within the operational effectiveness. To a greater degree, physiological parameters seem to determine the capacity to proper handling of a sensorimotor-driven BCI. In particular the amplitude values of various endogenous rhythms in the background EEG turned out to be suitable predictors for a subsequent ERD/ERS performance. Beyond, the presence of such characteristics obviously provides the basis for a measurable improvement of the individual achievements. Accordingly, subjects that were lacking the physiological requirements consistently failed to enhance their performance, even during several sessions of training. In the case of **SSVEP**, while the state-of-the-art uses stimulation frequencies lower than 30 Hz, the approach in BRAIN has been to apply flickering frequencies in the high frequency range (>30 Hz) in order to diminish the stimulus annoyance and lower the risk for photo induced epilepsy. New algorithms based on spatial filtering have been developed to enable detection of such SSVEPs in the EEG. For the selection of the optimal flickering frequency, a BCI testing front end has been developed. This software is a friendly, straightforward software **wizard** that walks the user through a series of tests to determine optimal parameters within two BCI approaches (SSVEP and ERD/ERS). Selecting various stimulation frequencies is especially challenging in the **high frequency** range because only few of them can elicit sufficiently high SSVEPs for BCI purposes. Experience has shown that the underlying resonance phenomenon evolves extremely selectively with strong responds to predetermined frequencies. As a matter of fact we detected specific EEG oscillators in the high frequency range that were already observed in similar studies (Herrmann 2001; Wang et al., 2006), particularly 32 and 40 Hz. However, despite these stable cortical reactions we had to move away from one of BRAINs original objectives, namely a calibration procedure that leads to an individualized parameter set - reusable over at least a transitory period. The preferred induced driving responses turned out to be subject to high intraindividual variations. Consequently, a personalized 4-way high frequency SSVEP system seems to require regular (in terms of daily) repeated calibration sessions. To bypass this limitation it was proposed to use a single stimulation frequency but several phases. This approach was successfully applied into the BRAIN system. Since only one flickering frequency has to be consulted, the selection process can be arranged more efficiently in particular however not exclusively on the basis of the above mentioned preferred resonance frequencies.

Figure 35: SSVEP testing in the community (a) High Frequency SSVEP operation at Cedar Residential Home and (b) High Frequency SSVEP phase testing at Cedar Training Centre.

Intuitive Universal Interface and Applications: BCIs typically use a simple, conventional interface that is identical for all users. BRAIN focused on the application architecture and modes of user interaction for customisable, practical and user friendly BCIs. Our solution rested upon offering a wrapper for unifying and integrating diverse domotic standards and protocols accompanied by an intuitive and extendible graphical user interface that can be customised to the user needs. That is a more intuitive universal interface (IUI) and applications that are easier to learn and use. The **IUI** consists of two main components and allows BCI control of environmental devices, communication and entertainment utilities. The first IUI component is the intuitive graphical user interface (**IGUI**), which is the visual aspect of the design that the user interacts with and may be tailored to the users in terms of the BCI paradigms that they find effective, their overall capabilities, and the applications that they need. The IGUI provides an on screen menu structure showing the actions available to the user at any given time and reacts to the user selections made through the BCI system. That is it interacts with BCI components coming from BCI2000. An example of the IGUI screen customised for ERD/ERS and using three mental tasks is presented in Figure 36a. Icons have been used to promote usability. The IGUI architecture allows for 4-way or 3-way interaction, as appropriate to the user's capabilities. Feedback provides an indication of current status of the interaction. The architecture has permitted interaction with signal processing options (other than BCI2000), which promotes generalisation, and could facilitate uptake by other projects.

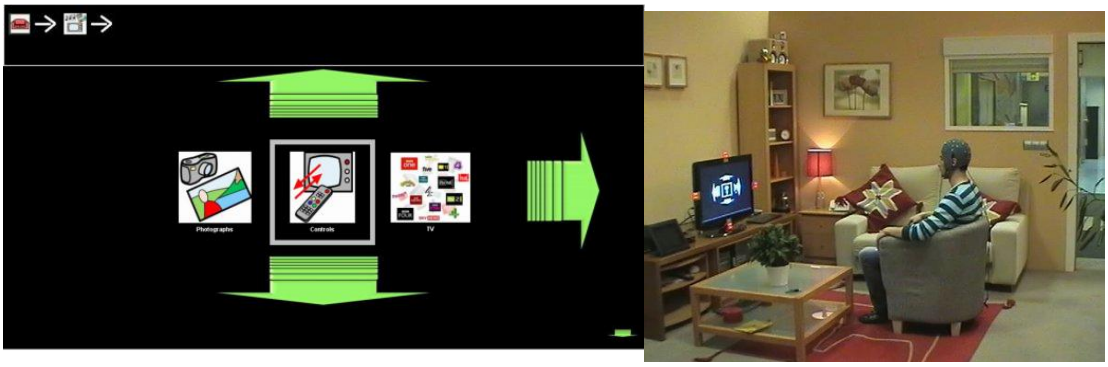


Figure 36: (a) ERD/S IGUI interface (b) Handling domotic devices with the BCI.

The second component is the universal application interface (**UAI**), from which the IGUI can interact with applications for environmental control and also PC based packages such as media players and communication devices. The UAI provides a generic platform on which to incorporate new applications, and forms the bridge between the BCI platform used here (BCI2000), IGUI, and applications and devices. The objective of the UAI is to make available to the user different applications that he/she can control through the IGUI. Due to the limited interaction that the BCI allows, all applications have to be designed as a collection of simple commands that the user can select as icons in the IGUI. The UAI is also responsible for the execution of the commands. In many cases these commands require interaction with a variety of devices. UPnP has been selected as the communication protocol used in the BRAIN middleware layer, due to the following advantages: UPnP provides an interoperable specification with common protocols to other technologies, offering the possibility of wrapping other technologies, it is extendable and widely used by manufactures and vendors. Applications were implemented as OSGi bundles for easy installation and management. A multi-media server recognises devices connected and disconnected to the network without need of configuration. Figure 36b shows a participant who controls different domotic devices with the SSVEP BCI.

Evaluation: All BRAIN deliverables emphasise usability across a range of different users with disabilities and limitations. Deliverables have been tested with healthy persons and specific persons who have impairments caused by brain injury. Testing formally took place at the Cedar Foundation and Telefonica I+D. Within the scope of the BRAIN project two high impact research studies with 86 and 71 subjects from volunteer visitors to the BRAIN booth were carried out at the International exhibition **Hannover Fair** in April 2010 and **CeBIT** in March 2011, respectively. The first study examined correlations among BCI performance, personal preferences, and different subject factors such as age or gender for two sets of SSVEP stimuli: one in the medium frequency range and another in the high frequency range. Results showed that most people, despite having no prior BCI experience, could use the SSVEP BCI system in a very noisy field setting. Moreover, demographic and other parameters did not have significant effect on the SSVEP performance. The second study evaluated new hardware and software components with regard to BRAIN superior objectives, namely the practicability and the individualisation of an envisaged final BCI system.

From the experience gained in BRAIN, we propose that BNCI has the following paths to follow:

1) **Technical**

    a. Further improvement of signal processing algorithms: e.g. quick screening to ascertain whether further testing is likely to be beneficial (for both SSVEP, but especially ERD/ERS).
    b. Further improvement of the aesthetics of the system: smaller amplifier, headcap, a robust package, easy set up software. This should address acceptance.
    c. Open BCI. We should encourage algorithms, code etc to be put into the public domain, under GNU licence for example, so that the community can benefit from it.

2) **User Population testing**

    a. As a broad tool; integration with eye tracker systems for a multi modal hybrid in the general Assistive Technology Domains.
    b. As a more specific tool; Identification of specific clinical groups that BCI will help exclusively (beyond ALS but with clinical support). A stable state of the art system should be deployed and there should be no attempt to change any operational parameters. This would be a controlled intervention to assess BCI in a more relevant user population than BRAIN.

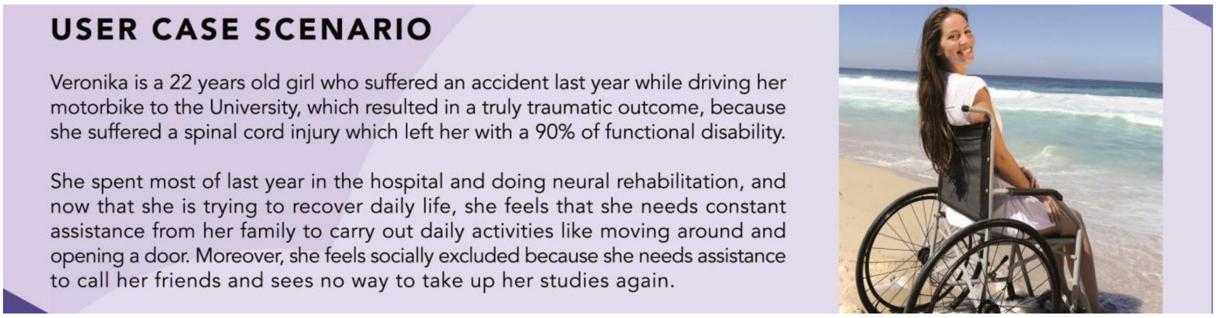
3) **Emerging BCI applications.** As communication restoration tools, use of BCIs is limited to a small percentage of the population. BCI technology however, can be applied for a wider range of applications including sleep enhancement, cognitive enhancement, and affective human computer interfaces.

4) **BNCI solutions for home based diagnosis.** BNCIs have a unique property of having access to the activity of the CNS. As such, BNCI technology can be used for early diagnosis of neurophysiological disorders such as dementia, schizophrenia, and Parkinson.

BrainAble

Autonomy and social inclusion through mixed reality Brain-Computer Interfaces: Connecting the disabled to their physical and social world.

Motivation and Need: Motor disabilities of people arising from any origin have a dramatic effect on their quality of life. Some examples of neurologic nature include a person suffering from a severe brain injury resulting from a car collision or individuals who have suffered a brain stroke. For years, the severely disabled have learned to cope with their restricted autonomy, impacting on their daily activities like moving around or turning on the lights and their ability for social interaction.



USER CASE SCENARIO

Veronika is a 22 years old girl who suffered an accident last year while driving her motorbike to the University, which resulted in a truly traumatic outcome, because she suffered a spinal cord injury which left her with a 90% of functional disability.

She spent most of last year in the hospital and doing neural rehabilitation, and now that she is trying to recover daily life, she feels that she needs constant assistance from her family to carry out daily activities like moving around and opening a door. Moreover, she feels socially excluded because she needs assistance to call her friends and sees no way to take up her studies again.

Figure 37: One example of a person who could benefit from BrainAble technology.

The project BrainAble is about empowering Veronika and others like her to mitigate the limitations of the everyday life that they encounter. Our initiative is to research, design, implement and validate an ICT-based HCI (Human Computer Interface) composed of BNCI (Brain Neural Computer Interface) sensors combined with affective computing and virtual environments.

Project overview: In terms of HCI, BrainAble improves both direct and indirect interaction between the user and his smart home. Direct control is upgraded by creating tools that allow for the controlling of inner and outer environments using a “hybrid” Brain Computer Interface (BNCI) system able to take into account other sources of information such as measures of boredom, confusion, frustration by means of the so-called physiological and affective sensors.

Furthermore, interaction is enhanced by means of Ambient Intelligence (AmI) focused on creating proactive and context-aware environments by adding intelligence to the user's surroundings. AmI’s main purpose is to aid and facilitate the user's living conditions by creating proactive environments to provide assistance.

Human-Computer Interfaces are complemented by an intelligent Virtual Reality-based user interface with avatars and scenarios that will help the disabled move around freely, and interact with any sort of devices. Even more the VR will provide self-expression assets using music, pictures and text, communicate online and offline with other people, play games to counteract cognitive decline, and get trained in new functionalities and tasks.

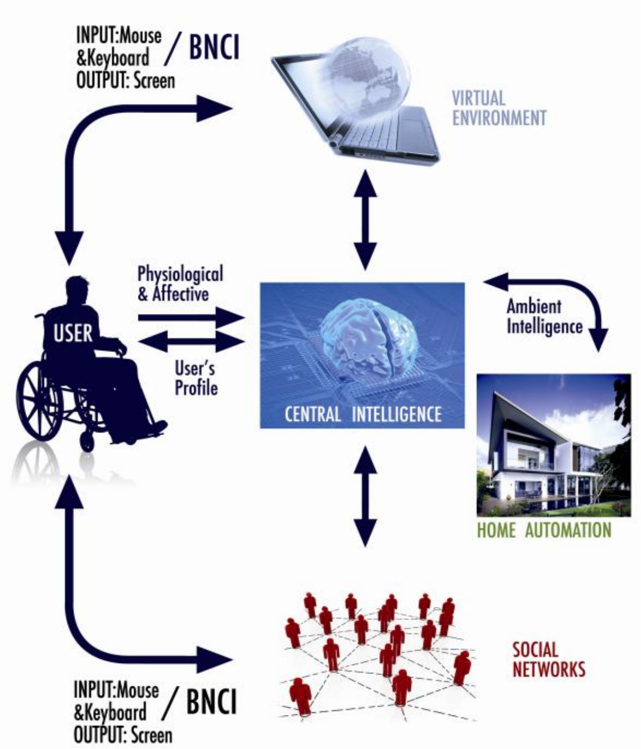


Figure 38: The BrainAble approach uses BCI and BNCI technology integrated with ambient intelligence in virtual environments.

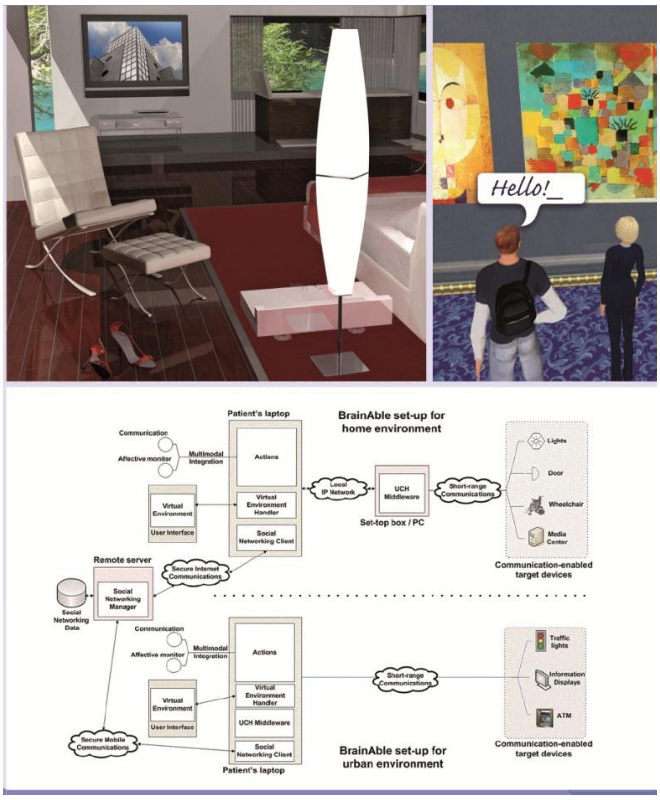


Figure 39: The top panels present one of the BrainAble virtual reality displays. The bottom section shows the BrainAble architecture.

Major accomplishments: At the end of the first year, BrainAble finished the first year prototype that demonstrates an AmI smart home system controlled via a BNCI interface. The prototype provided a proof-of-concept of the BrainAble system, which includes a BNCI to interact with: (1) inner environment functionalities such as controlling a commercial television and lamp (2) a virtual avatar in a virtual model of the user's home; and (3) an outer environment giving more participation in today's modern social networks with access to the micro-blogging service Twitter.

The main scientific and technical achievements include the development of a novel interface to switch between BNCI applications, the Hex-O-Select; Ambient Intelligent techniques such as the Context Facilitation for BCI interfaces which was presented in international congresses; and incorporation of the URC/UCH standard that facilitates the integration of new services or devices. Several scientific papers about hybrid BCI, adaptive BCIs, and BCI in virtual reality environments have been published.

The BrainAble project has been demonstrated and disseminated in dozens of conferences, workshops, conventions, and other professional events. For example, BrainAble had a booth and demonstration at the Brussels ICT Expo 2010, Third International meeting on Technology and Innovation for Persons with Disabilities in Sao Paolo, and the First Innovation Convention 2011 at Brussels. BrainAble work has been presented all over the world, including at the Society for Neuroscience conferences in San Diego and Washington, DC, the Gao lab in Beijing, and the Second Workshop on Assistive Technologies in Qatar.

Figure 40: A visitor to the BrainAble booth at the Brussels 2010 ICT Expo selects "2" using a P300 BCI.

As an outcome, our initiative will produce a commercial product and a set of technologies intended to assist people with severe physical disabilities. The technology has the potential to assist those with special needs such as individuals living with Motor Neurone Disease or locked-in patients. The modular architecture and middleware utilized by BrainAble to connect user-centered interactive immersive environments to networks of devices and people have many applications in high-tech home automation devices and intelligent and integrated smart homes.

BrainAble recommends these directions for FP8:

1) **BCIs combined with other systems**
   a. Hybrid BCIs that use information from the brain, heart, eyes, muscles, and other inputs. Hybrid BCIs that combine different BCIs are also important.
   b. Using BCI and BNCI as part of an assistive technology system together with eye trackers, Wii based controllers, EMG switches, or other tools.
   c. Combining BCIs with ambient intelligence and context aware computing.
   d. Using virtual reality to enhance more natural interaction

2) **Testing with target users in realworld settings**
   a. Work with partners who have access to target users in realworld settings and experience working with them.
   b. Integrate feedback within the duration of the project.

3) **Clustering with projects inside and outside the cluster**: Many relevant projects and disciplines outside of the cluster are not well known within BCI research groups. Examples include projects focused on rehabilitation support technologies, smart homes, device control, interface development and HCI, teletherapy, and telemonitoring.

4) **Infrastructure:** Many aspects need to be developed, including better standards, support for end users and their carers in field settings, benchmarking tools, file formats, universal interfaces, and more conferences and workshops focused on specific issues.

DECODER

DECODER is a European collaborative project that will deploy Brain-Computer-Interfaces (BCIs) for the detection of consciousness in non-responsive patients.

DECODER will develop BCIs into single-switch based systems to practically enhance inclusion of patients who have otherwise only little or no ability to interact with their environment and share Information and Communication Technologies (ICT).

Motivation and Need: Each year, a large number of people are diagnosed with a disorder of consciousness or a disorder leading to motor impairment. Such people are then confronted with two severe gaps of knowledge:

- Firstly, there is a likelihood of up to 40% that they will be misdiagnosed
- Secondly, if motor impairment becomes permanent a single-switch device independent of motor output is not readily available

We may classify non-responsive patients according to their aetiology into two large groups:

1. Patients who fail to respond due to low arousal, lack of intention or short attention span; the motor system may maintain a certain repertoire of function in those patients. Examples for such diseases are:
    - Unresponsive wakefulness syndrome, e.g. after traumatic brain injury, stroke, or anoxia
    - Minimally conscious state, e.g. traumatic brain injury, stroke or anoxia
    - Akinetic mutism, e.g., after lesions in the anterior cingulate cortex
    - Parkinson’s disease

2. Patients who do not respond due to failure of the motor system, in presence of a preserved awareness. Examples of such disease are:
    - High-level spinal cord injury
    - Amyotrophic lateral sclerosis
    - Multiple sclerosis
    - Muscular dystrophy
    - Stroke (brainstem and cerebellar)

Brain disorders (psychiatric, neurological) are amongst the leading causes of disease and disability. Data from WHO suggest that brain disorders cause 35% of the burden of all diseases in Europe. Among brain disorders, those of interest in DECODER can represent the cause of the most severe levels of disability.

It is important to mention that it is not only the patients themselves who are affected by these diseases. The uncertainty of diagnosis strongly affects partners and relatives of patients and the inability to communicate poses a tremendous burden for those who are caring for the patients. Thus, the diagnostic battery and the ssBCI with its applications developed by DECODER will bring a significant improvement to the quality of life of patients and their families.

Project Aims: There are two equivalent primary aims of DECODER:

1. **Overcome the diagnostic gap** by promoting and establishing diagnostic tools for non-responsive patients which will be easy to handle, to apply and the results of which will be unequivocal. A hierarchical approach to cortical processing and consciousness will be developed and established mainly on the basis of the EEG as it provides a brilliant resolution in time of brain activity. As the spatial resolution of the EEG is less fine graded than is possible by imaging technology, this gap will be bridged with optical imaging. Current diagnostic tools on the basis of functional magnetic resonance imaging will be transferred to optical imaging (near infrared spectroscopy) which can be applied at the patients' bedside.

2. **Overcome the output gap** by further developing and adapting existing BCI systems and applications to single-switch BCI control. As currently funded projects (TOBI and BRAIN) will provide practical assistive BCI, we will focus on adapting this technology to provide single-switch control. This is important as it can be envisaged that non-responsive patients, even after rehabilitation, will not be able to recover motor or cortical functioning to such an extent that they will be able to control multi-switch devices or hybrid BCIs. Thus, DECODER is aiming at promoting single-switch BCI for inclusion by developing new software tools for the recognition of intention in brain activity and for translating this intention into commands for single-switch BCI control.

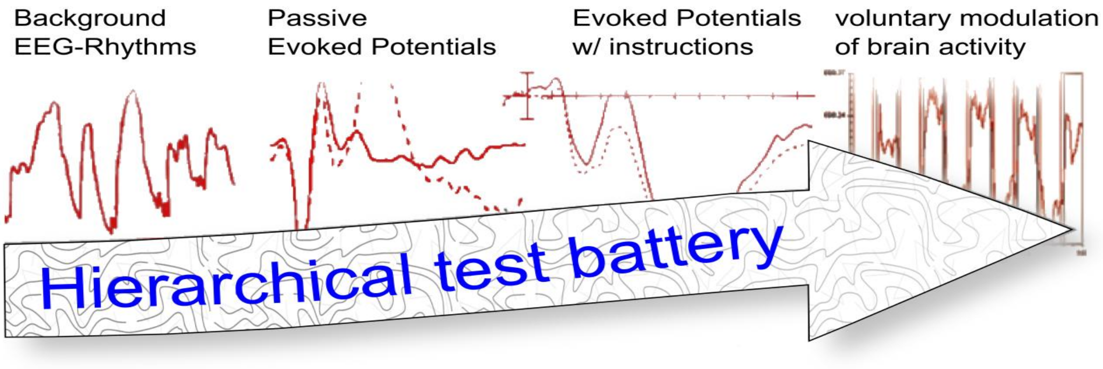


Figure 41: Cognitive performance will be assessed passively and actively thereby constituting a hierarchical approach which will be realised with EEG and imaging technology.

In addition, DECODER lays a strong focus on **evaluation and dissemination** of its results.

With a strong patient oriented focus, DECODER proposes BNCI:

- **To focus on its potential user base**: People with motor impairments and/or cognitive impairments represent a strong potential user group for BCIs. We believe it therefore essential to evaluate new developments in brain computer interfaces in these groups. An application in psychiatric diseases is promising (e.g., in ADHD and depression).
- **To focus on usability**: Being systems in constant development, many BCIs are still cumbersome to use from an end-user-point of view. However, if BCIs are to make a difference they must be easy to use by the target group.
- **To focus on availability and dissemination:** broad dissemination requires broad education and easy application including remote monitoring. Thus, BNCI and tele-health must be connected.

Future BNCI

Future Directions in Brain/Neuronal Computer Interaction

Future BNCI is a Coordination and Support Action (CSA) funded by the European Commission. CSAs, unlike some other projects, are not responsible for producing original scientific research nor technical achievements. Instead, CSAs are support actions, devoted to helping other projects and facilitating an improved infrastructure. Future BNCI ran from January 2010 until December 2011. Future BNCI attained these goals through various means, and produced several lasting outcomes such as a website, several peer-reviewed articles and conference contributions, a book that will soon be released through Springer Publishing, and this roadmap.

Motivation and Need: BCI and BNCI systems are at a critical point in their development. There is tremendous attention to research and increased opportunity for progress. However, expectations are high and there are serious problems emerging within the BNCI research community. The community needs some support to communicate more effectively, develop a better infrastructure, and better capitalize on emerging opportunities. FBNCI is motivated by this need.

Project Aims: The vision of Future BCI was to support a thriving, efficient, well-connected BCI community. This vision entailed the following goals:

1. Develop clear standardized terminology;
2. Identify specific opportunities and roadmaps;
3. Encourage discussion and collaboration among key academic and commercial stakeholders;
4. Disseminate knowledge and strategic objectives to established and new groups and to the public at large.

Future BNCI addressed these goals through four objectives:

1. A thorough literature review of relevant academic references and commercial developments to consolidate existing knowledge and establish what is known and not known;
2. Targeted discussion with the top academic and commercial stakeholders through email, informal discussion, and the other mechanisms to establish a common framework upon which a BNCI community can be built;
3. Organisation of events including a conference, workshops, and special sessions to encourage participation, disseminate the findings of the targeted discussions, and stimulate further discussion;
4. Establishment of electronic resources such a single centralized website with definitions, a database of key articles and research groups, relevant news from businesses and the popular media, a discussion forum, lists of relevant conferences and other events, and materials from classes about BCIs and related topics to provide a starting point for a common EU BNCI community and engage stakeholders and the public at large.

Future BNCI sought to disseminate information to many groups:

- Existing and new academic stakeholders, including established researchers and students
- Existing and new commercial stakeholders
- Medical practitioners, including doctors, nurses, therapists, and caregivers
- Popular media sources, including magazines, webzines, and news programs
- Different user groups, including:
    - Conventional BCI users (persons with severe motor disabilities)
    - Persons with less severe motor disabilities
    - Persons seeking rehabilitation of disorders including autism, stroke, and emotional disorders
    - Healthy users
- The public at large

Expected results: FBNCI was supposed to produce several visible results:

- Febuary 2010: Website infrastructure in place
- April 2010: Website updated with content
- Junuary 2010: State of the art reports completed[67]
- September 2010-November 2011: Numerous workshops and events
- March 2011: Summaries of Sep 2010 conference workshops publicly available[68]
- December 2011: Roadmap completed and publicly available.
- December 2011: Book chapters sent to publisher

Figure 42: Two photos from FBNCI events in September 2010. In the left panel, Febo Cincotti and Christa Neuper talk during the FBNCI conference. The right panel shows the FBNCI booth at the Brussels Expo, which we shared with our cluster projects BrainAble and Brain as well as the BrainGain project. A group of local students (wearing red caps) visited the booth to learn more about BCIs and BCI research groups.

---

[67] http://future-bnci.org/index.php?option=com_content&view=article&id=58&Itemid=59

[68] http://future-bnci.org/index.php?option=com_content&view=category&layout=blog&id=84&Itemid=87

Accomplishments: FBNCI attained all of these results on time. In addition, we exceeded the requirements in various ways. We were required to host only two workshops in 2011, but hosted five. We also hosted both a “BNCI Village” presenting exhibitions from the H3 cluster and a talk session at the ICT Exposition in Brussels in September 2010. We coordinated several informal evening discussions, a cluster teleconference, and other events. These events provided considerable added opportunity to interact with stakeholders. No publications were required, but the project produced several peer-reviewed publications in established journals (e.g., Allison, 2011; Nijboer et al., 2011a, 2011b, 2011c; Allison et al., 2012). We gave dozens of talks presenting FBNCI and cluster work. We hired a graphic artist and developed the logo for our H3 cluster, through consultation with other projects and the European Commission. We made several visits to major stakeholders’ groups, including the Gao lab in Beijing, Philips Research in Eindhoven, and the US Army lab in Aberdeen, generally at their expense, to see their results firsthand and discuss major issues with them. We helped present the 2011 BCI Award during the 2011 Graz BCI conference. We passed out countless flyers from cluster projects, and brought posters representing these projects to some events such as the Utrecht 2011 BCI conference. The video documentaries and interviews were never mentioned in the project proposal, and were added during the second year thanks to our collaboration with the filmmaker, Ms. Sanmarti.

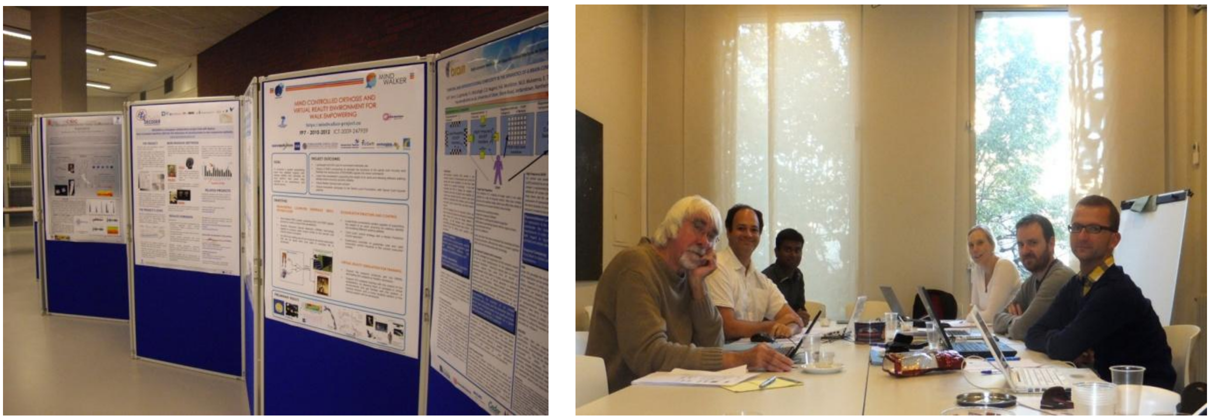


Figure 43: The left image shows posters from H3 cluster projects at the Utrecht 2011 BCI conference. FBNCI set up many of these posters to facilitate dissemination. The right image shows some FBNCI team members discussing the roadmap. From left to right: Anton Nijholt (U Twente), Brendan Allison (TU Graz), Gangadhar Garipelli (EPFL), Femke Nijboer (U Twente), Stephen Dunne (Starlab), and Robert Leeb (EPFL).

Although the FBNCI project ended, some impact will still occur. Our book through Springer publishing will be available in early 2012. We have another article in review that may be published next year. EPFL plans an additional workshop to focus on follow-up issues, and we plan to present the roadmap at the TOBI workshop in March 2012. We have been very active trying to encourage a BCI Society and will continue these efforts. Dr. Nijboer will extend the ethical materials, and the TOBI project will take over other aspects of the project. We may produce additional video materials. And, since many of us remain interested in BCIs and concerned with relevant issues, we will continue some of our efforts to advance the technology and improve the infrastructure.

We have not provided a summary of our project recommendations here, since they are summarized elsewhere in this roadmap. Please also feel free to contact the Project Coordinator, Dr. Allison[69].

---

[69] Until 31 March 2012: allison(at)tugraz.at; then bci2k2(at)yahoo.com

MINDWALKER

Mind controlled orthosis and VR training environment for walk empowering

Motivation and Need: Sensors technologies and electronic systems computing power has improved drastically in the last decade. In particular, a number of potential robotics applications have progressively became more and more concrete and plausible. In the same manner, research work related to BNCI recently turned into more and more promising and applicable results with new potential applications.

MINDWALKER is an initiative that aims at investigating how those technologies can be integrated and effectively applied for the purpose of substituting to wheelchairs, in the case of people being affected by spinal cord injuries (SCI) resulting in partial or complete locomotion disability.

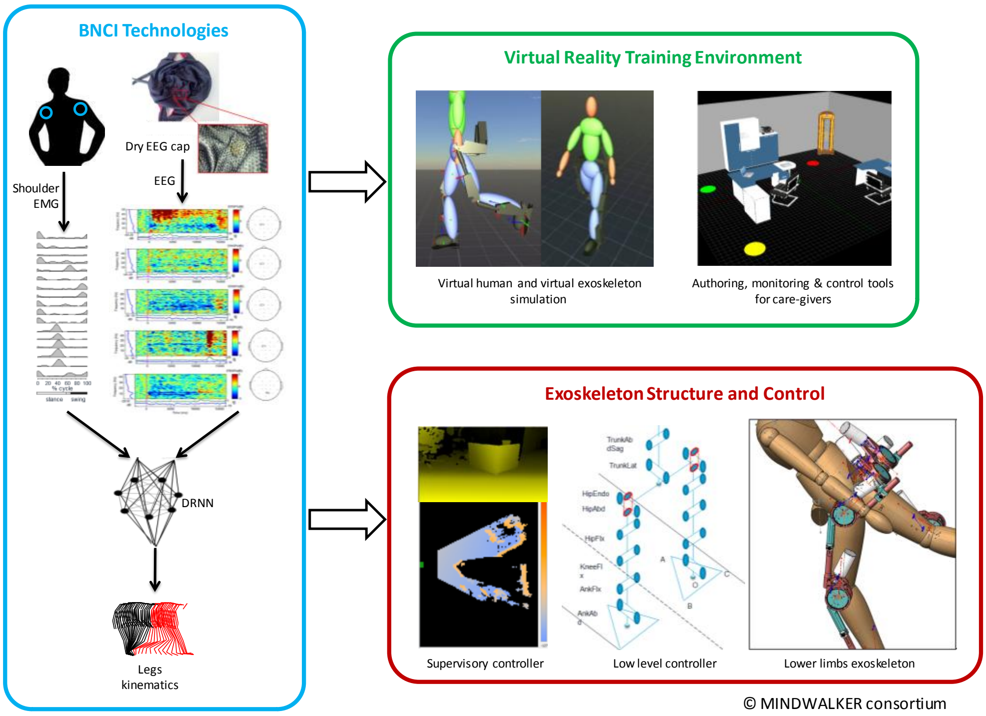
In short, MINDWALKER aims at making use of the natural brain signals usually associated with walking, in order to directly control a robotic lower limbs orthosis worn by the disabled person. The approach is expected to empower the wearer with walking ability, without the need for crutches.

MINDWALKER is a research project, and therefore does not aim at delivering any commercial grade product at the end of the project. It is rather intended to investigate promising approaches to exploit brain signals for the purpose of controlling advanced orthosis, and to design and implement a prototype system demonstrating the potential of related technologies.

The developed technologies will be assessed and validated in the third year of the project with the support of a clinical evaluation procedure involving SCI subjects. This will allow the measuring the strengths and weaknesses of the chosen approach and to identify improvements required to build a future commercial system.

System components: The MINDWALKER system will consist of:

1. A lightweight, dry EEG cap perceiving the brain signals related to the locomotion.
2. A BNCI chain, allowing the acquisition of BNCI signals (EEG and EMG) and to process them in order to generate kinematic control signals for the legs.
3. A robotic lower limbs orthosis (aka. exoskeleton) to be worn by the user, and perform the locomotion, along with a computing unit hosting the BNCI chain processes and the exoskeleton motion control processes.
4. A dedicated training environment: specific training approaches will be needed for MINDWALKER. Training tools simulating the walk in a virtual environment (the approach is called Virtual Reality) will be developed, so that the users can conveniently get acquainted with the system before safely wearing and making use of MINDWALKER in real environments.



© MINDWALKER consortium

Figure 44: MINDWALKER general principles.

BNCI Subsystem: The BNCI aims at recording and interpreting the brain signal so that it can control the orthosis the way it would be done if the spinal cord was not injured, i.e. ideally without requiring the user to concentrate on the movement. For that purpose, a cap to record the brain signals is being prototyped to be used in everyday life. A novel specific device, with dry electrodes that are simple to use, is being developed in the MINDWALKER project.

© Université Libre de Bruxelles

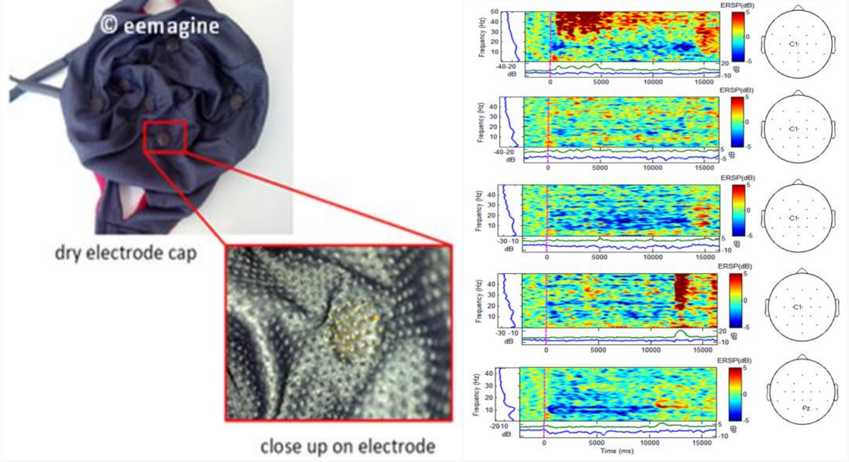


Figure 45: Left image: Dry Electrode EEG Cap Prototype (called SWEEBS). Right image: Motor cortex EEG sample obtained during walking trials.

The BNCI processing chain is implemented within the OpenVIBE open source setup. A Dynamic Recurrent Neural Network (DRNN) in particular is a core component of the BNCI processing chain. A Central Gait Pattern Generator (CPG) has been developed, with the ability to generate walking patterns in a tunable manner. This is intended to be used both as a reference, and possibly as a way to smooth (convolution) kinematics control commands issued by the BNCI chain. An SSVEP based approach is investigated as a possible mean to address states transition events in the control chain (e.g. starting/stopping). In addition, EMG from the shoulders has been demonstrated in the MINDWALKER experiments to be exploitable for generating kinematic control signals.

© Fondazione Santa Lucia

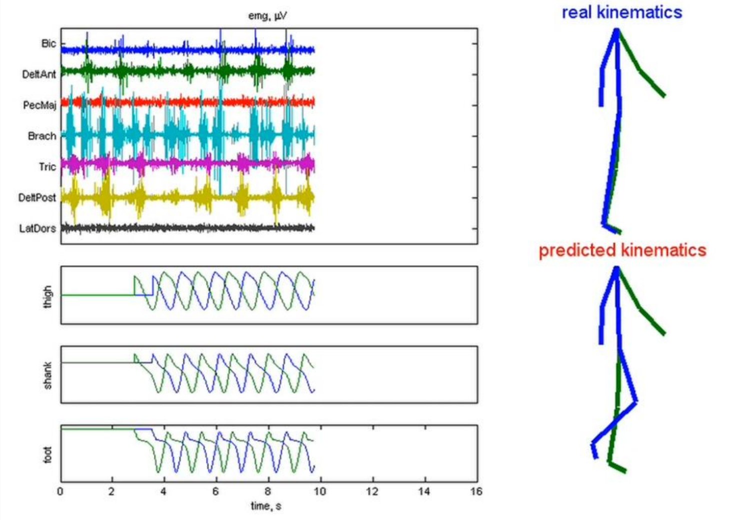
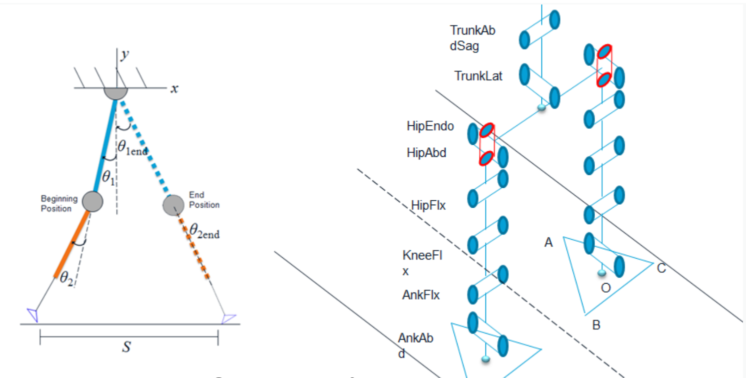


Figure 46: Prediction of walking kinematics from shoulders EMG with arms swing.

Robotic Lower Limbs Orthosis Subsystem: The purpose of the robotic lower limb orthosis, also called the exoskeleton, is to support the user and enable different walking modalities and gaits. It is a mechanical structure with sensors and actuators providing the power of walking and dynamically stabilizing the human-exoskeleton system. Specific actuators with springs (series elastic) are implemented to optimize the energy consumption of the exoskeleton.

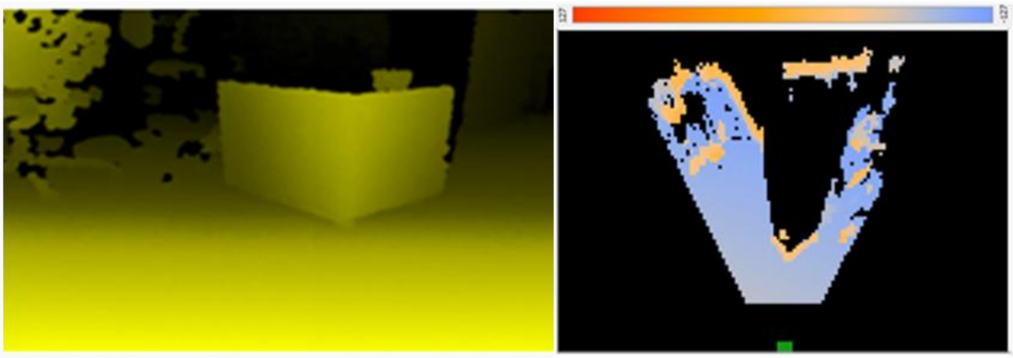
Lower limbs exoskeleton mechatronic structure and actuator: Associated with a portable computer, it is controlled through the BNCI chain fed by the user's biosignals. The low level control of the exoskeleton relies on a Model Predictive Controller (MPC) that includes both the human model and the exoskeleton model, along with a model of their interaction. The predictions allow refining of the kinematic control commands as issued by the BNCI chain, taking into account the forces and torques measured with the exoskeleton. In case of perturbation (e.g. loss of balance, collision…), the MPC will generate mitigation control commands to recover from the situation.



© University of Twente

Figure 47: Lower limbs exoskeleton kinematic model and control parameters.

In addition to the low level controller, a supervisory controller component is developed in the project, as a way to improve the safety of the users while using the system. It consists of a computing unit and a lightweight sensor for real time 3D environment model building that is translated into a digital elevation map (DEM).

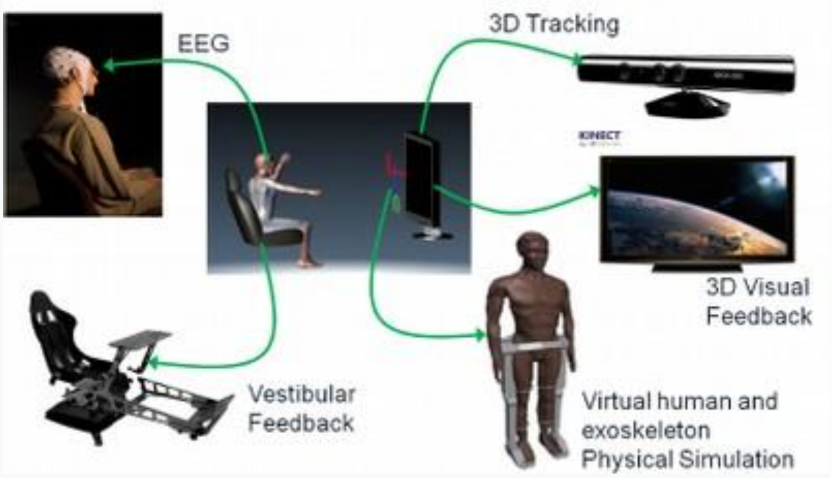


© Space Applications Services

Figure 48: Environment modeling and obstacles detection in the supervisory controller.

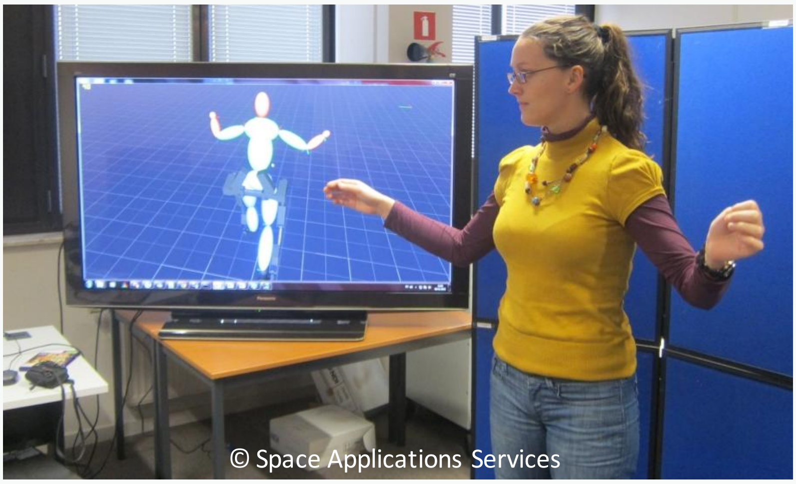
Obstacles presenting a risk for the user are identified in the map and notified to the low level controller that takes them into account within its models. This allows e.g. stepping above an obstacle to prevent a collision with the foot. These safety enhancing behaviors are expected to improve the overall usability, both in reducing the risks for the users and increasing their confidence in the system. It is a complementary safeguarding layer to the BNCI chain that can occasionally mitigate the consequences of shortcomings in the BNCI, for the sake of safety.

Virtual Reality Training Environment: MINDWALKER makes use of Virtual reality to stimulate and support the patient while he/she is trained on how to use and control the system. 3D environment simulation supports two training phases, with a large 3D display screen to facilitate immersion.



© Space Applications Services

Figure 49: Components of the Virtual Reality Training Environment.



© Space Applications Services

Figure 50: Upper body real time motion capture (kinect based) and VR rendering.

Major outcomes: The project has completed its second year out of three. The results include:

- Early in the project, important efforts have been devoted to collecting user requirements with a rather wide community of end users (a total of 42 SCI subject contributed, and 15 medical staff).
- Multiple BNCI approaches have been researched, with applicable results in particular based on SSVEP and shoulder EMG for the kinematics control of the lower limbs exoskeleton. Further results on visual motor cortex stimulation (virtual reality based) have been obtained, though they are not considered reliable enough at this stage for the targeted application. Related work with “walking ideation” has been performed, and is still considered a challenging part of the work that, at the current stage, is not yet mature enough for the targeted application in the project.
- A lower limbs exoskeleton has been designed and partially manufactured and assembled. This exoskeleton is designed to allow real time balance control, and should allow the wearer to stand up and walk without crutches.

- A model based controller for the exoskeleton has been developed and is being further improved for the proper control of the developed lower limbs exoskeleton. In a simulation setup, the current version of the controller is able to notice discrepancies with respect to an ideal behavior (perturbation), and is able to trigger balance recovery actions.
- An exoskeleton supervisory controller stage has been developed for the purpose of adding a safety layer to the system. This component performs modeling of the environment in the vicinity in real time (digital elevation map), and allows triggering behaviors to mitigate risks for the user (e.g. limiting the speed when getting close to an obstacle, or stepping over an obstacle if feasible).
- A virtual reality training environment has been released with online subject's upper body motion capture and near real time physics simulation and visual rendering of a 3D manikin along with the model of the developed exoskeleton and contact with the ground.
- A dry electrodes EEG cap and optimized electronics for signal acquisition has been manufactured, with EEG acquisition performances comparable to those of traditional wet caps as available on the market. Ergonomic aspects are being further addressed and improved, to make it more useable and acceptable for end users.

ROADMAP RECOMMENDATIONS AND PROPOSED BNCI ORIENTATION

- For concrete BNCI applications aimed at the control of a robotic system, it is strongly recommended to favor multi-modal BNCI approaches rather than a single BNCI track. Each approach may prove to perform better under certain environmental conditions and certain situations. The challenge is then to properly characterize and scope the contexts and situations for which particular approaches perform better.
- For robotic control applications, especially those with a potential impact on user's safety, it is advised to have BNCI control components be complemented with safeguarding processes that can build up a certain awareness of the context, and that can either inhibit incompatible high level control requests coming from the BNCI components, or trigger by itself safeguarding processes to mitigate situations considered as risky. However, it is also advised that the "proactiveness" of such processes be tunable, to adjust to the needs and expectations of users – bold users may prefer relying exclusively on the BNCI system (which is fair, should the BNCI control approach be very transparent from a user point of view), while other users may prefer relying on additional safety warranties from the system (to prevent collisions or falls, in the case of MINDWALKER).
- Non-invasive, highly transparent (i.e. with usage it becomes unnoticeable – both for the user and for people in his/her surroundings) BNCI based control of systems is a very high value objective for the close future. Such systems should moreover ideally have the capability to evolve and adapt with the user own evolution and changes.

MUNDUS

MUNDUS is an assistive framework for recovering the direct interaction capability of severely motor impaired people based on arm reaching and hand function. Most of the solutions provided by Assistive Technology for supporting independent life for severely impaired people completely substitute the natural interaction with world, reducing their acceptance. Human dignity and self-esteem are more preserved when restoring missing functions with devices safeguarding self perception and first hand interaction while guaranteeing independent living.

MUNDUS uses any residual control of the end-user, and thus it is suitable for long term utilization in daily activities. Sensors, actuators and control solutions adapt to the level of severity or progression of the disease, allowing the disabled person to interact voluntarily, naturally and at a maximum information rate.

MUNDUS targets are the neurodegenerative and genetic neuromuscular diseases and high level Spinal Cord Injury.

MUNDUS is an adaptable and modular facilitator, which follows its user along the progression of the disease, sparing training time and allowing fast adjustment to new situations. The MUNDUS controller integrates multimodal information collected by **electromyography**, **bioimpedance**, **head/eye tracking** and eventually **brain computer interface** commands. MUNDUS actuators modularly combine a lightweight and non-cumbersome **exoskeleton**, compensating for arm weight, a biomimetic wearable **neuroprosthesis** for arm motion, and **small and lightweight mechanisms**, to assist the grasp of collaborative **functional objects** identified by radio frequency identification. The lightness and non cumbersomeness will be crucial to applicability in home/work environments.
Specific scenarios in **home and work environments** will be used to assess, subjectively and quantitatively, the usability of the system by real end-users in the living laboratory facility. More information is available on our website: http://www.mundus-project.eu/.

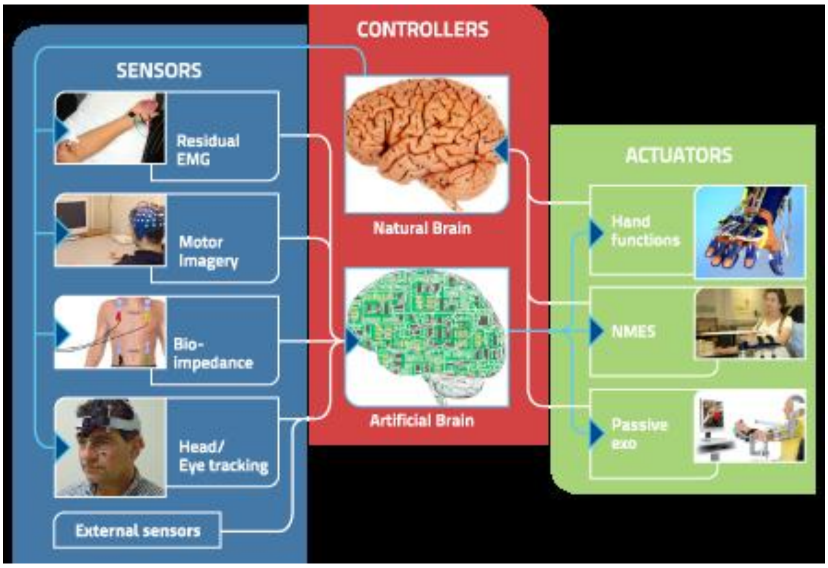


Figure 51: Schema of the MUNDUS concept.

MUNDUS examples

This section contains possible examples of modules built on the MUNDUS platform, along with the corresponding sketch of the user condition. **Red body districts reflect impaired regions, while green ones are still working.**

SITUATION 1:

The person has some residual control of the muscles of the arm and of the hand but the voluntary contraction is not sufficiently strong. MUNDUS biomimetic NMES and exoskeleton are used to increase the force and assure task accomplishment. Control of NMES is proportional to the voluntary residual contraction.

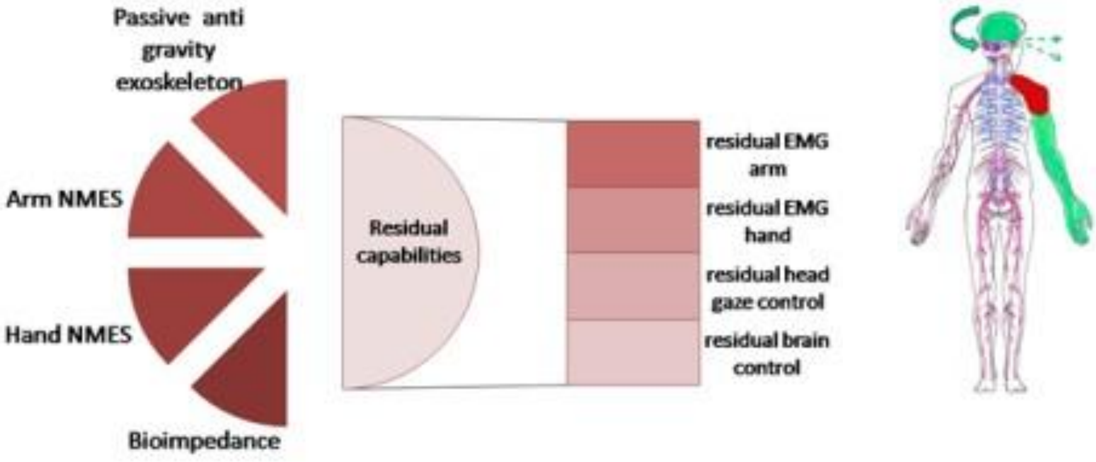


Figure 52: MUNDUS situation one.

SITUATION 2:

The person does not have any residual muscular activity in the upper limb. The trigger of the movement intention and end point positioning is controlled by head/gaze rotation. In addition RFID allows the recognition of objects to drive grasping.

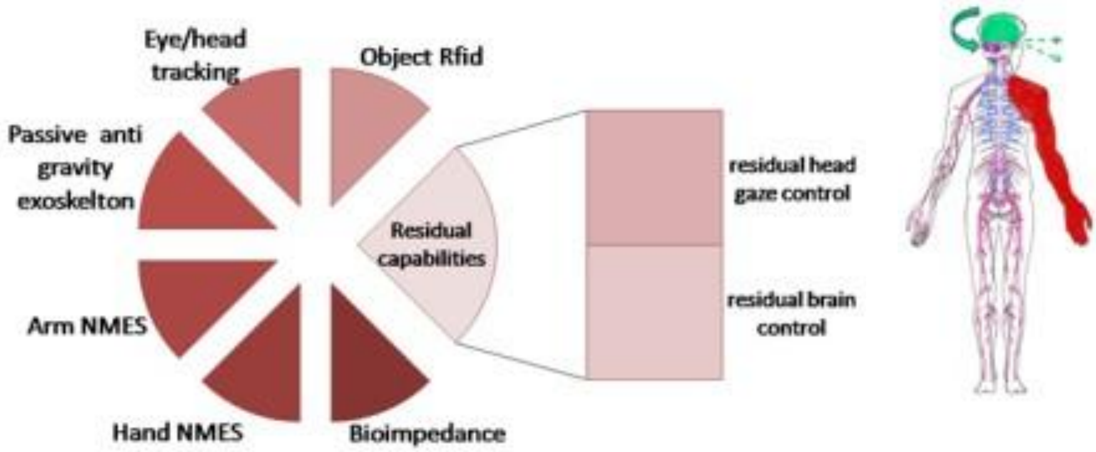


Figure 53: MUNDUS situation two.

SITUATION 3:

The person has no more control of any muscles, and only limited gaze exists, albeit sight is preserved, so that brain signals are used to control the movement task. MUNDUS will control the hand position along a pre-defined trajectory thanks to BCI signals and RFID will be used to recognize objects and drive grasping.

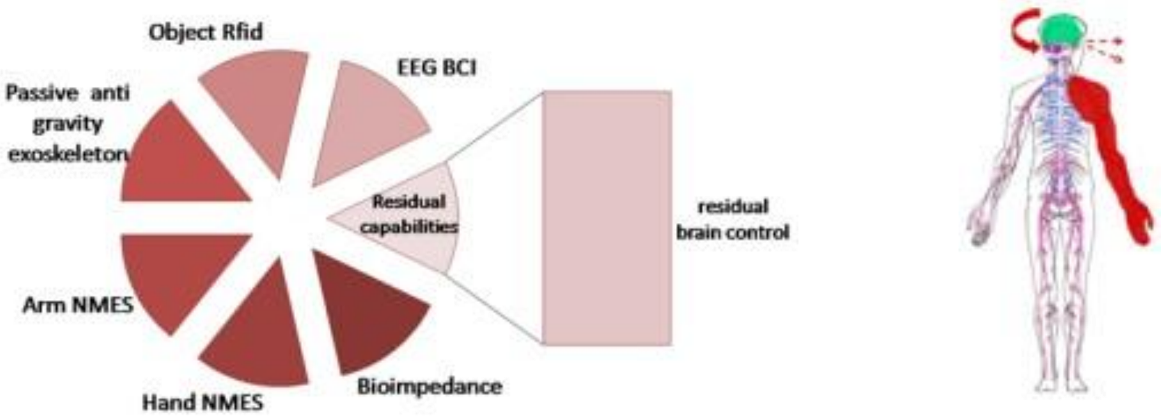


Figure 54: MUNDUS situation three.

Major accomplishments: MUNDUS aims at developing a composite system able to support task performance driven by a voluntary input, according to controlling solutions tailored to the specific capabilities of the single user. MUNDUS achievements are related to the following 7 goals:

1. Integrate sensors, actuators and NP to restore and/or augment the capabilities of disabled people.
2. Exploit ICT methods for developing a new generation of arm NP.

3. Advance current BCI systems by extracting linear control information evolving with the pathology and including NMES for BCI training.
4. Develop light, passive arm exoskeleton for gravity compensation.
5. Advance current AT devices by adding environment based hand assistance.
6. Advance in a multimodal, adaptive control and self learning approach.
7. Evaluate acceptability by end-users in home and work scenarios.

ROADMAP RECOMMENDATIONS

The future of BNCI systems is not easy to predict, but these are the research lines we consider promising and would be most interested in developing:

1) **BCI as a tool to study the brain:** We believe that the signal processing tools developed and applied in the BCI field can be used in specifically designed closed-loop experiments to gain a better understanding of cognitive processes and of the functioning of the brain.

2) **BCI as a tool for motor-rehabilitation:** Due to the ability of BCI methods to detect subthreshold motor activity, this is a promising direction for clinical applications of BCIs.

3) **BCI technology as a tool to introduce neuroscientific analysis in the development of products:** Sophisticated EEG analysis can be used to assess the quality of products in development and their usability. This shows a clear perspective for neurotechnology to penetrate into the industry.

TOBI

TOBI (Tools from Brain-Computer Interaction) is a large European integrated project which will develop practical technology for brain-computer interaction (BCI) that will improve the quality of life of disabled people and the effectiveness of rehabilitation

TOBI will develop practical technology for brain-computer interaction; i.e., non-invasive BCI prototypes combined with other assistive technologies (AT) that will have a real impact in improving the quality of life of disabled people. These non-invasive BCI are based on electroencephalogram (EEG) signals. TOBI seeks to develop BCI assistive technology endowed with adaptive capabilities that augment those other AT they are combined with. In such a hybrid approach users can fuse brain interaction and muscle-based interaction or can switch between different channels naturally (based on monitoring of physiological parameters or mental states).

In TOBI we have identified 4 application areas where BCI assistive technology can effectively support people with motor disabilities, namely:

1. Communication & Control,
2. Motor Substitution,
3. Entertainment, and
4. Motor Recovery.

For each of these application areas the project has developed a number of BCI prototypes. At the beginning of the third year of the project we have finished testing the first versions of our prototypes with end users. Based on the collected results and feedback from end users, we have kept the following prototypes for further development and testing:

5. Hybrid P300 Text Entry (Communication & Control),
6. Hybrid MI Text Entry (Communication & Control),
7. FES Orthosis (Motor Substitution),
8. Telepresence Robot (Motor Substitution),
9. Connect-4 (Entertainment),
10. Photobrowser (Entertainment),
11. Music Player (Entertainment), and
12. Motor Rehabilitation (Motor Recovery).

Importantly, new versions of all these prototypes are now compliant with the common implementation platform of our hybrid BCI architecture and implement the different interfaces developed in TOBI. Furthermore, following the user-centered approached adopted in the project, first versions of the prototypes were thoroughly redesigned or fine tuned following the evaluation with and by end users. The final versions of the prototypes have started to be tested with end users, a work that will form the focus of our scientific activities during the fourth year of the project. Initial results are quite positive.

During the third year of the TOBI project the main objective has been to demonstrate the degree of robustness of our work and prototypes to all our target audiences. To do so, we have invested a large amount of resources in giving a number of live demos of our prototypes in different settings —twelve live demos in this third year. As a highlight, we can mention that we participated in the opening of the European Future Technologies Conference and Exhibition (FET11) in Budapest on 4-6 May 2011, where TOBI's brain-controlled telepresence robot brought to the Commission Vice-President Ms. Neelie Kroes a red push button for her to press and officially open the FET11 conference (see Figure 55). Members of the TOBI team also demonstrated this and several other brain-controlled devices during the 3 days of the exhibition.

Figure 55: TOBI's brain-controlled telepresence robot brought to the Commissioner a red push button for her to press and officially open the FET11 conference.

These demonstrations are a continuation of our effort initiated in year 2, in particular the live demos our TOBI exhibit presented of six prototypes during the ICT Exhibition 2010 held in Brussels on September 27-29, 2010. Visitors were also allowed to interact with the demos. In the first three demos, people controlled software for communication (text entry and a web browser) and two physical devices for motor substitution (an FES neuroprosthesis and an assistive telepresence robot) by using their spontaneous brain activity. The next two prototypes exploited natural brain responses to items appearing on the computer for entertainment (a photo browser and brain painting). The last demo was a new commercial wireless helmet made of dry electrodes that visitors could wear to immediately visualise their brain state. Figure 56 gives a snapshot of our ICT stand while two demos were running in the presence of the media and public (the BCI subjects are occluded by visitors). Figure 57 shows another ICT demonstration: brain painting, where a subject composes a piece of art through a P300-based BCI.

Live demos have attracted large media coverage and attention, and also reinforce the scientific visibility of TOBI and its members. Two indicators proving so are the large number of peer-reviewed papers published during the third year of the project (41 journal papers, 31 conference papers, and 13 posters) and, perhaps more impressively, 19 keynote/invited talks given by TOBI members at different meetings (mainly international and not only in Europe). Furthermore, research conducted in the framework of TOBI has been covered by the journal Science three times, two on occasion of the participation at AAAS'11[70]

Apart from demonstrating the robustness and maturity of the BCI technology developed in TOBI through extensive live demonstrations of our prototypes, which is also a direct evidence of the progress in the state of the art achieved in the project, another scientific objective for this year concerned the further development of the hybrid BCI (hBCI) architecture and its components in order to come up with fully integrated prototypes. All prototypes are now compliant with the common implementation platform of our hybrid BCI architecture and implement the different interfaces developed in the project[71]. A complete BCI system can thus now be embedded in generic interfaces.

Figure 56: Snapshot of our stand at the Brussels ICT Exposition in 2010 while two demos were running in the presence of media and public (the BCI subjects are occluded by visitors).

---

[70] (a live chat, http://www.tobi-project.org/2011/02/22/live-aaas-olaf-blanke-and-jose-del-r-millan-robotics, and a podcast, http://www.tobi-project.org/2011/02/23/podcast-using-thoughts-control-robots) and a third time after the publication of the first results of the test of our telepresence robot with end-users (http://www.tobi-project.org/2011/09/06/ science-magazine-disabled-patients-mind-meld-robots).

[71] Furthermore, various EEG processing platforms (EEGLab, OpenVIBE, FieldTrip, xBCI) have already agreed on using the tools implemented by TOBI or have expressed their interest. We also continue our contacts with companies willing to make their data transmission compatible with our standards. Additionally, our common implementation platform will be used by two new EC funded projects, ABC and BackHome.
Open-source reference implementations of all before mentioned interfaces are available on http://sourceforge.net/p/tools4bci/ home/ (reachable also from the TOBI website at http://www.tobi-project.org/download).

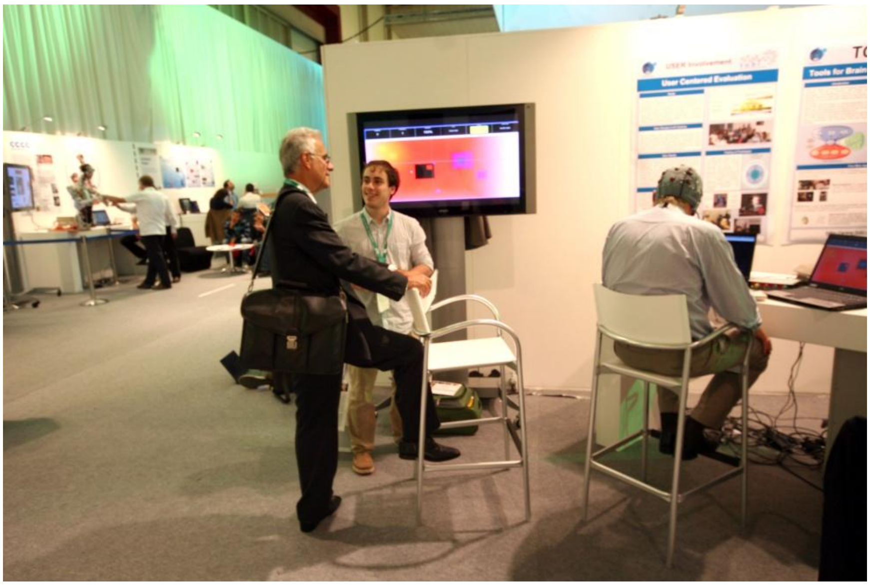


Figure 57: Live demonstration of brain painting at the ICT Exhibition 2010. The subject to the right composes a piece of art through a P300-based BCI.

We have also accelerated the integration of other components developed in the research WPs in the different prototypes according to their needs. In particular, a few prototypes are using hybrid signals —a combination of EEG and EMG, or several EEG components—, namely ‘Hybrid P300 Text Entry’, ‘Hybrid MI Text Entry’, ‘FES Orthosis’, ‘Connect-4’, and ‘Motor Rehabilitation’. Shared control principles are incorporated in the prototypes ‘Hybrid MI Text Entry’, ‘Telepresence Robot’, and ‘Music Player’. Finally, some adaptation principles are already integrated in the prototypes ‘Hybrid MI Text Entry’, ‘FES Orthosis’, ‘Telepresence Robot’, and ‘Music Player’.

Project Coordinator:

Professor José del R. Millán

RECOMMENDATIONS FOR FUNDING

In agreement with our Advisory Board, it is advised to do more basic research to understand better the underlying electrophysiology in order to improve the BCI systems. Also, priority should be given to basic research in novel BCI principles leading to robust and efficient brain-controlled devices over long periods of time.

TREMOR

An ambulatory BCI-driven tremor suppression system based on functional electrical stimulation.

Motivation and Need: Tremor is the most common movement disorder and it is strongly increasing in incidence and prevalence with ageing. More than 65% of the population with upper limb tremor presents serious difficulties in performing the activities of daily living (ADL). Tremor is not life-threatening, but it can be responsible for functional disability and social inconvenience. It is typically managed by means of drugs, surgery (thalamotomy), and deep brain stimulation, but treatments are not effective in approximately 25% of patients.

Project Objective: The main objective of the project is to validate, technically, functionally and clinically, the concept of mechanically suppressing tremor through selective Functional Electrical Stimulation (FES) based on a (Brain-to-Computer Interaction) BCI-driven detection of involuntary (tremor) motor activity:

- The system will detect and monitor involuntary motor activity (tremor) through a multimodal BCI. The proposed BCI will combine CNS (Electroencephalography, EEG) and PNS (Electromyography, EMG) data with biomechanical data (Inertial Measurement Units, IMUs) in a sensor fusion approach. It will model and track tremor and voluntary motion.
- It will also include a multi-channel array FES system for selective stimulation of muscles for tremor suppression while reducing the influence on voluntary motion.
- For a potential commercial exploitation the embodiment must fit potential user expectations in terms of cosmetics, functionality and aesthetics.

TREMOR proposes a multimodal BCI in which the main goal is identifying, characterizing and tracking involuntary motor bioelectrical activity as a command to trigger a biomechanical suppression of tremor. Figure 58 illustrates the general concept of TREMOR.

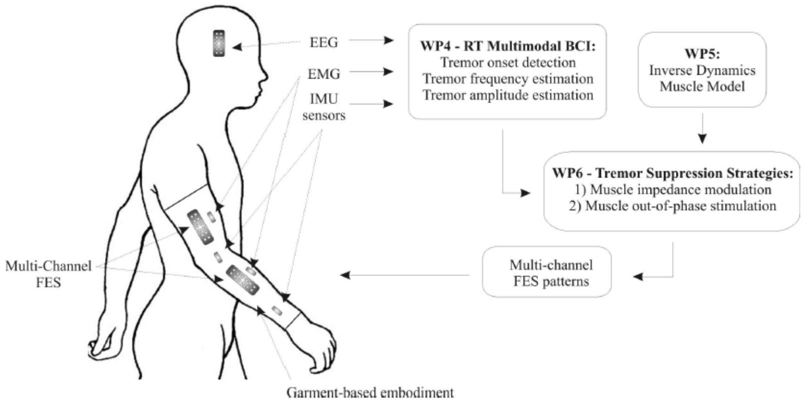


Figure 58: Concept of the TREMOR system.

The BNCI comprises the recording of electroencephalographic (EEG) and electromyographic (EMG) activity, together with motion capture with inertial measurement units (IMUs). Each sensor modality aims at extracting certain information, following a hierarchical integration scheme. In more detail, the implementation of the mHRI is as follows (see Fig. 1). The EEG exploits the direct measurement of the planification of movement in order to naturally trigger the system. However, the anticipation with which movement can be predicted from ERD analysis varies both between and within subjects, and thus a positive detection of movement intention needs to be maintained for a period t_{EEG_OUT}, to guarantee that the sEMG has time to detect the onset of both the voluntary muscle activity and the concomitant tremor. This in turn triggers the stimulation, which is modulated based on the instantaneous tremor amplitude and frequency derived from the inertial sensors, since the sEMG will be contaminated by the physiological artifacts that appear due to FES. In addition, sEMG indicates the specific locus of the tremor, a piece of information that is used by the controller to select the optimal stimulation site, and yields the tremor frequency of the muscles, which is employed by the inertial sensor algorithm for its initialization. This hierarchical integration scheme is summarized in Figure 59.

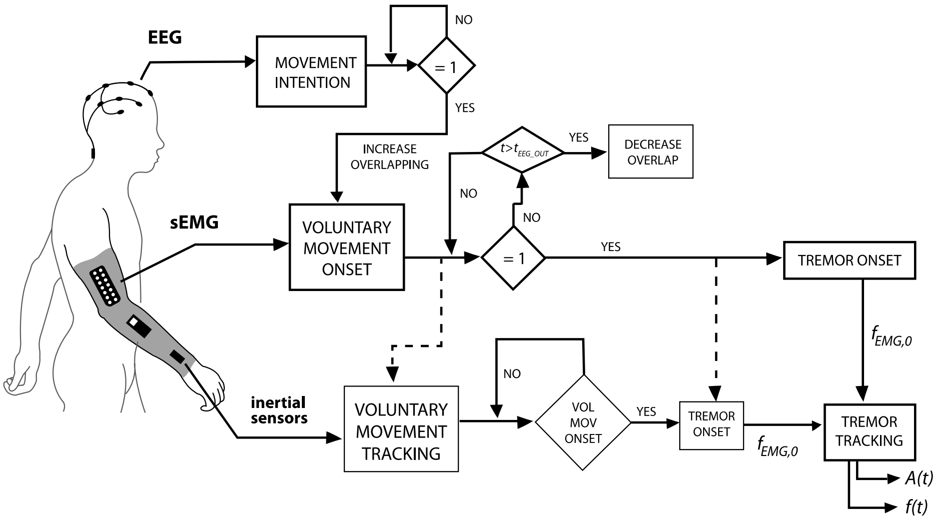


Figure 59: Diagram that illustrates the mHRI to drive a neurorobot for tremor suppression. The figure shows the normal performance of the system (thick boxes), and the redundant and compensatory mechanisms (thin boxes). Redundant (dashed line) and normal (solid line) flows of information are also differentiated).

The EEG algorithm runs in overlapping windows (ov_{EEG}) of duration T_{EEG}. At the same time, the sEMG algorithm is executed in windows of duration T_{EMG} and overlapping ov_{EMG}. The latter is increased to ov_{EMG_ho} during the period t_{pred} after a positive detection of the EEG classifier to accelerate the identification of the concomitant voluntary and tremulous muscle activity; simultaneously, the EEG algorithm goes idle, and the voluntary movement filter of the inertial sensors starts running, to minimize its settling time. In the presence of tremor, the sEMG algorithm provides the inertial sensors with an estimation of tremor frequency fEMG and the stimulation starts.

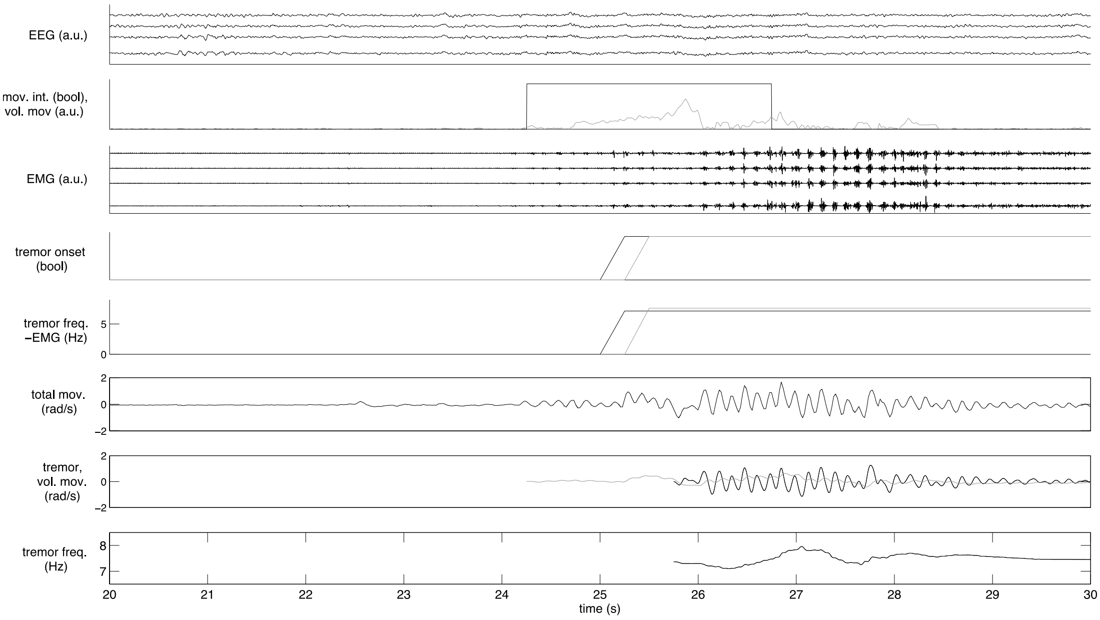


Figure 60: An example of tremor characterization during a volitional task with the mHRI. The plots show from top to bottom: 1) a few EEG channels, 2) the output of the EEG classifier (black) and the normalized and rectified reference voluntary movement (gray), 3) a few EMG channels from wrist extensors, 4) tremor onset as detected by EMG analysis of wrist *extensors* (black) and flexors (gray), 5) tremor frequency as estimated from EMG analysis at the time of detection, for wrist extensors (black) and flexors (gray), 6) the raw wrist flexion/extension recorded with inertial sensors, 7) the estimation of tremor (black) and voluntary movement (gray) derived from the inertial sensors, and 8) the tremor frequency estimated from the inertial sensors' data.

Figure 60 shows a representative example of the multimodal Human Robot Interface (mHRI). The plot depicts both, the raw signals acquired by the different sensor modalities that constitute it (the first, third and sixth plots), and how the different algorithms are triggered and executed. First, the EEG classifier (second plot) predicts the intention to move (anticipation time 0.44 s). This triggers two events: i) the EEG classifier goes idle for 2.5 s, and ii) the overlapping of the analysis windows of the sEMG algorithm is increased. During this interval, the sEMG algorithm detects the onset of tremor in the presence of concomitant voluntary activity (fourth plot), and yields an estimation of tremor frequency (fifth plot). At this moment the neurorobot begins to actuate, and it relies entirely on the tremor parameters derived from the inertial sensors –instantaneous amplitude (the estimated tremor is shown in the seventh plot) and frequency (eighth plot)– to modulate its control action. Notice that the inertial sensor algorithm is initialized to the tremor frequency provided by the sEMG.

In summary, the results indicate that the mHRI is capable of consistently anticipating the intention to move (in those patients that exhibit ERD), and that the onset of tremor in the presence of concomitant voluntary movement is rapidly detected (average delay for all patients is 1.11 ± 1.39 s for voluntary movement detection, and 0.76 ± 0.45 s for tremor detection), and hence the neurorobot starts assisting with a short delay. Moreover, the delay in the detection of both voluntary movement and tremor increases considerably in the patient without EEG-based movement anticipation (average delay 1.83 ± 1.77 s and 1.79 ± 0.91 s or the voluntary activity and the tremor respectively) when compared to the other patients (average delay in all trials 0.88 ± 0.45 s and 0.77 ± 0.45 s for the voluntary activity and the tremor respectively). On the other hand, accurate tracking of tremor amplitude (average RMSE 0.18 ± 0.17 rad/s) and frequency (average CV of the RMSE 0.77 ±

0.71) is achieved, and importantly for the controller, with almost zero phase. As a matter of fact, the average delay of the tremor estimation with respect to the offline reference is $3 \cdot 10^{-4} \pm 6 \cdot 10^{-4}$ s, calculated the from maximization of the cross-correlation function.

Regarding the movement anticipation, we observe, as expected, notable inter-subject differences. Moreover, remarkable intra-subject differences appear, as suggested by the, in general, large standard deviation. As a matter of fact, larger anticipation was found in bimanual tasks. Nevertheless, the EEG classifier provides, for all of them, a good performance in terms of movement anticipated (Recall), and robustness to false activations (Specificity).

Major accomplishments: In the framework of the TREMOR project a multimodal BCI for real-time characterization of tremorous and concomitant voluntary movements to drive a tremor suppression neurorobot was developed. This multimodal BNCI is implemented in a hierarchical approach, as described in the document, and implements the cognitive interaction (cHRI) between the user and the neurorobot developed in TREMOR.

Results shown demonstrate the ability of the cHRI to predict the user’s intention to perform a volitional movement, to detect the presence of tremor from sEMG, and to estimate its instantaneous amplitude and frequency out of kinematic information. Moreover, a number of features that will serve to enhance the reliability of the neurorobot were developed, for example: 1) taking advantage of the sEMG algorithm to estimate the onset of voluntary movement, to compensate for BCI based classification errors, 2) using the frequency estimation obtained by the IHT algorithm as an initial guess for the IMU based algorithm to track tremor features, 3) implementing machine learning techniques to adjust the parameters of the Bayesian classifier online, based on the execution of a voluntary movement.

This multimodal approach represents a step forward in the BCI field. The novelty of our concept is:

- The TREMOR concept attempts to implement a self-training process through correlation of EEG-EMG. In our approach, the EEG baseline associated with the no movement status is updated online based on the information provided by EMG sensors.
- The algorithm to detect movement intention that we have developed constitutes a step forward in BCI Systems since: 1) it is an asynchronous online system, 2) it does not require subject training, and 3) it has been validated with patients with neurological conditions, i.e. different types of tremors.
- The multimodal BCI increases robustness of classical BCI systems through the use of redundant information at different stages of the neuromotor process: EEG (CNS), EMG (PNS) and IMU (biomechanics).
- The fusion of EEG and IMU modalities implemented learning mechanisms for the single trial EEG classifier. The Bayesian classifier resulted in an adaptive system that tries to cope with the variability in EEG. This approach improves the performance of the asynchronous classifier and compensates for the non-stationary characteristics of EEG.
- The fusion of EMG and IMU information provides precise characterization of both voluntary and tremolous movements in real time for every upper limb joint.
- The TREMOR concept reduces the computational burden as each modality is prone to provide different kinds of knowledge in a computationally inexpensive manner: EMG for tremor onset, EEG for intentionality of limb motion, IMUs for tremor amplitude and frequency. This allowed the implementation of a truly Real-Time system.

RECOMMENDATIONS FOR FUNDING

Please see the recommendations from our “Better” project, described above. Generally, we recommend applying BNCI technology to scientific research (particularly in motor control), tools for training specific patient groups, improved clustering and interaction with relevant groups, and improved infrastructure, particularly benchmarking and standardized evaluation and comparison metrics. We also encourage “hybrid” BNCI systems that use the best combination of EEG, EMG, or other physiological signals for each user and situation.

Way

Way is a new project, scheduled to begin right around the completion of this roadmap. The project does not yet have a logo, website, or major accomplishments. This section reprints the official project summary for the European Commission.

This project addresses the scientific problem of recovery of hand function after amputation, or neurological disabilities like spinal cord injury, brachial plexus injury, and stroke. It introduces several conceptual novelties which explicitly take into account and overcome the limited band-width in actual Brain-Neural Communication Interfaces (BNCI). WAY demonstrators are able to restore a physiological bidirectional link between artificial aids and patients, and will be shown in clinical studies to improve the ability of users to perform activities of daily living (ADL) and thus to attain enhanced autonomy and quality of life. In other words, the project investigates new WAYs to link the brain with upper limb aids. This result is obtainable by employing already available sensorized hand assistive devices within the consortium-a dexterous prosthesis and an exoskeleton-and by developing non-invasive wearable interfaces designed for bidirectional data flow of sensory information and motor commands. The BNCI of WAY range in location, directionality, and working principles: efferent ones will implement biosignal processing exploiting machine learning for predicting user intentions (EEG, EOG, or EMG), while afferent ones will generate multi-modal stimulation patterns (vibro and electrotactile). The core of the system is the controller that dynamically processes sensor signals generated by the users and the device and drives efferent channels. The main novel feature is that the controller communicates with the user by means of temporally discrete signals that represent either commands or functional goal accomplishments and thereby mimics high-level control in normal humans. The demonstrators will thus minimize the cognitive load of the users while providing necessary feedback for adequate control. WAY bridges several currently disjointed scientific fields and is therefore critically dependent on the collaboration of engineers, neuroscientists and clinicians.

Other Projects

As BNCI research becomes more global, fragmentation and duplication may increase.

The H3 Cluster includes only thirteen projects. There are many other projects that focus primarily on BNCI research around the world, and other projects that include BNCI development as part of a project with a different focus. For example, some projects focused on robotics, rehabilitation, or assistive technology may incorporate relevant technology, and may not be well connected with other relevant research efforts.

This section includes short summaries of other projects that are not part of the H3 Cluster. Since the H3 Cluster includes only multinational European projects focused on noninvasive BNCIs, we made an effort to include other types of projects. These include multinational projects funded by the EC outside of our cluster, national (not multinational) projects, invasive efforts, and projects funded outside of the EU.

BrainGain

Neurotechnologies for health, well-being, and entertainment.

BrainGain is a Dutch research consortium consisting of researchers, industry and potential users of Brain-Computer and Computer-Brain Interfaces. The consortium started in September 2007 and is funded by SmartMix, a Dutch initiative to support applied research. BrainGain is researching applications for both ill and healthy users, and aims to develop both excellent scientific knowledge and off-the-shelf products or ready-to-use therapies.

There are three main topics: Brain-Computer interfaces, neurostimulation and neurofeedback (see Figure 61). These topics are divided over 7 projects.

Fact sheet:

21 partners (industry, universities, patient organizations)

- Total budget: 24 million Euro (± 35 million USD)
- Run time: 2008-2013
- Funded by: Smart Mix Program of the Dutch Ministry of Economic Affairs and the Ministry of Education, Culture and Science
- 112 BrainGainers
- Produces more than 15 peer-reviewed papers per year
- Two patents
- 1 spin-off company up and running
- 2 spin-off companies underway

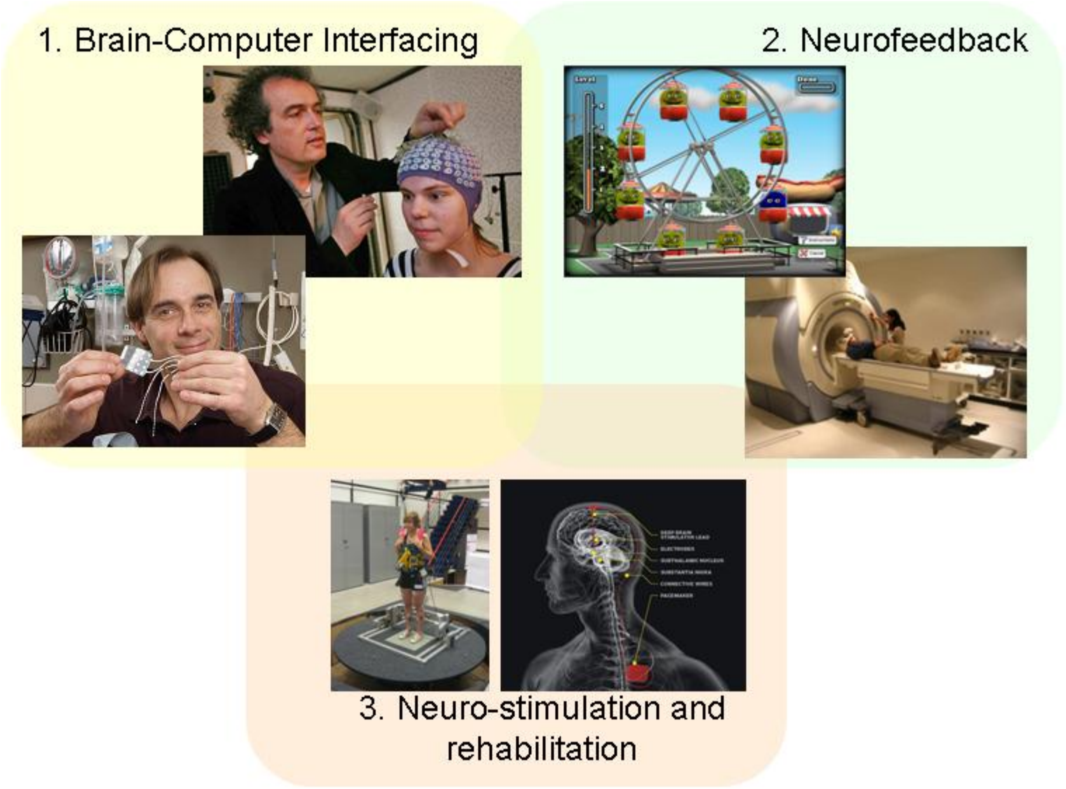


Figure 61: Three main topics of BrainGain.

BrainGain consists of seven projects:

Project 1: Control and communication for patients by BCI

In this project, Brain-Computer Interface solutions are investigated for patient groups with severe disabilities to interact with their surroundings. Applications include controlling devices such as wheelchairs, ambient controls and language interfaces, but also direct muscle stimulation.

Project 2: BCI applications for healthy users

Applications for healthy users include entertainment, such as computer games, but also systems that support users in situations of information overload. Detecting from brain measurement what someone is seeing or experiencing is useful in many settings, such as when monitoring visual attention or evaluating an interface.

Project 3: The power of intracranial EEG for BCI

Measuring brain activity directly from the cortex, instead of from the scalp, has many advantages in developing applications that eventually will not need surgical intervention. Increased measurement resolution allows for more precise use of our knowledge of the brain in the applications that are being developed.

Project 4: Modulation of abnormal brain activity by neurostimulation

Deep Brain Stimulation (DBS) has shown promise as a new treatment method for several illnesses. For instance, in Parkinson Disease, tremor can sometimes be completely suppressed when applying DBS. These methods and other rehabilitation tools are being researched and further developed in this project.

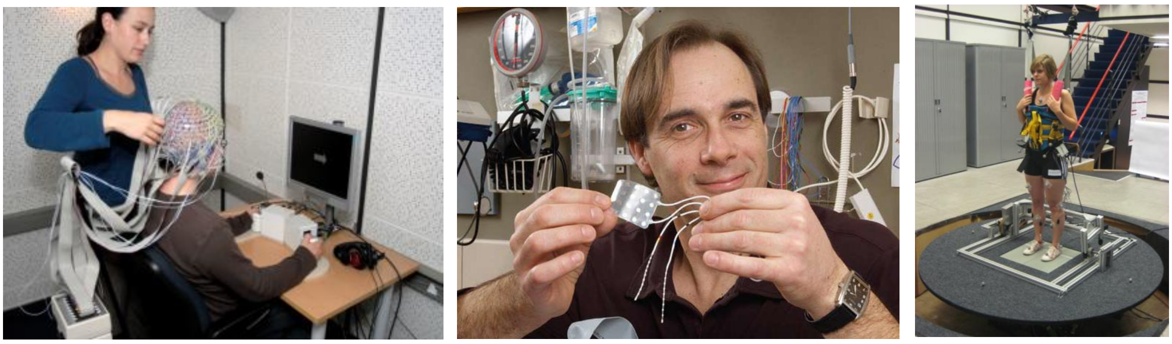


Figure 62: These three images present work from the first, third, and fourth BrainGain projects.

Project 5: Self-modification of brain activity by feedback and training

This project critically evaluates the effect of conventional EEG neurofeedback in patients with ADHD and develops and examines the effects of innovative fMRI neurofeedback. Furthermore, the brain activity correlates of mindfulness therapy and intensive cognitive training are examined in order to develop new and effective training programs for cognitive and mental problems in patients and healthy controls.

Project 6: System integration and software development

To advance the state-of-the-art BCI, this project develops and integrates the necessary hardware, software tools and analysis methods. Standardization of real-time communication protocols and the dissemination of new methodology and software tools for advanced real-time signal processing will benefit both companies and research institutions. The two core products are the FieldTrip toolbox for offline analysis (http://www.ru.nl/donders/fieldtrip) and the BrainStream platform for realtime analysis (http://www.brainstream.nu). This project facilitates overall valorization by contributing key enabling technologies and consultancy services (see also project 7) to the partners involved with the individual work packages in projects 1-5.

Project 7: Dissemination and Valorisation

Societal Value

BrainGain aims to communicate and translate its research into societal value as widely as possible:

- Communication to **science** through for example conference presentations, journal papers, and research visits.
- Education of master and PhD students through for example BCI and neurofeedback courses at four Dutch universities, master and PhD theses, summer schools.
- Communication to the **general public**. For example: researcher’s nights, demos, lectures at primary and secondary schools, media exposure.
- Communication to the **user population**. Newsletters for patient organisations, lectures at stakeholder workshops.

Commercial Value

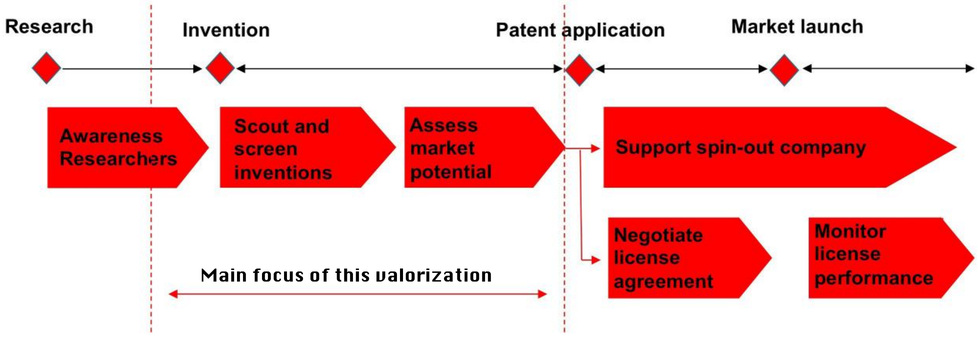


Figure 63: The BrainGain plan to generate commercial value.

Commercialisation goals until the end of 2013:

- Spin-offs generated: 3
- Patents: 5-10
- Applications for valorization grant: 1 per project

Contact Information

Peter Desain
Scientific coordinator
p.desain@donders.ru.nl

Jan van Erp
Scientific coordinator
jan.vanerp@tno.nl

Marc Grootjen
Business coordinator
marc@grootjen.nl

Susanna Bicknell
Project manager
S.Bicknell@fnwi.ru.nl

Femke Nijboer
press/publicity coordinator
femke.nijboer@utwente.nl

Video: http://www.youtube.com/user/BrainGainConsortium

Web: **www.braingain.nl**

Twitter: **@braingain_NL**

LinkedIn: **BrainGain group**

Project Recommendations

Please contact the BrainGain team for recommendations.

CONTRAST

An individually adaptable, BNCI-based, remote controlled Cognitive Enhancement Training for successful rehabilitation after stroke including home support and monitoring.

Funding scheme: Collaborative Project
Budget: €3.2 million
Duration: from 01/11/2011 to 31/12/2014
Participants: University of Würzburg; University of Graz, Fondazione Santa Lucia IRCCSUniversity of Luxemburg, T-Systems ITC Iberia S.A.U., Mind Media, Hasomed
Project coordinator: Prof. Dr. Andrea Kübler
Project website address: http://www.contrast-project.org (available in February 2012)

Millions of people live with the consequences of stroke, which often include cognitive impairments. CONTRAST targets the cognitive function of interest directly in the brain by investigating and targeting the use of biofeedback in the rehabilitation process after stroke.

CONTRAST strives to bridge the existing gap between clinical rehabilitation and care, and patients monitoring and support at home by developing easy-to-use auto-adaptive human-machine interfaces (HCI). Our highest aim is to deliver a comprehensive product for the sub-acute rehabilitation phase as well as at the patients' home thereby supporting patients' independent, socially integrated living.

CONTRAST's deliverables include the development of training modules for cognitive enhancement which are tailored to the individual. We will develop, test, and upgrade our brain-neural-computer interface (BNCI) neurofeedback tools, based on findings that increasing power in specific EEG frequency bands can improve long-term cognitive performance. At the same time remote data processing and support systems will allow for continuous monitoring of health parameters to evaluate individual progress and provide a solid basis for shared patient-expert decisions.

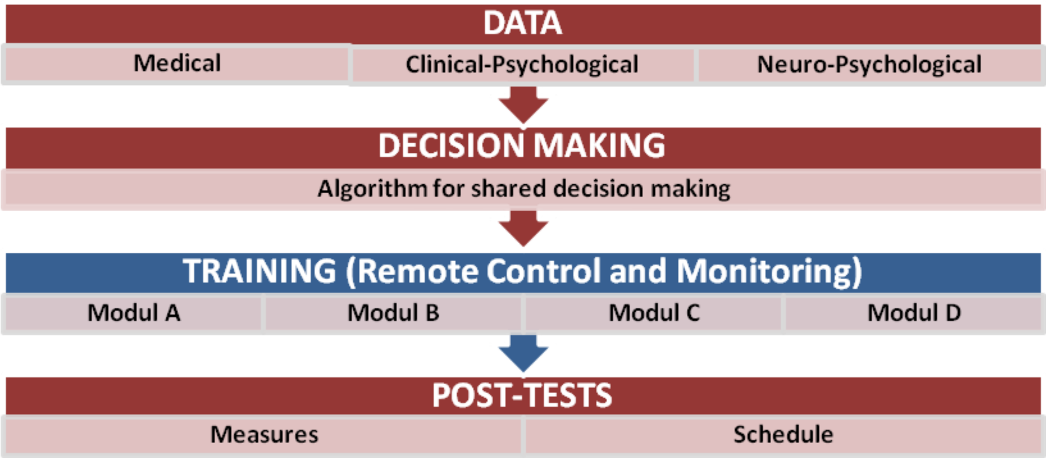


Figure 64: CONTRAST: Central Elements.

The aims of CONTRAST are the development of …

- … a ***new architecture of HCI*** that is adaptive and integrates remote processing and shared decision making.
- … an accurate, individually tailored ***intervention*** for the improvement of cognitive function ***guided*** by ***medical*** and ***neuropsychological assessment***.
- … a BCI ***neurofeedback based*** cognitive enhancement ***training*** including Virtual Reality approaches.
- … a continuous onsite and remote ***monitoring*** of ***health parameters*** and evaluation.

In addition, CONTRAST aims for a high degree of ***exploitation*** and ***dissemination***.

While these are ambitious aims, the combination of Universities, Companies, Hospitals, Rehabilitation Centers and User Groups within CONTRAST provides the experience, connections, and infrastructure necessary to have a real impact on disease management, medical knowledge, Personal Health Systems, and stroke patients.

Thus, CONTRAST will contribute to new medical and practical knowledge for guiding and improving intervention for daily life functioning after stroke.

Suggestions/Recommendations for future research priorities:

1) Applicability of the BNCI in clinical routine and extension to other patient groups for cognitive enhancement
   a. Stroke
   b. Traumatic brain injuries
   c. Epilepsy
   d. ADHD

2) Enhancing the end product by adding useful features
   a. Tele-monitoring
   b. Multiple supervision
   c. Integration of multiple data sources
   d. Virtual Reality approaches

3) Using BNCI as a research tool for elucidating the neural basis of behaviour

FUTURAGE

FUTURAGE
A ROAD MAP *for* AGEING RESEARCH

Executive summary

The FUTURAGE Road Map for European Ageing Research was launched in October 2011 after a two year project funded under FP7 (FP7-HEALTH-2007-B/No 223679). It contains the research agenda that will enable Europe to respond successfully to the unprecedented demographic challenges it faces. Its twin starting points are the high priority allocated to population ageing, by Member States and the European Union as a whole, and the fundamental importance of scientific research as the driver of innovations in public policy, in a wide range of clinical and other professional practices, and in the development of products and services. The combination of science and innovation will be the cornerstone of Europe's future success, both in terms of economic growth and the promotion of social quality for all citizens, and that equation lies at the heart of this Road Map.

The Road Map for ageing research is the product of the most extensive consultation ever undertaken in this field, involving all of the major stakeholder groups and end users of ageing research, and spanning a 2 year period. A specially designed iterative process ensured that the specific research priorities were not identified by scientists alone and were subjected to a high degree of reflection and cross-examination from a wide range of stakeholder perspectives, including policy makers, practitioners, business people, older people and their NGOs as well as scientists. This process led to an extraordinary broad and deep consensus on the major future priorities.

The Road Map itself consists of three main chapters. The first of these sets the scene by describing briefly the demographic context and emphasising the huge challenge facing the European Innovation Partnership pilot initiative on Active and Healthy Ageing (EIPAHA) if it is to achieve its goal of increasing average healthy life expectancy across the EU by 2 years by 2020. Then the links between this document and some of the other major European policies concerning ageing are summarised.

A key role of the introductory chapter is to explain the importance of active ageing to the Road Map. Originally one of the individual priority topics generated by the iterative process it was subsequently elevated to the central theme of the Road Map. In addition the case is advanced for a new comprehensive approach to 'active ageing' which includes all activities, physical or mental, and all age groups. Then each of the major research priorities is linked to the active ageing core theme on the assumption that this should be a central aim of ageing research.

The Road Map is also based on eight basic assumptions, which should figure significantly in all priority topics:

- Multi-disciplinarity
- User Engagement

- Life Course Perspective
- Person-environment Perspective
- Diversities
- Intergenerational Relationships
- Knowledge Exchange
- Technological Innovation

The final contextual building block is a full account of how the Road Map was produced.

The second chapter forms the centrepiece of the Road Map. It is here that the following seven major priority research themes are described and explained using a common format. Within each theme the main priority topics are identified along with examples of specific research questions.

The major priority themes for future ageing research are:

- Healthy Ageing for More Life in Years
- Maintaining and Regaining Mental Capacity
- Inclusion and Participation in the Community and in the Labour Market
- Guaranteeing the Quality and Sustainability of Social Protection Systems
- Ageing Well at Home and in Community Environments
- Unequal Ageing and Age-Related Inequalities
- Biogerontology: from Mechanisms to Interventions

The third main chapter concerns the implementation of the Road Map and covers four critical issues, discussed in the text box below. Thus, this Road Map sets out the major research priorities for European ageing research over the next 10 or so years. It also calls for new approaches to ageing research which are more multi-disciplinary, life course focussed, user engaged and have a big emphasis on knowledge exchange. Furthermore it calls for a new vision of ageing which promotes its positive possibilities rather than deficits, inclusion and full citizenship rather than exclusion. Therefore the Road Map challenges all stakeholders in ageing research – policy makers and research funders; NGOs, practitioners, business people; scientists; and older people – to work in unison to ensure that the research maximises its impact on the well-being of all Europeans as they age.

For more information

The full Road map is available from www.futurage.group.shef.ac.uk/road-map.html. The complete Road Map includes full descriptions of the demographic context, policy priorities, the Road Map creation and production process, and significantly greater description and explanation of the seven major research priorities and key implementation priorities identified during the process.

Acknowledgements

The production of this Road Map was a remarkably collaborative effort and our sincere thanks are expressed to everyone who took part in the national consultations, workshops, Forums, Council of Scientists and who contributed to the drafting of the Road Map document. A full list of contributors and a full set of acknowledgements is available from www.futurage.group.shef.ac.uk/resources.html.

For more information on the FUTURAGE project and all its activities, please visit the website www.futurage.group.shef.ac.uk.

The third main chapter of the Futurage roadmap identifies the following four major issues and research priorities:

First of all it is vital for Europe to invest in ageing research infrastructure. The case is made for a European Institute of Ageing, but, at the very least, there must be some coordination mechanism of the kind that the European Research Area in Ageing (ERA-AGE) has been providing since 2005, but with an enhanced capacity.

The second implementation priority is to ensure the future development of scientific expertise in this field. There is a need for additional capacity building at all levels – doctoral programmes, post-doctoral programmes and mid-career development programmes – otherwise Europe will not be able to match North America and Asia in research and innovation in ageing.

Thirdly, user engagement is a critical element of implementation as well as a fundamental assumption of future ageing research. User engagement was allocated an equal status to science in the production of the Road Map and the main challenges for both scientists and research funders in implementing the principle of user involvement are laid out in Chapter 3 of the Road Map document.

Fourthly, linked to user engagement, knowledge exchange or knowledge transfer is a neglected aspect of ageing research. The pilot EIPAHA should provide the framework to remove barriers to successful innovation in this field. What is needed is a new priority for knowledge exchange in which project funding rests not only on scientific excellence but also on the quality of the knowledge exchange plans.

sBCI

Swift Brain-Computer Interface systems for daily applications (sBCI).

sBCI (swift Brain-Computer Interface systems for daily applications) develops a lightweight and portable multimodal Brain-Computer Interface (BCI) combining EEG and eye tracking.

The sBCI project is founded by the Federal Ministry of Economics and Technology (BMWi, Germany) under grant sBCI (16136BG).

Duration: from 01/09/2009 to 02/29/2012

Participants: Friedrich-Wilhelm-Bessel-Institute research association (FWBI), Bremen, Germany; Institute of Psychology I at University of Leipzig, Germany; Institute of Psychology and Cognition Research at University of Bremen, Germany

Scientific representative of the project's coordinator: Prof. Axel Gräser, FWBI

Project website address: http://www.fwbi-bremen.de/index.php/bci/articles/sbci-296.html

sBCI (swift Brain Computer Interfaces for daily applications) develops lightweight and portable multimodal Brain Computer Interfaces (BCIs) to provide the best combination among different communication and control channels. This project promotes inclusion by integrating BCI technology into everyday living environments minimizing work for users' supporters and providing the user with several hours independence. The solution proposed by sBCI was the combination of SSVEP (steady-state visual evoked potentials) and ERD/ERS (event-related (de)-synchronization), with environmental observation and eye-tracking (if remaining motion is available) to enhance the inclusion for a range of different disabled users while minimizing dependence on caregivers.

sBCI-headset:

The primary goal of sBCI was the development of an easy wearable and appealing multi-sensor device and the data fusion of BCI paradigms with other input modalities like eye-tracking. The sBCI multimodal device has been integrated into an easy-to-use headset (See Figure 66: BCI headset, which includes: hard case cap with 22 electrode positions, two eye cameras and one camera for monitoring the environment, and a miniature SSVEP stimulator with four SMD (surface-mounted device) LEDs allowing 4-way SSVEP interaction. The CAD-model of headset was developed based on the 3D-model of adult head and was manufactured by using rapid prototyping technology. Each electrode adaptor includes a spiral spring (range of spring is about 5 mm). Our future tests will investigate the possibility to provide sBCI-headsets in three different sizes in order to fit the head of any user.

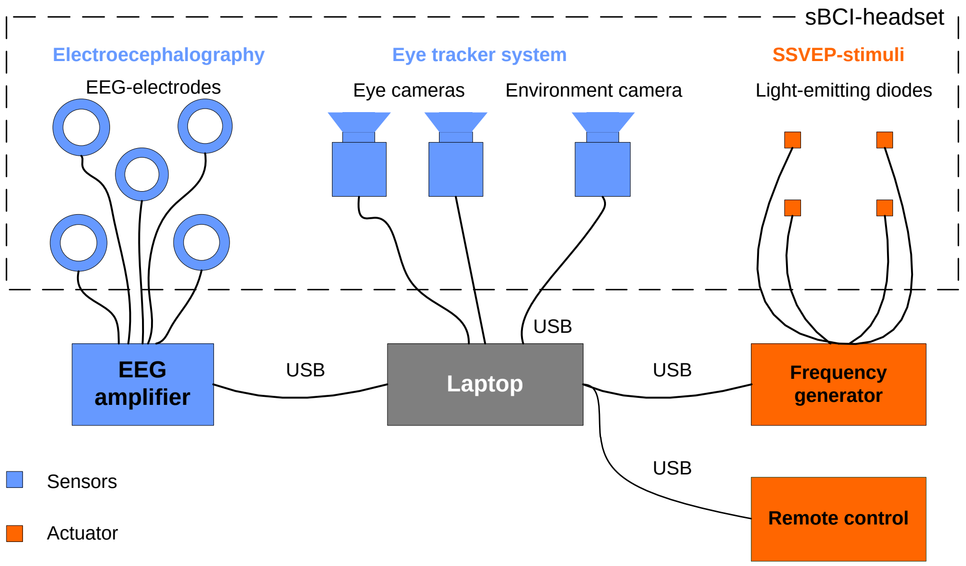


Figure 65: **Overview of the hardware components.**

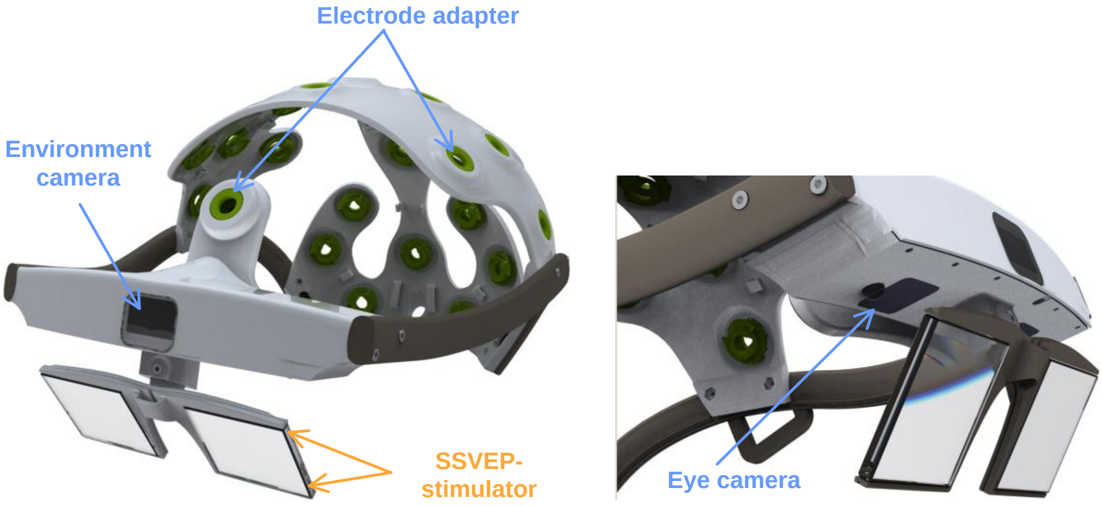


Figure 66: **BCI headset.**

Eye-tracker:

A further task is to develop a head-mounted eye tracker and integrate it into the sBCI-system. The eye tracking system is used to detect the user’s intention to interact with a specific device in the environment. Based on estimation of the gaze direction the eye tracker detects the object of interest. This device is selected if the user’s gaze dwelled on it for more than predefined fixation interval. The object recognition approach is based on visual markers (2D barcodes).

Brain-Computer Interface:

A Brain-computer interface is used to operate the selected device. Depend on each subject’s preference, s/he can choose between SSVEP-based BCI, MI-based BCI and using both. Each command coming from the BCI is accompanied by audio and visual feedback.

Signal processing of the SSVEP-based BCI uses minimum energy combination method to create a spatial filter that magnifies the SSVEP response and cancels noise. The arrangement of SSVEP-stimuli (nearby eyes) allows the generation of stimulation frequencies by using tiny light emitters (2x1.25 mm).

Signal classification of MI-BCI is based on spectral power estimation computed in individualized frequency bands, which are automatically identified by a specially tailored AR-based model. Relevant features are chosen by a criterion based on mutual information. Finally, relevant features are used to train a multinomial logistic regression classifier for the detection of different motor imagery classes (e.g., right hand, left hand, and feet).

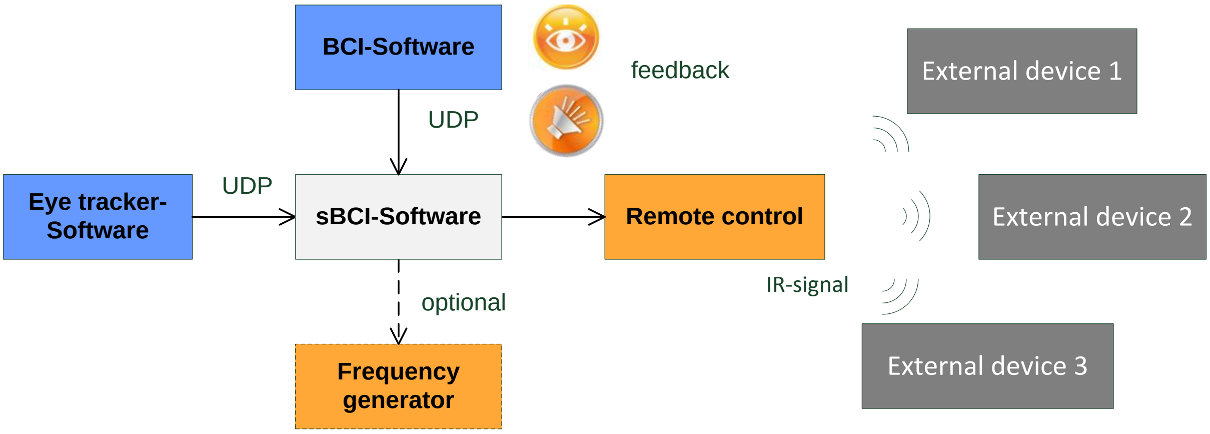


Figure 67: sBCI-Software architectures.

Figure 67 shows the user friendly Human Machine Interface for home control devices. This interface interacts with BCI commands coming from the BCI2000 software platform, which incorporates the sBCI signal processing routines. Our current interface contains three external devices: internet radio, fridge and microwave.

In general, the sBCI-system works in a sequential hybrid approach in which external devices are selected with the help of an eye tracking system and then operated via BCI.

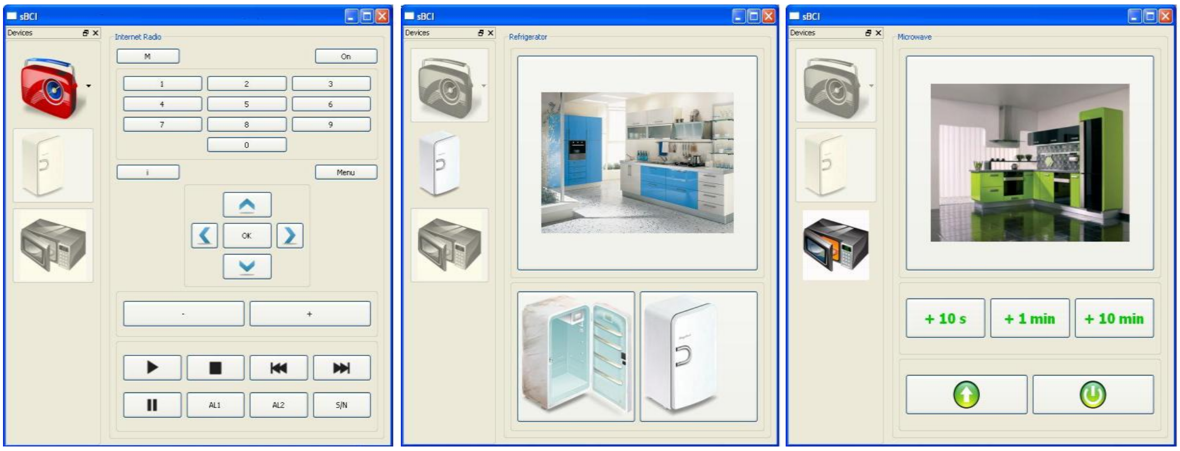


Figure 68: sBCI-Human-machine interface.

Recommendations for FP8:

Non-invasive BCIs:

Hardware:

- Further improvement of the aesthetics of the system: smaller amplifier (integrated into BCI cap), esthetical headset.
- Development of signal-processing algorithms running on FPGA/DSP.

Signal processing:

- Accurate and robust adaptation of signal processing algorithms (especially in the case of MI-based BCI). Changes in the subject's brain processes (like new cortical activities, change of recording conditions, changes of operation strategies) drop the classification accuracy and affect the BCI-performance. The adaptive algorithm has to recognize these changes and react on the alterations.

Invasive BCIs:

Fundamental research:

- Dynamic interactions between neuronal populations most likely play an important role in neuronal processing. Measuring such interactions is therefore expected to be a rich source of information, especially in a more realistic and thus more complex scenario. Therefore we need (1) research investigating the patterns of dynamic interactions between nearby as well as distant groups of neurons and their meaning for neural information processing. (2) We need research testing the suitability of such identified, meaningful interactions for the extraction of information and a variety of possible innovative BCI approaches.
- To introduce information into the cortex an improved understanding of the dynamics of activating local populations, e.g. in cortical columns, is required. Therefore a better understanding of the dynamic properties of activity caused by natural stimulation is required and investigations into how such natural patterns can be induced by artificially stimulating local groups of neurons in the brain (bidirectional BCI).

Aside from hearing there is a great lack of knowledge how and where stimulation for other sensory modalities could result in natural or semi-natural perceptions. The research is required which defines the fundamental activation patterns that have to be induced to evoke simple perceptions.

Hardware:

- Miniaturized recording and stimulation hardware for opto-genetic approaches.
- Wireless, fully implanted microelectrodes which can move through the tissue.

Ethical, Legal and Social Issues

Introduction

Brain-Computer Interfacing is a field that quickly gives rise to questions about ethical, legal and societal issues (ELSI), many of which are similar to the issues related to brain imaging and other applied neuroscience fields. In the past topics like modified food, cloning and stem cell therapy have already triggered a concern about human identity and dignity, but nowadays neural engineering and applied neuroscience confront us even more with disappearing boundaries between humans and technologies. The issues related to brain-computer interfacing could be distinguished dependent upon three different societal levels (see Figure 69):

1. Issues related to the research and development of BNCI technologies.
2. Issues related to use of BNCI technology by individuals in their daily life.
3. Issues related to the impact of BNCI technologies on society as a whole.

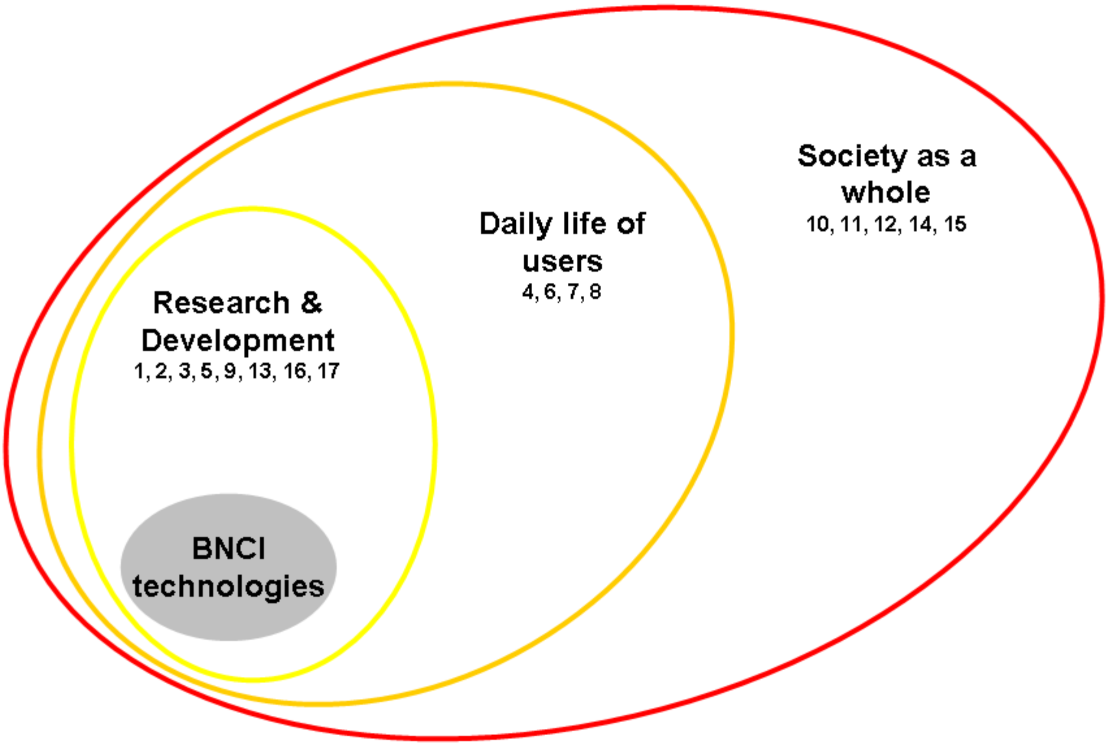


Figure 69: BCNI technologies at three different societal levels. The numbers in each level indicate which ethical issues have been identified.

The emerging neuroethical debate

The nascent neuroethical debate has identified several topics of importance to Brain-Computer Interfacing: 1) obtaining informed consent from people who have difficulty communicating, 2) risk/benefit analysis 3) shared responsibility of BNCI teams (e.g. how to ensure that responsible group decisions can be made), 4) the consequences of BNCI technology for the quality of life of patients and their families, 5) side-effects (e.g. neurofeedback of sensorimotor rhythm training is reported to affect sleep quality) 6) personal responsibility and its possible constraints (e.g. who is responsible for erroneous actions with a neuroprosthesis?), 7) issues concerning personality and personhood and its possible alteration, 8) therapeutic applications, including risks of excessive use, 9) questions of research ethics that arise when progressing from animal experimentation to application in human subjects, 10) mind-reading and privacy, 11) mind-control, 12) selective enhancement and social stratification, 13) human dignity, 14) mental integrity, 15) bodily integrity, 16) regulating safety, 17) communication to the media (Allison, 2010; Grübler, 2010, 2011; Clausen, 2008, 2009, 2010; Fenton and Alpert, 2008; Haselager et al., 2009; Nijboer et al., 2011a,b; Schalk, 2008; Schermer, 2009; Tamburrini, 2009; Walter, 2010).

However, the results from this initial debate do not seem to be fully integrated into BNCI research. BNCI researchers, like neuroscientists, may have good reason for their reluctance to wade into ethics. The questions raised are likely to be open-ended, and their arrival in the world both inside and outside the laboratory may be some way off (Editorial, 2006). Furthermore, many BNCI researchers come from an engineering background, and may have less training and understanding in ethical matters. Finally, BNCI researchers may be interested in ethical issues they are confronted with in daily work situations, while some ethicists focus on more abstract, but no less relevant, themes like enacted mind or embodied mind (Fenton and Alpert, 2008; Walter, 2010). Additionally, the public community may be more concerned with issues like mind-reading, animal experimentation and military applications. These different viewpoints and interests notwithstanding, we believe it is worthwhile to invite and support the BNCI community to articulate its (varying) views as clearly as possible. Obviously, this is not something that can be accomplished in a single grand effort, as extracting and clearly identifying the opinions of the eclectic members of a young, multi-disciplinary research field will take time. Different stakeholders need to become engaged in pondering, discussing, articulating, and disseminating ethical issues perceived to be central and/or most pressing. We therefore hope this section may invite other BNCI-researchers to give their thoughts on the ethical issues involved.

Before we continue, it is important to understand that BNCI technology encompasses a wide range of technology and potential users. The technology ranges from surgically implanted electrodes used in a clinical setting for severely impaired patients to ‘all in one’ headsets worn by gamers, which utilize appropriate neural/muscle signals for ‘infotainment’ interaction. In between there is an array of patient groups and serious industrial/military applications. With the former group, the brain-computer interface may be the most appropriate technology or even the technology of ‘last resort’ (for locked-in patients). Strict ethical and legal guidelines must be adhered and the clinical setting will inevitably promote this as it is likely that neurologists, surgeons and general medical practitioners are routinely involved in the patient’s care. In the latter case, i.e. for gamers, it is important that safety predominates. The utility of the interface and advantages provided will determine whether it is adopted for longer term use. Issues akin to repetitive strain injury (largely unanticipated when computer keyboards became mainstream) could potentially arise in the longer term and this could have legal (possibly retrospective) ramifications for suppliers. Industry/military will only adopt proven technology which provides clear advantages. In between the extremes lies a large spectrum of ‘clients’ for which BNCI could be used as an Assistive Technology, and hence which poses important ELSI challenges. This group may pose more of an ethical challenge as they will be largely community based, and may have less rigorous or less frequent clinical supervision.

Research and development of BNCI technologies

The past decades has seen many studies on brain-computer interfacing. These studies included a large variety of participants. We will make some educated guesses on the numbers of participants in European studies based on the literature:

- Dozens of persons with physical disabilities or in the locked-in state entered in research studies.
- Thousands of persons, including children, entered studies on neurofeedback.
- Thousands of healthy volunteers participated in BNCI studies in the labs of universities.

The ethical, legal and societal issues related to these studies lie mostly with the wellbeing and safety of the participants mentioned above. The current projects in the BNCI cluster all have ethical managers to manage ethical issues in their studies and all comply with the standard national and European regulations and the Helsinki Declaration[72]. The TOBI project (Project reference: 224631) has a dedicated work package on ethical issues related to BNCI, and the DECODER project (Project reference: 247919) also has deliverables on ethics and BNCI.

However, one could question if standard regulations are always fully sufficient to ensure the well being and safety of the most vulnerable of participants. We will mention three exemplary issues. First, the informed consent process with locked-in patients is very tricky (Haselager, 2009). Legally, researchers and physicians have to obtain informed consent from the legal guardian of LIS patients before the patient enters a study. In addition, one has to obtain informed assent from the patient. In the case of BNCI, studies typically last longer than just 1 session. Since LIS patients often have difficulties communicating, it may be difficult for them to express growing dissent by themselves. Thus, in practice it would be important to expand the guidelines such that the informed consent process becomes a repetitive procedure in the course of studies rather than a single event.

Researchers do not agree what the side effects of brain-computer interfacing are.

A second ethical challenge constitutes informing the legal guardian or LIS patient about side effects. Legally, this is mandatory before any study, yet practically researchers do not agree on side effects (Nijboer et al., 2011) and few studies exist which have examined the effect of regular BNCI training on the brain. Positive side effects have been found after so-called sensorimotor rhythm training (Hoedlmoser et al., 2008), but no one has ever looked at negative side effects. The study of side effects is particularly important since more and more projects currently aim to promote brain plasticity through neurofeedback for example to accelerate rehabilitation of stroke patients. If brain plasticity can be altered to produce different benefits, there may very well be also negative side effects. It is astounding that regulation to research neuropharmacology is so strict, whereas research on neurotechnology is so loose.

---

[72] http://www.wma.net/en/30publications/10policies/b3/17c.pdf

A third common practice in BNCI research is the re-use of previously gathered EEG data for new studies. Participants give their informed consent for study X with investigator Jack. Three months later, the same data, including biographical data from the participant, is handed over to Jack's colleague Wendy, who re-analyzes it for a new study Z. In principle it obviously makes sense to make use of available data. For certain publications you even have to make the data public available. However, research participants are not always informed about this, do not get a chance to express dissent, and never ever hear what happened to their data or resulting analyses. In a recent comment in Nature, Saha and Hurlbut make the same case against data mining in biobanks (Saha and Hurlbut, 2011). The authors argue to treat donors as partners in research: "*We need an alternative approach, in which donors are made partners by staying connected to research. Partnership is a win-win approach: it will build trust, make research better and faster, and generate large diverse cohorts with longitudinal data*". Similarly, BNCI researchers could inform participants better about the use of their data and provide feedback of results.

The three concerns discussed above are just a few in a long list of urgent and practical ethical issues that need to be addressed. BNCI researchers also want to see ethical guidelines. In a recent study by Nijboer and colleagues, 86 % of the respondent stated they would like to see ethical guidelines specific to BNCI research and BNCI use within 5 years (Nijboer et al., 2011). More than half of the respondents (57%) would like to see these guidelines within only 2 years.

To conclude, although current BNCI projects often have ethical managers, ethical advisory boards and effectively manage the well-being and safety of research participants, there are also a number of issues which are seemingly well organized in regulations, but poorly addressed in reality (for example obtaining informed consent with locked-in patients, shared responsibility issues in BCI teams etc.). In addition, more effort is needed to consider research participants and the general public as partners rather than donors and disseminate research results to them in an accessible and informative manner. This will empower the general public and increase societal acceptance and appreciation of neurotechnologies.

Using BNCI technologies in daily life

How do BNCI technologies affect users in their daily life? Will they make life easier? For example, can a LIS patient obtain more independence due to BNCI technologies? Can a gamer interact more natural with the videogame due to BNCI? Can a stroke patient leave the hospital sooner due to accelerated rehabilitation with BNCI support? Alternatively, can BNCI technologies create burdens or problems for users or their loved ones? For example, can the tedious procedures necessary to set up and customize many BNCI technologies for LIS patients add to the already long list of care activities for nurses? Do gamers develop mental or physical problems during chronic BNCI-supported gaming?

Most of these questions can probably be answered with empirical studies, but hardly any long-term studies exist on the impact of BNCI technologies on the daily life of users. Since BNCI technologies for assistive technology support are clinically tested and not yet used by persons at home independent from a research team, it is logical that we do not know the effects on daily life yet. However, commercial BNCI technologies are used by many healthy users (> one million persons), mostly for gaming purposes (e.g. Emotiv, Neurosky, Interactive Productline). We recommend a research study to approach some of the consumers of commercial applications to investigate the effect of these products on their lives. For example, Michael Reboli, a customer at Amazon, says that the use of the Uncle Milton Star Wars Force Trainer "gives a good feeling in the head" (see Figure 70).

Most Helpful Customer Reviews

13 of 13 people found the following review helpful:

★★★★★ **so much fun. and relaxing!**, 15 Sep 2009

By Michael Reboli - See all my reviews

REAL NAME

Durability: ★★★★★ **Fun:** ★★★★★ **Educational:** ★★★☆☆

This review is from: **Uncle Milton Star Wars Force Trainer (Toy)**

Well, this is one of the best thing of this decade.

It really does work (although the lower levels seems to be more of a "calibration" type of thing.

However there's a "surprise" waiting for you when you reach the Master level - you're not allowed to "drop" the ball, or your progress on that sublevel are gone...

Took me about 1 hourish to reach the master lever, and it is way harder indeed!

it does bring a good feeling in the head though -

I think this could be very usefull for someone trying to meditate also! :)

Figure 70: Left: picture of a child using the Uncle Milton Star Wars Force Trainer. Right: Evaluation of the product by Mr. Reboli on www.amazon.com.

In the next section we will discuss how BNCI technologies could affect society as a whole.

Impact of BNCI technologies on society

> "We are living in an era of change where we really need to think ahead in order to protect human dignity."

The rapid technologization of our world exposes a dilemma for humanity. As Arthur puts it: "*We put our hope in technology, but our trust in nature*" (Arthur, 2009). In an aging society, with a rapid increase in the number of people with neurological disorders which will require solutions from neuroengineering, we will have to better address society's concerns. We are already behind schedule. Neurotechnologies like brain-computer interfaces raise public concern since they confront us with issues of existential nature: who are we? Are we only our brains and bodies? How much technology do we wish to have in our bodies and brains? Do we want our brains to be 'read' by technology? Vitorrio Prodi, member of the European Parliament (MEP) remarked at a recent conference[73] (see Figure 71): "*We are living in an era of change where we really need to think ahead in order to protect human dignity*".

Research on neurotechnology is moving so fast that it threatens to leave the stakeholders behind. Policymakers say they are aware that addressing ethical concern is of utmost importance for the design, development and acceptance of neurotechnologies. However, as Van Keulen and Schuijff comment: "*it is remarkable that […] the EU is not yet funding any large ethical, legal and or*

---

[73] Science and Technology Options Assessment (STOA) conference: "making perfect life – bioengineering in the 21st century ", 10 November 2010.

sociological project in neurosciences, or in neural engineering for that matter" (p. 123; van Est et al., 2010).

Figure 71: Vittorio Prodi (MEP) and Malcolm Harbour (MEP) discussing at the "Making Life Perfect" STOA conference. PHOTO © European Union.

"It is remarkable that […] the EU is not yet funding any large ethical, legal and or sociological project in neurosciences, or in neural engineering for that matter"

Indeed, the European Union (increasingly) funds more projects centered on brain-computer interfacing than other technologies (€ 11 million in FP6 and € 34 million in FP7, not including projects that include but do not focus on BNCIs). However, only *two* consortia (TOBI and DECODER) have work packages or deliverables dedicated to ethical issues, although some consortia, like BRAIN, have an ethical advisory board. Similarly, in the Netherlands, a large national project called BrainGain[74], which focuses on neurostimulation (e.g. through DBS), neurofeedback and Brain-Computer Interfacing, received € 14 million funding (total budget € 25 million) through the SmartMix program of the Ministry of Economic Affairs and the Ministry of Education, Culture and Science, without having to dedicate *even one* deliverable to ethics. Thus, huge efforts are made by the EU to advance technology development, but ethical, philosophical and societal framing within the neuroengineering projects lags behind. However, the EU and several of its nation members do have projects which focus on the societal consequences of applied neuroscience and bio-engineering. These projects are poorly connected to existing neuroengineering project. In the next section we will give a short overview of these projects.

---

[74] http://www.brainandcognition.nl/websites/nihc.nsf/pages/SPES_82SKQC_Eng

Overview of ELSI Networks

"Making Perfect Life"

The project 'Making Perfect Life' constitutes a search for social meaning of the so-called NBIC convergence, the powerful combination of nanotechnology, biotechnology, information technology, and cognitive science (Van Est et al., 2010). The second phase of this STOA project resulted in a monitoring report "Making perfect life: bio-engineering (in) the 21st century" (van Est et al., 2010). These activities discuss how bio-engineering is the new black in the 21st century world of science and technology. On the 10th of November 2010 a conference was held in the European Parliament to update and advise the members of the parliament. A recording of this conference can be watched via the website of the European Parliament[75].

A whole chapter entitled "Engineering on the brain" is dedicated to neuroengineering, including brain-computer interfaces. Figure 72 shows how Van Keulen and Schuijff frame BNCI technologies in relation to other neuroengineered technologies.

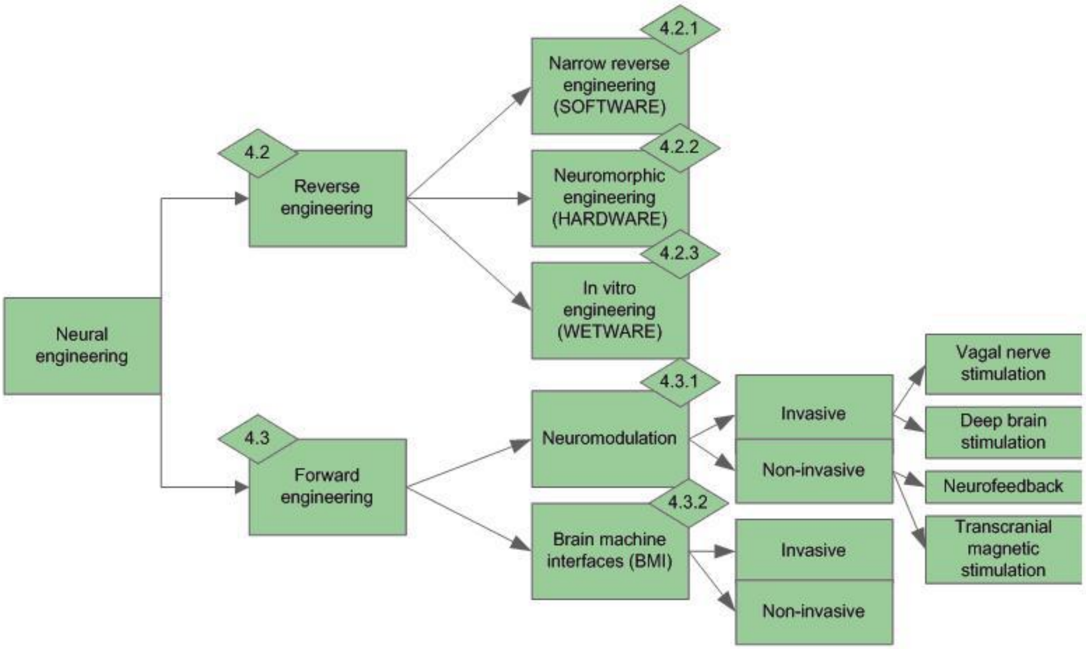


Figure 72: Different neuroengineering approaches. Source: Making perfect life: bio-engineering (in) the 21st century. Interim study. Monitoring report (IP/A/STOA/FWC-2008-96/LOT6/SC1)[76].

"European Citizens' Deliberation on Brain Science"

European Citizens' Deliberation on Brain Science was a two-year pilot project led by a European panel of 126 citizens. A partner consortium of technology assessment bodies, science museums,

---

[75] http://www.europarl.europa.eu/wps-europarl-internet/frd/vod/player?eventCode=20101110-1330-COMMITTEE-STOA&language=en&byLeftMenu=researchotherevents&category=SPECIAL&format=wmv#anchor1

[76] http://www.rathenau.nl/uploads/tx_tferathenau/STOA_report_MPL_25okt2010_FINAL_02.pdf

academic institutions and public foundations from nine European countries launched this initiative in 2004 with the support of the European Commission.

The initiative gave European citizens a unique opportunity to learn more about the impact of brain research on their daily lives and society as a whole, to discuss their questions and ideas with leading European researchers, experts and policy-makers, put them in touch with fellow citizens from other European countries and make a personal contribution to a report detailing what the people of Europe believe to be possible and desirable in the area of brain science and what they recommend policy-makers and researchers consider for future developments in this field.

Through this approach, the Meeting of Minds initiative sought to meet EU calls for greater public involvement in the debate on future research, technological decision-making and governance.

The overall objective of the Meeting of Minds initiative was to involve European citizens in assessing and publicly discussing the issue of brain science with relevant research, policy and ethics experts, various stakeholders as well as representatives of European decision-making organisations.

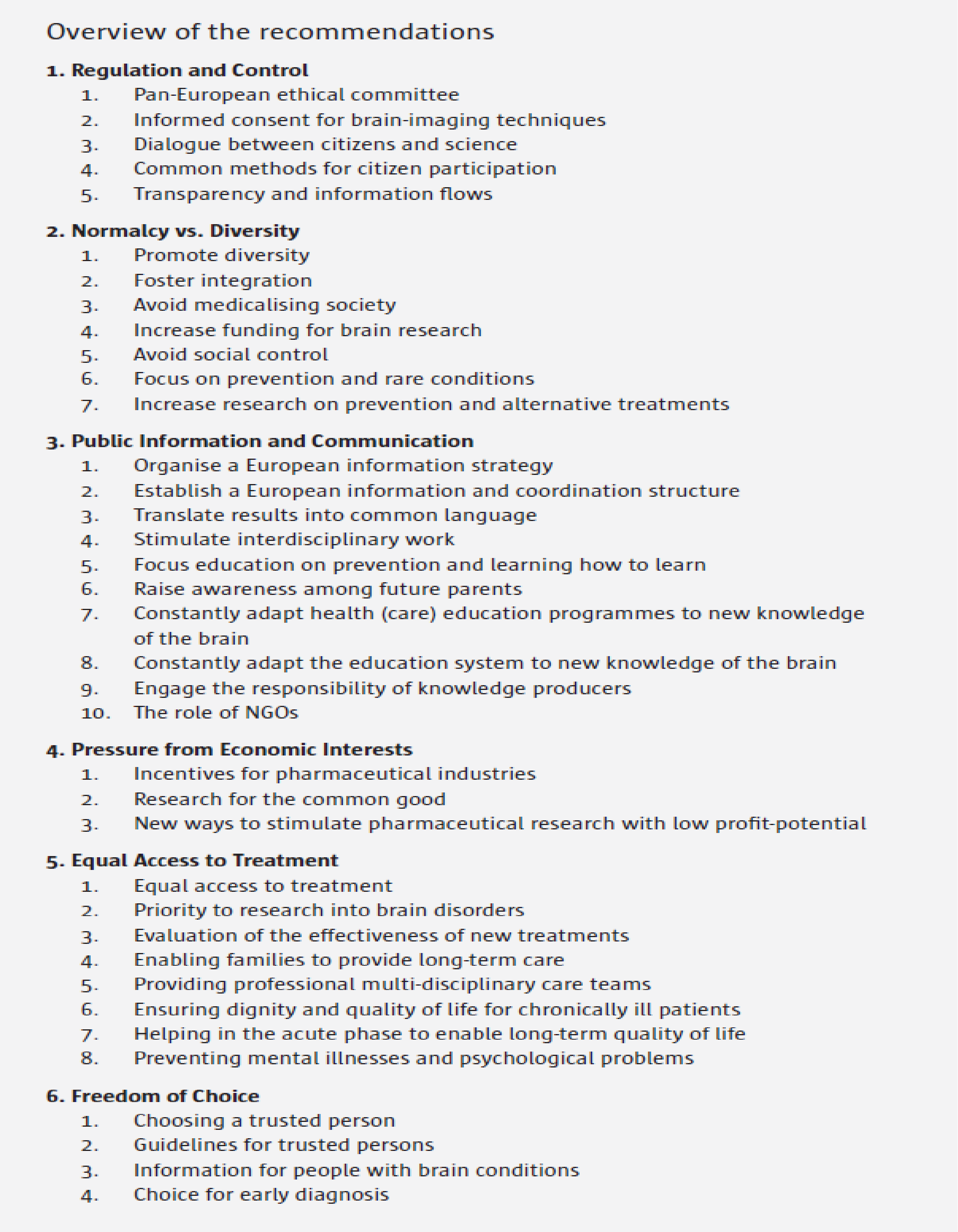
As such, the initiative aimed to give relevant inputs into European policy-making and wider public debate on brain science. It also helped set the issue of brain science on the policy and wider political agenda. Meeting of Minds helped develop new forms of social debate and decision-making processes at European cross-national level.

As a result, in January 2006, the European citizens' panel presented its European Citizens' Assessment Report containing 37 recommendations on the ethical, legal, social and economic implications of advances in brain science[77] (see Figure 73). Many recommendations could serve the field of brain-computer interfacing. Here are three examples:

- “We recommend organising advisory citizen participation at regional, national and EU levels We recommend that research universities, science organisations and pharmaceutical companies organise citizen participation at regional, national and EU level to give feedback on their research work” (p. 86, *European Citizens’ Assessment Report - Complete Results*, 2006).
- “We recommend that the EU, in parallel to increasing support for brain research, includes this research in a framework of continuous ethical evaluation” (p. 88, {Panel, 2006 #976}).
- “We recommend coaching science students from the very outset to use common language when talking about their work without oversimplifying the information. Scientists should be encouraged to translate ‘brainy’ results and scientific texts into common language, if necessary in collaboration with skilled people (e.g. science journalists)” (p. 89, *European Citizens’ Assessment Report - Complete Results*, 2006).

---

[77] http://www.meetingmindseurope.org/Download.aspx?ID=744



Overview of the recommendations

1. **Regulation and Control**
    1. Pan-European ethical committee
    2. Informed consent for brain-imaging techniques
    3. Dialogue between citizens and science
    4. Common methods for citizen participation
    5. Transparency and information flows
2. **Normalcy vs. Diversity**
    1. Promote diversity
    2. Foster integration
    3. Avoid medicalising society
    4. Increase funding for brain research
    5. Avoid social control
    6. Focus on prevention and rare conditions
    7. Increase research on prevention and alternative treatments
3. **Public Information and Communication**
    1. Organise a European information strategy
    2. Establish a European information and coordination structure
    3. Translate results into common language
    4. Stimulate interdisciplinary work
    5. Focus education on prevention and learning how to learn
    6. Raise awareness among future parents
    7. Constantly adapt health (care) education programmes to new knowledge of the brain
    8. Constantly adapt the education system to new knowledge of the brain
    9. Engage the responsibility of knowledge producers
    10. The role of NGOs
4. **Pressure from Economic Interests**
    1. Incentives for pharmaceutical industries
    2. Research for the common good
    3. New ways to stimulate pharmaceutical research with low profit-potential
5. **Equal Access to Treatment**
    1. Equal access to treatment
    2. Priority to research into brain disorders
    3. Evaluation of the effectiveness of new treatments
    4. Enabling families to provide long-term care
    5. Providing professional multi-disciplinary care teams
    6. Ensuring dignity and quality of life for chronically ill patients
    7. Helping in the acute phase to enable long-term quality of life
    8. Preventing mental illnesses and psychological problems
6. **Freedom of Choice**
    1. Choosing a trusted person
    2. Guidelines for trusted persons
    3. Information for people with brain conditions
    4. Choice for early diagnosis

Figure 73: 37 recommendations from the European Citizens' Assessment Report – Complete Results (2006).

“European Neuroscience and Society Network”

Funded by the European Science Foundation and convened by researchers at the BIOS Centre, LSE, the European Neuroscience and Society Network (ENSN) has been established to serve as a multidisciplinary forum for timely engagement with the social, political and economic implications of developments in the neurosciences, a field that has experienced unprecedented advances in the last twenty years.

A series of workshops and conferences, to be held in both Europe and North America, will bring together life scientists and social scientists, leading to the publication of annual volumes in international journals.

The ENSN is directed by a Steering Committee consisting of representatives from Austria, Denmark, Estonia, Finland, Germany, Netherlands, Norway, Portugal, Switzerland and the UK. Chair of the ENSN is Professor Nikolas Rose, Director of the BIOS Centre for the study of Bioscience, Biomedicine, Biotechnology and Society.

“Brains in Dialogue”

Brains in Dialogue (BID) was a three year project funded by the European Commission under the Seventh Framework Programme and coordinated by the Interdisciplinary Laboratory of Advances Studies at SISSA, Trieste, Italy. The main goal of the project was to build an effective dialogue among key-stakeholders in a crucial area of health advancement: Brain Science, and in particular Predictive Medicine, Brain Imaging and Brain Machine Interfaces. Advancements in these fields continuously provide new and very valuable information aimed at understanding how the most vital organ works and how neurological diseases can be treated.

The project established a fruitful dialogue and public engagement among European stakeholders in these areas by:

- Organizing a series of workshops and open forums to produce accurate and sound scientific information on the state of the art, the promises and the risks linked to those topics and discuss the associated ethical and social issues.
- Building a press office able to spread the collected information efficiently.
- Establishing and maintaining a website hosting a radio and TV-web activity to disseminate the information at different levels and facilitate the communication.

“European Group on Ethics in Science and New Technologies”

The EGE is an independent, pluralist and multidisciplinary body advising the European Commission on ethics in science and new technologies in connection with Community legislation or policies. The EGE members serve in a personal capacity and are asked to offer independent advice to the Commission. They have been appointed on the basis of their expertise and a geographical distribution that reflects the diversity in the European Union.

For every full Opinion to be issued by the Group, a roundtable is held before the Opinion is adopted, to which representatives of the Institutions of the European Union, experts of the fields, parties representing different interests, including NGOs, patients and consumer organisations and industrial stakeholders, are invited to participate in the debate.

“Brain, Self and Society in the 21st century”

BSS is a three-year project located within the BIOS Centre at LSE and funded by the Economic and Social Research Council (ESRC). Its goal is to map the social and political impacts the 'new brain sciences' are having on our understanding of selfhood, personhood, and identity and with what consequences and implications.

Discoveries and advances in the neurotechnologies, neurogenetics and psychopharmacology just to mention a few branches of the neurosciences are already impacting upon educational practices, in diagnosis and treatment of children's problems at school, on the criminal justice system and judgments of risk, and of course on mental health practice and policies.

There has been much speculation about these issues but less empirical sociological research. This project will chart the emergence and spread of this way of thinking about human beings, their minds and brains, and the new techniques of intervention that are being developed.

Summary of achievements and challenges for BNCI technologies

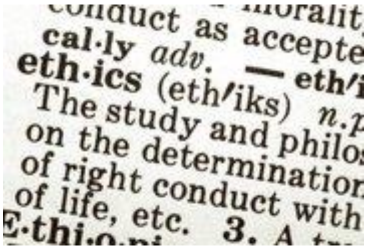
In Table 15 we summarize the main achievements of each ELSI project. Most projects have been very successful in the involvement of the general public. The projects also had a direct link to policymakers, consumer organizations and patient organizations. The challenge for the ELSI debate on BNCI technologies will be to also engage the general public, reach the policymakers, patient organizations and consumers.

Project	**Achievement**	**Gap/Challenge for BNCI specifically**
Making Life Perfect	Neuroengineering convergence	Continued pace of change identifies further ELSI issues for BNCI
European Citizens’ Deliberation on Brain Science	Involvement of the public in brain science, input to policy making	Further involvement required, particularly from the potential beneficiaries of BNCI research
European Neuroscience and Society Network	Forum for engagement with the social, political and economic implications of developments in the neurosciences	Forum for the engagement in BNCI research
Brains in Dialogue	Dialogue in health	Need a channel to combine

	advancement: Brain Science, Predictive Medicine, Brain Imaging and Brain Machine Interfaces	BNCI with traditional imaging neuroscience
European Group on Ethics in Science and New Technologies	Experts, NGOs, patients, consumer organizations, industrial stakeholders	Further public engagement with BNCI
Brain, Self and Society in the 21st century	Understanding of selfhood, personhood, and identity and with what consequences and implications	Understanding how selfhood, personhood, and identity may change through BNCI use

Table 15: Existing stakeholder engagement and ELSI challenges for BNCI.

Recommendations to Address ELSI



cal·ly *adv.* — eth′i
eth·ics (eth′iks) *n.p*
The study and philo
on the determination
of right conduct with
of life, etc. 3. A

The European Union ensures that ‘All the research activities carried out under the 7th Framework Programme shall be carried out in compliance with fundamental ethical principles”. These ethical principles, for example the Helsinki Declaration, are not specific to brain-computer interfacing and uncertainty can easily occur in regard to their interpretation. In addition, thoroughly addressing the ethical, legal and societal implications of brain-computer interfacing entails more than simply following ethically sound research procedures. It should not be sufficient for any consortium to state “we comply with the fundamental ethical principles”. Dealing with ethics also does not equal checking of the table in Section B4 ethical & gender issues, as commonly practiced. It also should entail creating a larger, more philosophical and societal framework for the research and development of the proposed BCNI technologies.

We recommend support for:

- We strongly encourage promoting cooperation between ELSI projects and BNCI projects in future rather then having them run in parallel.
- Each project should be explicitly required to address the ethical, legal, and societal issues raised by their project.
- Each project should devote at least one task to learning about relevant institutional, local, regional, national, and other guidelines and ensuring ethical compliance.
- The next BNCI research cluster should have at least one project, ideally a CSA or IP, with at least one work package devoted to relevant ELSI. This should include strong interactions with the new cluster and relevant outside stakeholders.
- Additional succinct dissemination to the public should happen for in each public deliverable. This dissemination might occur through a press release, two short paragraphs for the newsletter of a patient organization, or a 2-minute YouTube explanation about the most important results in the deliverable.
- We fully support the recommendations from the citizens’ report (European Citizins Assessment Report, 2006). We recommend that research universities, science organizations and pharmaceutical companies organize citizen participation in BNCI projects at regional, national and EU level to help steer research questions and identify ethical issues.
- Organizing summer schools to educate PhD students working in the field of neuroengineering on neuroethics.
- A future funding call to assess BNCI purely as an Assistive Technology, e.g. by adopting existing technology (hardware, software) and specifically addressing the ELSI issues.

Recommendations for BCI and BNCI Related Joint Research Agendas within FP8

This document is intended primarily to facilitate decisions regarding funding directions. It is directed primarily at European Commission officials evaluating BNCI research funding within the Eighth Framework Programme (FP8). This document may also be of value to other funding agencies (governmental, commercial, nonprofit, and other), companies and analysts, scientists, media, doctors, current or potential BCI users, students, and the public at large.

This document is part of a roadmap developed by the Future BNCI project, which consisted of four European BNCI institutions supported by a strong International Advisory Board. Our website at future-bnci.org has more information about our project and our roadmap. The roadmap contains many other elements that could facilitate funding decisions, such as literature reviews, descriptions of problems and challenges, user surveys, and a five year view on BNCI future directions.

Definition and Scope

BCIs rely on direct measures of brain activity, whereas BNCIs may also rely on other physiological signals[78]. The terms "BCI" and "BNCI" are much narrower than "neurotechnology". For example, devices that write to the brain or perform routine medical diagnostics are not BNCIs. Devices such as cochlear implants, deep brain stimulators, or neurological assessment tools are not discussed here. We do discuss some related directions, such as passive BCIs and basic science research, as do other roadmap sections[79]. We focus on issues and recommendations for the next five years.

Recommendations: Scientific and Technical Research

BCIs have four components: sensors to detect brain activity, signal processing tools to extract relevant information, a device or application that is controlled, and an application interface that governs the interaction of these components (Wolpaw et al., 2002; Pfurtscheller et al., 2008). The recommendations below highlight different issues that relate to different components, and some other material that pertains to multiple components.

Sensors

One of the biggest problems with most noninvasive BCI systems is the need for sensors that rely on electrode gel. Surveys of healthy and disabled users (e.g., Huggins et al., 2010; Kübler et al., 2010; Zickler et al., 2011) reveal that users dislike conventional gel-based systems and the associated time and inconvenience. Active electrodes can reduce preparation time and the need for skin abrasion. Electrode systems that function with water or with no liquid of any kind can reduce preparation time, cleanup time and inconvenience. Some such systems have been developed partly through our H3

---

[78] "Introduction" discusses definitions, and "Glossary" contains many terms and definitions.

[79] For example, "Devices, Applications, and Environments for Everyone" discusses passive BCIs, "Case Scenarios" includes passive BCI examples, and "Surveys of Stakeholders" discusses views on what BCIs are.

cluster in FP7, such as the water based electrodes from EGI and TMSi and dry electrodes from different groups. We introduced the term “practical electrodes” to refer to both dry and water-based electrodes.

Practical sensors generally do not provide the same signal quality as gel based systems, despite some claims. Evaluating and benchmarking different sensor systems is important, and there should be a strong effort to develop and apply objective measures to clearly measure success. For example, some groups such as a US Army research team in Aberdeen, Maryland are working on a “phantom head” that would generate the same signals on demand. This phantom head would enable repeatable, objective testing of different electrode systems and configurations in different environments.

Also, signal quality is not the only key measure. Systems should be evaluated on “real” preparation time, meaning the time from when a sensor system is sitting on a table to when the user can use an application. Delays for repositioning the headset or adjusting electrodes must be considered. Other recommended criteria include portability (including whether cables are needed), appearance, cost, cleaning time, and comfort. An objective test battery might apply a series of specific tests to provide an overall performance index, akin to common tests to assess microprocessors or complete computer systems. The benchmarking should assess robustness in different situations, such as motion artifacts or user fatigue, across different types of BNCI control signals such as SSVEP, ERD, P300, eyeblink, etc. In addition to improving the final product, manufacturers have commented that reducing assembly time is also important.

Today, the lack of objective measurement criteria impedes effective comparisons of different systems. Some manufacturers or laboratories have said that their system provides equivalent control to gel-based systems, when in fact this requires looking at only a subset of data. For example, performance may be reported for only elite subjects performing an easily detected task such as closing the eyes. Signal quality might be impaired in a practical electrode, but performance might not depending on how thresholds are set or other parameters. The need for standard measurement and reporting guidelines and tools is further addressed below.

“Non-contact sensors”, which can sense physiological signals without touching the skin, are also gaining attention. Non-contact sensors seem appealing because they could ultimately provide an even less obtrusive sensing option. However, non-contact sensors will probably not provide useful direct brain recordings within five years. There is a little more hope for other physiological signals.

Some groups have been interested in BCIs based on sensors that rely on non-EEG signals, such as fNIRS, fMRI, or MEG (Wolpaw et al., 2006; Allison et al., 2007; Coyle et al., 2007; Mason et al., 2007; Soraghan et al., 2008; Bauernfeind et al., 2008, 2011; Kanoh et al., 2009). If any BCI can really provide rehabilitation or enhancement, with significant benefits over other technologies, then sensors may be less of an obstacle. The inconvenience of systems based on abrasive gel, or even cumbersome sensors such as fMRIs, might be insignificant. Otherwise, BCIs based on fMRI and MEG are less promising funding directions. Although fNIRS is much more practical than fMRI and MEG due to the improved cost and portability, fNIRS cannot provide the temporal resolution of EEG. fNIRS may be more promising for monitoring, diagnosis, and basic science research related to BCIs (Sitaram et al., 2009; Bauernfeind et al., 2011; Halder et al., 2011).

Thus, the urgency of improved sensors varies with the application, need, and other factors. In many BCIs and related systems, improved sensors are not a major barrier to entry. Javier Minguez, from

> "There are applications, today, with wet electrodes. It's all about added value, not just convenience."

the University of Zaragoza and the startup company BitBrain, said: "There are applications, today, with wet electrodes. It's all about added value, not just convenience." Dr. Minguez reported that they tested a gel-based electrode system for cognitive enhancement with 150 clients, and only one client complained about gel. Similarly, some users have been happy with neurofeedback systems that rely on gel-based electrodes, reflecting that they perceive the overall benefits of the complete system to outweigh the costs. Gel-based electrodes, fMRIs, and other systems are routinely used in medical diagnosis. The point is that improved sensors are important, but are not essential for all situations.

Invasive and noninvasive BCIs

In many ways, the Seventh Framework of the European Commission has made excellent funding decisions that have impacted BCI research and European dominance. The funding for European noninvasive BCI research in the H3 cluster has paid off in many ways, as measured by both the number and impact factor of publications, new technologies, patients helped, improved infrastructures, etc. Furthermore, this funding occurred while the US reduced BCI research funding. As a result, the EC is emerging as a leader in noninvasive BCI research.

This position will not last without increased funding. The US, China, and other national governments have increased funding support recently, which should translate into solid outputs soon. In only one high profile example, the US Army Research Laboratory (ARL) awarded $5,000,000 per year for five years, with likely renewal for another five, to a project led by Drs. Scott Makeig and Tzyy-Ping Jung. The project is an ambitious research effort involving noninvasive BCIs and similar monitoring technologies. Within mainland China, the Gao lab in Beijing has been especially prolific, and many new labs are emerging or improving. Shanghai alone has the Jin, Zhang, and Lu laboratories, and Dr. Jung and his colleagues in nearby Taiwan have the first cell-phone based BCI. Many other countries are gaining traction in the BCI community, notably Japan, Singapore, India, Canada, and Mexico.

On the other hand, the EC has provided very little support for invasive BCI research. As a result, the US has remained more active in invasive BCI research over the last several years. This split between the EU and US is not especially new. The 2007 WTEC report on BCIs also notes that North America tends to focus on invasive BCIs, while Europe tends to focus on invasive BCIs: "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."[80]

Invasive BCIs should advance considerably in the next five years, and will also lead to solid improvements in basic science. For example, new intracranial studies are revealing new information that can not only improve invasive BCI control but also help understand the brain mechanisms underlying basic mental phenomena (Schalk et al., 2008; Miller et al., 2009, 2011; Hermes et al., 2011).

---

[80] http://www.dtic.mil/cgi-bin/GetTRDoc?AD=ADA478887

At the Utrecht BCI conference in May 2011, among other invasive BCI talks from European and American speakers, Prof. Andy Schwartz presented some impressive videos, such as the first time a monkey could control a robotic arm with all seven degrees of freedom. This talk underscored two other issues. First, in addition to funding issues, animal research is more difficult in the EU than the US, due partly to different opinions and policies. These issues go beyond the scope of this document, but indicate that any funding efforts should be especially attentive to demonstrating applications in humans. This is a second relevant issue – excluding ECoG studies with epilepsy patients, who are only implanted for a few days, there has been very little invasive BCI work with human subjects. There is some underappreciated opportunity translating the results of invasive BCI work from animals to humans.

We conclude that both invasive and non-invasive research should be funded with the Eighth Framework. Ultimately, there will be two user groups for BCIs: people who could use invasive BCIs, and people who cannot, due to reasons such as cost, appearance, or ethical factors. It would be premature to abandon either direction (Millán and Carmena, 2010)[81].

Signal processing

Signal processing has long been an area of particular attention within BCI research. There have been four major international data analysis competitions, resulting in numerous papers (e.g., Xu et al., 2004, Blankertz et al., 2004). These events reflect some early and very successful international collaborative efforts, which brought together many groups, inspired them through competition, and drew attention to signal processing challenges. Furthermore, the BCI literature has always been rich with signal processing publications.

We recommend funding projects that use signal processing to improve BCI reliability. This has been repeatedly emphasized as one of the top problems in BCI research. At the 2011 Utrecht BCI conference, Jonathan Wolpaw gave a talk and presented reliability as the top problem. Reliability means that a BCI should work any time, in any environment or situation, with any user, despite environmental noise, poor lighting, or other challenges. This is largely a signal processing challenge, which is partly a basic science issue. Signal processing would benefit from more long term basic science, ideally with many users, to explore non-stationarities and changes with fatigue, BCI training, disease progression, medications, and other factors.

One facet of reliability has gained considerable attention: reducing “BCI illiteracy” (Kübler and Müller, 2007; Allison and Neuper, 2010; Allison et al., 2010; Brunner et al., 2010, 2011; Vidaurre et al., 2010; Vidaurre and Blankertz, 2010). This is an effective research direction, and is already reducing the number of subjects who cannot use BCIs. Additional funding to reduce illiteracy should focus on users (especially patients) in realworld settings. This is also a reason to fund hybrid BCI research, since hybrid BCIs can also reduce illiteracy (Brunner et al., 2010, 2011).

As discussed below, hybrid BCIs raise new signal processing challenges. Integrating different signals from different sources needs further research. Also, there are some particularly rich opportunities for improved signal processing within invasive BCI research. Signals recorded from within the brain have

---

[81] A roadmap appendix about invasive and noninvasive BCIs contains further details.

received less attention from the BCI signal processing community, so there may be more “low hanging fruit” (Millán and Carmena, 2010).

Devices and applications

The EC has provided funding for BCIs to control new devices and applications. Examples of new device directions from our H3 cluster alone include an FES system to suppress tremor and gait rehabilitation, assisted mobility, and grasp restoration tools (through TOBI, Tremor, Better, and Mindwalker). Our cluster also produced new applications, such as the Universal Application Interface (UAI) and Hex-O-Select (HOS) system to switch between interfaces (through Brain and BrainAble) and BrainPainting (through TOBI).

The field is (and should be) in transition from simply trying to develop new applications and devices to developing them more intelligently, as well as developing support tools. More intelligent devices and applications could allow users to focus on goals instead of the intermediate steps to achieve them (Wolpaw, 2007; Cherubini et al., 2008). BCIs can benefit from software that makes them aware of four things – the user state (such as fatigued), the system state (such as whether the battery is low), the physical environment (such as nearby obstacles), and the broader environment (such as which friends are online). This idea has also been called context awareness or ambient intelligence.

However, new devices and applications are of limited value if people need a technician to switch between them. BCIs must become more flexible, and hence we recommend support to develop tools to switch between interfaces, ideally without burdening the user nor requiring additional hassle such as putting electrodes over new areas or switching to a special monitor for advanced visual stimuli. Much of the progress in our cluster, such as the Universal Application Interface (UAI), AsTeRICS toolkit, TOBI Common Implementation Platform, and Hex-O-Select (HOS) are still in development, and they have only been developed around the applications in those projects. Also, software to manage different applications should account for hybrid systems, in which a user may want to switch between inputs as well as applications. This software should also make it easy for a user to control the same application with a different signal, such as switching from EMG to EEG control if a user is fatigued (Müller-Putz et al., 2011; see the hybrid BCI discussion below).

Application interfaces and environments

There have been numerous different projects that aimed to develop different application interfaces (aka software platforms or operating systems) for BCIs. These include BCI2000, OpenVibe, the TOBI common implementation platform, BCI++, xBCI, BCILab, and BF++. These projects all have essentially the same goal: providing a universal platform that can allow people to use EEG commands to control different devices or applications. These tools have been highly effective in reducing the barrier to entry in BCI research. They are either open source or freely available to (at least) academic institutions. They have benefited from ongoing funds from many different sources, including within our cluster (Brunner et al., in press).

We strongly recommend against any funding to develop new BCI software platforms from scratch. There are already too many, and (as noted) the platforms have many overlapping features. Some groups have made the mistake of underestimating the challenges involved in developing a new realtime EEG data collection software system, such as developing modules to present stimuli and record data with millisecond precision (e.g., Bayliss, 2004).

Efforts to encourage platforms to merge have not been successful and are quite challenging. The idea sounds appealing, but ignores many fundamental technical differences between the systems, and raises the question of who will do the work of integrating different systems. Such efforts should only be funded with a priori agreement from the different developers, and a clear delineation of what will be merged. Systems should include support for non-EEG inputs, enabling a universal platform for hybrid BNCI systems. The TOBI Common Implementation Platform allows different EEG and non-EEG systems to work together, but needs further development.

> “People do not see any incentive to abandon their platforms and use another one.”

Developing software that uses existing code for novel directions is much more promising, such as new BCI applications or more natural, usable versions of existing tools. Funding should instead be directed to extend an existing platform. The decision of which platform to extend will be difficult and emotional. Many people have devoted tremendous efforts, over many years, to their platform. Prof. Gerwin Schalk, the lead developer of BCI2000, said that “People do not see any incentive to abandon their platforms and use another one. I have worked on BCI2000 for over ten years. It is the most developed and the most widely used, and I think it is the best one.” We wrote a book chapter that discusses different BCI platforms and will be available a few months after this roadmap is completed (Billinger et al., in press).

Research continues to show that well-designed, immersive environments can yield many benefits (Leeb et al., 2007, Tan and Nijholt, 2010). Such efforts should be supported, including “serious gaming” and virtual reality for control of avatars and virtual objects, especially in social environments. The new interest in rehabilitation creates a need for new environments and new ways to represent (for example) the movement of a virtual hand based on a stroke patient’s movement imagery.

Consortia devoted to improved applications should include at least one partner with a strong understanding of human-computer interaction (HCI) principles, and another who understands relevant applied psychology such as neurofeedback. Game companies could be good partners for certain consortia, as well as other types of software developers.

We also recommend funding projects that explicitly aim to develop environments unique to different disabled populations. People with visual deficits or neuropsychiatric disorders such as hemineglect may require environments that do not rely on visual stimuli. Users with dementia or memory disorders may need environments that provide frequent reminders or represent the overall system state in an informative but nonintrusive way. More generally, flashy environments may be less popular with older users. Such consortia should not only include at least one partner with access to patients and relevant experience, but (ideally) BCI partners with patient exposure as well.

Hybrid BCIs/BNCIs

A hybrid BCI combines a BCI with another communication device. This device could be another BCI, a system based on other physiological signals like an EMG switch or eye tracker, or a mainstream interface like a keyboard, mouse, or joystick. There are many ways that the additional interface could benefit different users. The additional interface could improve information transfer rate (ITR) in a few ways, such as by providing a "backup" to increase accuracy or reduce errors (Brunner et al., 2011; Fazli et al., 2012), reducing the time per selection (Jing et al., in review) or adding an additional dimension of control (Li et al., 2010; Su et al., 2011; Zander et al., 2011; Allison et al., in review). The additional signal could also help when the user is fatigued, a common problem with some patients. For example, an EEG BCI might provide a backup communication system when an EMG based system is unavailable due to fatigue, or give users longer to make a selection if they are tired (Kreilinger et al., 2011; Leeb et al., 2011). The additional signal could provide users with an "off" switch when users are fatigued or otherwise not paying attention to the BCI (Pfurtscheller et al., 2010; Panicker et al., 2011).

Hybrid BNCIs have clearly emerged as a prominent new direction in BNCI research. Until about 2008, most academic BCI and BNCI research focused on systems that used one kind of input signal, such as the P300, SSVEP, or (in the case of BNCIs) eye movement or muscle activity. Hybrid BCI research has been published by numerous different groups, reflecting many different sensor combinations, signal processing implications, applications, and application environments (e.g., Allison et al., 2007, 2010, in review; Scherer et al., 2007; Brunner et al., 2010, 2011; Lee et al., 2010; Li et al., 2010; Millán et al., 2010; Pfurtscheller et al., 2010a, 2010b; Leeb et al., 2011; Müller-Putz et al., 2011; Panicker et al., 2011; Su et al., 2011; Zander et al., 2011; Jin et al., in review).

Much of the hybrid work described above resulted from our H3 cluster. Funding for hybrid BCI research should be expanded, with emphasis on specific directions. Both hardware and software integration are important. That is, different sensors must be smoothly integrated into a complete system, and software must effectively fuse information from different sources. This fusion entails many new signal processing challenges. There should be strong support for new paradigms – new task combinations to achieve different goals, ideally augmented with ambient intelligence and shared control so the overall system can be most effective with the least input. Conversely, hybrid BNCI research opens new possibilities for providing information about the user state to an intelligent BNCI system. Another important challenge is designing effective environments, with immersive feedback that reflects contributions from different signals as needed. Many initial hybrid BCI efforts used very simple interfaces, since the goal was mainly to validate proof of concept (e.g., Brunner et al., 2011; Li et al, 2011), and so there is considerable opportunity to extend these and other initial validation efforts into more advanced systems (Su et al., 2011).

Passive BCIs and BNCIs

Some groups have used terms such as "passive BCI", "affective BCI", "emotive BCI", or "mental state monitor" to describe devices that directly measure brain activity, and often provide real-time feedback, but do not require intentional mental activity for each message of command (Cutrell & Tan 2008; Müller et al., 2008; Garcia Molina et al., 2009; Mühl et al., 2009; Nijholt et al., 2011). These types of devices have been explored in the EEG literature for decades. Passive monitoring systems might detect information that users generate without any conscious effort, which might reflect alertness, frustration, errors, deception, image detection, workload, etc. Over ten years ago, there were many articles addressing such systems (Farwell and Donchin, 1991; Gevins et al., 1995; Trejo et al., 1995; Jung et al., 1997; Schalk et al., 2000; Seymour et al., 2000). Devices that can detect these states might adapt software in realtime, warn of dangerous levels of fatigue or overload, automatically correct errors, facilitate usability testing or neuromarketing, enhance neurofeedback and some psychiatric applications, help people detect deception or dangerous objects, or simply contribute to an entertaining game or device.

This is a broad range of quite useful applications. Some products are already available, particularly for neuromarketing and various games. The availability of practical electrodes could make many of these applications more feasible, and we do expect wider adoption of passive monitoring systems based on the EEG and other signals.

On the other hand, with such a long list of potential passive BCI applications, some directions will be more successful than others. Caution is also important because passive BCIs have often been presented in an overly promising light. For example, Gevins et al. (1995) wrote that: "… rapid progress is being made in the engineering of recording systems that are small, rugged, portable and easy-to-use, and thus suitable for deployment in operational environments. … These research and engineering successes suggest that it is reasonable to expect that in the near term a basic enabling technology will be deployed that will permit routine measurement of brain function in operational environments." Portable recording systems matching this description are only beginning to hit the market, and can provide only limited information about brain function. Some basic problems will be at best only partly mitigated in the next five years. They do not work for all users, and are usually inaccurate, especially for fine gradations such as medium vs. high workload (Allison and Polich, 2008). There are many other basic mental states that cannot be reliably detected. For example, despite ample effort, EEG based systems cannot reliably detect whether a user is happy or sad in realtime. Hence, while many passive BNCI directions are promising, misleading expectations can lead to disappointment and false hope, much like other BNCI directions.

BCI technology for basic and diagnostic research

BCI research is an applied science; most BCI developers aim to build a better BCI component rather than address basic science questions. However, there are many promising opportunities to use BCIs to study the brain. BCIs could lead to improved understanding of brain changes during stroke and treatment, and BCIs based on motor imagery could induce neural plasticity to facilitate recovery (Pfurtscheller and Neuper, 2006; Birbaumer and Cohen, 2007; Millan et al., 2010; Caria et al., 2011; Grosse-Wentrup et al., 2011; Kaiser et al., 2011). Both of these contributions could lead to faster and more effective recovery, but are fairly new directions that need further study. BCI-based stroke rehabilitation is a very active area of research today.

BCI technology might also improve the flexibility, accuracy, and specificity of neurofeedback tools and other systems to diagnose and treat different disorders, such as Alzheimer's disease, autism, epilepsy, schizophrenia, and attentional or emotional disorders (Birbaumer et al., 2006; Pineda et al., 2008; Neuper and Pfurtscheller, 2010; Becerra et al., 2011; Ruiz et al., 2011). These BCIs, like BCIs to treat stroke, might often use non-EEG based methods, such as fMRI, fNIRS, or invasive methods.

Neurofeedback research has been active for decades, and was often oversold. However, some current directions are both new and promising, such as the inclusion of new signal processing approaches, practical electrodes, improved software, new imaging methods, applications to new disorders such as autism and new insights from basic science research. Although significant further research is needed for both foundational issues and practical implementation, and long term side effects also need to be studied, the potential benefits justify the high risk that some directions will not be fruitful over the next five years.

This is another area where BCI technology can influence basic science. There is inadequate understanding of the ways that feedback training (including neurofeedback) changes the brain, particularly over the long term. This research area may become especially important if neurofeedback systems become more prevalent, and may become necessary for developing effective safety recommendations, regulations, and ethical guidelines.

Both invasive and noninvasive BCI methods have improved our understanding of basic psychological phenomena. For example, EEG, fMRI, MEG, fNIRS, and invasive methods have helped clarify the regions and frequencies active during distinct motor, language, visual, and other cognitive tasks in articles that incorporated BCI methodologies and/or data (Neuper and Pfurtscheller, 2001; Eliassen et al., 2008; Miller et al., 2010, 2011; Bauernfeind et al., 2011; Halder et al., 2011; Haufe et al., 2011; Hermes et al., 2011). There is substantial promise for further progress in the next five years and beyond.

The wider distribution of physiological recording systems may create other opportunities for basic research. If thousands of people choose to wear sensors that record signals from the brain and body, the resulting data could be extremely valuable for a variety of research purposes. This prospect raises some ethical and societal issues; data should only be made available to researchers in anonymous, secure form with permission from all involved.

BCI technology can also be used to study why some people are unable to effectively use BCIs. One recent study found that people who do not show a strong aptitude for BCIs based on imagined movement also show little activation in sensorimotor areas when observing movement (Halder et al., 2011). Other studies could explore causes of failure in other types of BCIs, such as P300 or SSVEP (Allison and Neuper, 2010). Like other directions presented here, this research direction could benefit both basic and applied science. Scientists could learn more about how the brain functions during different tasks as well as develop improved methods to match people with the right BCI and help poor BCI performers.

Recommendations: Coordination and Support

Infrastructure

BCIs and BNCI research is advancing more rapidly than its infrastructure. Ethical guidelines, universal methods for calculating and reporting bit rate and other facets of BCI performance, benchmarking, common terminologies, certifications for support personnel when needed (especially with patients), file formats, web-based support and information tools, software and hardware standards[82], positive and accurate media representations, and improved BCI platforms all need to be further developed. These are major issues, and require a fair amount of effort, study, and interaction. Different project types, especially CSAs, could foster these developments through directed research, conferences and workshops, publishing articles, testing software and equipment, IP development, documentation, and public dissemination efforts.

There have been some efforts to improve BCI infrastructure. Several groups have developed helpful online resources in the last few years. Online repositories of data are available[83]. A website provides a summary of clinical trials in the US involving BCIs. No corresponding website exists in Europe, and could be helpful[84]. Articles have described and encouraged common methods for reporting bit rate (Townsend et al., 2010; Jing et al., 2011; Billinger et al., in press). The TOBI Common Implementation System is a new online BCI system developed to work with combinations of EEG and other inputs, facilitating hybrid BCI research across groups (Brunner et al., in press). Other BCI platforms have been developed or extended, and Tsinghua University developed the first online BCI platform designed to work with different groups' BCIs, and used it for an online competition at their 2010 BCI conference. A "phantom head" that produces the same electrical signals every time could facilitate standard measurement batteries for EEG and related systems. These and other efforts have been very heavily supported by government funding efforts; for example, five of the BCI platforms described in the book chapter above (Brunner et al., in press) acknowledge government support, as do most online BCI resources. Ongoing support will be needed to continue and extend such efforts.

A BCI Society could be helpful in many of these tasks. FBNCI has been active in promoting a BCI Society in recent conferences and publications (Allison, 2011; Nijboer et al., 2011). This would be a group of established researchers who could develop a self-sustaining organization. While some senior researchers have expressed interest, setting up such a Society properly requires time and collaboration. Tasks include developing initial membership, establishing bylaws, electing or approving new officers and other members, interacting with other entities, collecting dues as needed, etc.

Ethics

All BNCI research raises ethical, legal, and social issues (ELSI). Presently, consortia are required to heed local, institutional, national, EU, and other guidelines when conducting research, and there is some effort (such as a work package within TOBI) to address larger ethical issues. There should remain strong attention to ensure that projects are aware of relevant ethical guidelines and comply with them throughout the planning, implementation, and follow-up phases.

In addition, many broader ethical issues are emerging within BNCI research that are largely underappreciated. The next research cluster should include a project, ideally a CSA or IP, with at least one work package devoted to broader ethical issues. This project should be responsible for working with other projects, both in the cluster and elsewhere, and interacting with relevant external entities.

[82] www.bcistandards.org

[83] See the Data Analysis competition website below or http://www.brainsignals.de

[84] http://clinicaltrials.gov/ct2/results?term=brain-computer

Similarly, to avoid unwritten expectations, each cluster project should be explicitly required to coordinate with this project, such as through workshops or teleconferences. Relevant deliverables could include papers, conference presentations, and formal recommendations[85].

Competitions

“The BCI competitions organized by Berlin have been funded by the EU network of excellence PASCAL/PASCAL2. Such support is also desirable for the future.”

As noted above, the four BCI data analysis competitions were very successful. They not only encouraged research advancements, but they brought together groups from all over the world, gained positive publicity, fostered numerous publications, and left a legacy of cooperation and promise. The competitions were hosted by the Berlin BCI group, but featured organizers, datasets, and competitors from all over Europe and the USA as well as Singapore, Japan, China, Mexico, Israel, and other countries. Some of the former competitors produced joint articles that were inspired by the competition[86]. Hence, the events produced synergy as well as competition.

The data analysis competitions reflect effective use of European research funds. Benjamin Blankertz, who organized all four competitions and the upcoming fifth competition, said that “the BCI competitions organized by Berlin have been funded by the EU network of excellence PASCAL/PASCAL2. Such support is also desirable for the future.”

While data analysis competitions remain worthwhile, some new competitions have drawn attention to other facets of BCI research. For example, a new competition was recently announced to encourage improved Human-Computer Interfaces within BCIs[87]. In 2010, g.tec started an annual award called the BCI Award, which accepts any kind of BCI research[88]. The 2010 and 2011 BCI Award competitions each had about 60 submissions from around the world. Also in 2010, Tsinghua University hosted the first online BCI competition[89]. Participants sought to accomplish certain goals with their BCIs more quickly than other participants. Almost 20 groups participated, mostly from China, and a follow-up competition is planned.

There has even been some discussion of an X-prize in the US to foster some kind of neurotechnological breakthrough. Of course, providing a major cash award can spur innovation. However, the BCI data analysis competitions did not include a major financial prize. Participants were motivated by the thrill of competition, the public spectacle of announcing the winner at the New York BCI conferences, and the increased likelihood of publication that comes with winning an award. Therefore, it may not be necessary to provide a cash prize to encourage an effective competition.

[85] Please see “Ethics” for a more detailed discussion of ethical issues.

[86] http://www.bbci.de/competition/

[87] http://www.bcimeeting.org/HCI2011Challenge/

[88] http://www.bci-award.com/

[89] http://neuro.med.tsinghua.edu.cn/eng/index.php?option=com_content&task=view&id=164&Itemid=26

Support could be directed toward other costs, such as personnel costs involved in organizing and judging the competition, the awards ceremony, or judges' travel expenses.

Dissemination

We also encourage efforts to foster dissemination and present BCIs in a positive light. The BCI community is increasingly recognizing that the excessive hype may lead to a backlash, and there is a lot of misinformation about BCIs in the popular media (Racine et al., 2010). Our H3 cluster already has some funds for dissemination, which resulted in many tangible disseminables like journal articles, conference talks, booths at the Brussels ICT Expo in September 2010, etc. These efforts are important, but focus mainly on providing information to well-established insiders. Funding should be provided for more efforts aimed at other groups, like doctors, end users, and the public at large. For example, the BrainAble project has a friendly video aimed at non-experts[90], as has FBNCI[91]. The FBNCI project, in collaboration with many other projects, is developing a much larger video effort regarding BCIs. It is targeted to TV and other broadcast media. Bidirectional dissemination is also important, such as the "Open House" events in BackHome that provide interaction between researchers and target users.

User groups

Finally, call text and reviewer expectations should reflect the target user group(s), noting that new users are emerging. The critical challenge is not so much validating that a system could work – which is important but not adequate – but increasing usability in realworld settings. Project evaluators should distinguish between prototypes designed to show proof of concept and ready-to-deploy systems that work without project staff or other technical support present. For less disabled users, who may have access to other assistive technologies, hybridization with existing assistive technologies is especially important.

What about healthy users? While EU projects typically focus on people with some disability, the growing market for healthy users suggests that FP8 projects should address healthy users, and in some cases focus primarily on them. In addition to the financial benefits of supporting new efforts with new technology, encouraging BCIs for healthy users might ultimately make BCIs more feasible for all users due to the lower cost and wider availability of equipment and support.

---

[90] www.brainable.org

[91] Click "Videos" on the FBNCI website

Recommendations: Funding Instruments and Project Structure

Consortium compositions in joint research agendas

The EC has strongly encouraged projects that combine academic and commercial sectors, which has proven to be a solid and fruitful decision. Other sectors have been included; for example, many of our sibling projects in our H3 research cluster include institutions that represent end users. Some sibling projects have even been led by entities that are neither companies nor universities, such as Barcelona Digital or Consejo Superior de Investigaciones. We recommend further efforts to facilitate joint research agendas. These efforts should be flexible, and should be open to any sector that can contribute to project success.

In addition to encouraging a combination of sectors, the EC has also wisely encouraged projects with institutes from different disciplines. Other projects in our H3 cluster typically include institutes with experience in medicine, psychology, neuroscience, programming, mathematics, and different facets of engineering. While these disciplines are important in BCI research and should be included in future consortia, other disciplines should be encouraged. For example, some projects would benefit from expertise in human factors engineering and human-computer interaction, particularly with emphasis on special issues with disabled users. Partners with expertise in neuropsychology and neurophysiology should be included in some projects. A partner with a focus on ethical issues would also be helpful in some consortia. As with different sectors, different disciplines should be encouraged with emphasis on getting the right partners for each project rather than “covering the bases” with partners that may not be necessary. Consortia should have more flexibility to reorganize themselves based on their needs and partner contributions.

Administrative overhead

Some sources have noted FP7 projects have too much administrative overhead. This issue was addressed in publications in top-cited journals (Abbot and Weydt, 2000; Vogel, 2005; Editorial, 2010[92]). The latter article wrote that “Grantees, panel members and grant reviewers have complained about excessive bureaucracy.”

> “Grantees, panel members and grant reviewers have complained about excessive bureaucracy.”

This is also a frequent discussion point within the H3 cluster. Anonymous complaints were heard from multiple cluster projects about excessive reporting requirements. The unnecessary administrative overhead has limited the time and enthusiasm that consortia can spare, both for more substantial work within their projects and for seeking new projects from the same funding source. Groups that also participate in projects funded by other sources have generally reported that less administration is involved. While some administration and reporting is necessary, it is currently excessive. We recommend a serious reconsideration of what administrative efforts are really necessary and beneficial.

---

[92] http://www.nature.com/ncb/journal/v12/n4/full/ncb0410-307.html

Unwritten expectations

Most funded research projects include a written agreement that summarizes the goals, expected work, reporting mechanisms, payment, and other details. This document is called a “Description of Work” (or DoW) for projects in our H3 cluster and elsewhere. This document is the basis for negotiating details of the project before it begins, and then becomes the main document that project staff can use to hire personnel, allocate people to tasks, anticipate travel and costs, and otherwise manage projects. Therefore, this document is a contract that should contain a complete list of all work that is expected. This should serve as the basis for project evaluation; if the tasks described in the grant contract are completed, on time and to the satisfaction of the grant agency and its reviewers, then the project should be completed without trouble.

This has often not been the case within our cluster. The DoW seems to serve as a starting point for expected work rather than a summary of it. Projects in our cluster are routinely asked to do additional work beyond the DoW, while reduced expectations are rare and requests for added funding to accommodate added workload have literally made three Project Officers laugh. The point is not that attending expositions or other extra events is problematic, but that projects need to be informed of these expectations before the DoW is completed and respect resource limitations. If solid dates and details cannot be provided, then the DoW could include (for example) a deliverable that reflects participation in an as-yet-unscheduled event within a certain time range. Project coordinators generally have a very full schedule, and need to know what to expect as early as possible to plan accordingly.

Clustering and interaction

FP7 projects often encourage clustering, which refers to interaction within cluster projects, as well as strong interaction with other related projects. These are excellent ideas, but the implementation could be improved in many ways. First, if entities are expected to cluster as part of a project, then this expectation should be explicitly required in grant contracts. While reviewers in our cluster do look favorably on clustering, this is often an added rather than required component. Second, call text should provide some information about what clustering is appropriate and desired. In particular, funding multiple projects with nearly identical methods and objectives might conceivably lead to destructive overlap and unhealthy competition, with little incentive for collaboration or following a standard or guideline established by a competing project. Funding similar efforts is not necessarily problematic, but this overlap should be recognized to maximize possible synergy. Third, efforts to create events that are attended by cluster projects would be greatly facilitated by synchronizing them with other events such as major conferences, which reduces the cost and overhead of travel. Fourth, Coordination and Support Actions (CSAs), which are explicitly tasked with fostering clustering, should be further supported. Fifth, we recommend longer CSAs. The FBNCI CSA lasts for only two years. Sixth, we recommend additional funds and correspondingly higher expectations for cluster events. The FBNCI project coordinated a small but highly successful cluster conference in September 2010. With additional funds, new projects could organize more such events and invite more potential stakeholders. Seventh, we recommend providing Project Officers with discretionary funds that could be used to facilitate clustering in various ways.

In the H3 cluster, there has been more effort to encourage interaction within the cluster than with outside entities, such as EU funded projects from other clusters, national projects, and groups outside of the EU. We also recommend stronger support for collaborative efforts with relevant groups and projects outside of the cluster. BCI research is an increasingly multinational endeavor, and hence opportunities for constructive synergy with outside groups are continually increasing.

There were some even some examples of successful collaborative projects that included researchers in Europe and elsewhere. For example, during the early 2000s, a major bioengineering research partnership (BRP) involving the groups in Albany, Tübingen, and Graz was very successful. International collaborations should be further pursued in FP8. Projects with external collaborators should have a single review process, rather than requiring an independent review from the EU and any partner countries.

A related concern is the inadequate transfer of knowledge between BNCI research and related fields. People outside of BNCI research often have unrealistic views and expectations about what BNCIs can do. Dissemination to many different groups is necessary to help foster positive yet realistic expectations. Conversely, BNCI researchers could benefit from increased interaction with people in other relevant disciplines, such as materials science, communications, statistics, context aware computing, ambient intelligence, dynamical systems modeling, patient care, etiology and neuropsychology, human-computer interaction (HCI), ethics, and cognitive electrophysiology. This interaction could help fill any gaps in knowledge and foster new collaborations. Therefore, future projects should more strongly encourage appropriate interactions with outside entities.

Overlap

Many of the projects within our cluster pursue questions and apply methods that are more or less replicated in other cluster projects or outside efforts, often with very similar results. For example, many groups have developed practical electrodes, created new BCI software platforms, devised definitions and standards, or surveyed end users.

The first three examples generally reflect duplicated effort. Several different groups independently developed spring-mounted dry electrodes, tools to synchronize EEG data with stimuli with millisecond accuracy, or putatively canonical definitions and standards that cannot all be adopted. In FP8, such overlap should be identified during review or negotiation. In some cases, projects could be encouraged to work together much earlier by (at least) incorporating cluster teleconferences or workshops in relevant DoWs. This may be naïve in some cases, since projects and stakeholders are generally in competition, but potential overlap should at least be identified. Outreach outside of the cluster needs to be encouraged too.

On the other hand, the surveys of end users ultimately did not overlap. The surveys often asked different questions, and focused on different user groups, resulting in useful new information. Thus, constructive overlap is possible, such as when different methods result in different outcomes that supplement each other. This constructive overlap resulted from luck, not coordination.

Summary of Funding Recommendations

- Encourage new sensors that are comfortable and easy to set up, provide good signal quality, work in realworld settings, look good, and are integrated with other components.
- Pursue invasive and noninvasive BCIs, recognizing that they do not represent competing fields but different options that each may be better suited to specific users and needs.
- Signal processing research should focus not only on speed and accuracy but also reliability and flexibility, especially automated tools that do not require expert help.
- New BCI software platforms are not recommended. Rather, existing platforms should be extended, emphasizing support for different inputs, flexibility, usability, and convenience.
- Hybrid BCIs, which combine different BCI and BNCI inputs, are extremely promising and entail many new questions and opportunities.
- Passive BCIs and monitoring systems could improve human-computer interaction in many ways, although some directions (such as realtime emotion detection) remain elusive.
- BCI technology can be applied to related fields in scientific and diagnostic research. This tech transfer should be strongly encouraged and could lead to improved treatment.
- Many aspects of BCI and BNCI research are hampered by poor infrastructure. We recommend numerous directions to improve BCI infrastructure, including a BCI Society.
- Ethical, legal, and social issues (ELSI) should be explicitly addressed within each project, and the next cluster should include at least one WP to explore broader issues.
- Support BCI competitions, videos, expositions, and other dissemination efforts that present BCIs in a fair and positive light to patients, carers, the public, and other groups.
- Grant contracts should include all expected work, including clustering events, expositions, and unwritten expectations. Streamlining administration would help.
- Projects should specify target user groups and address any specific needs or expectations they have. Testing with target users in field settings should be emphasized.
- Interaction with other research groups and fields needs improvement. Opportunities to share data, results, experience, software, and people should be identified sooner.

Conclusion

BCI research is advancing rapidly. This progress is obvious through numerous objective sources, including academic publications, commercial sales, benefits to patients, and funding decisions by national entities. These objective sources, notably funding increases in many other nations, adumbrate considerable further progress over the next five years. BCI research has around the world advanced largely due to government funding and does not have the momentum to thrive without it. BCI technology is already proving useful within many other topics of interest within FP8, including health and e-inclusion for aging, disabled, and other users. A well-coordinated funding effort could yield benefits well beyond current BCI applications and users, and establish or restore European dominance in many topical and rapidly advancing fields.

Other sections of this roadmap contain further recommendations and additional details:

- Sections 3-5 contain our recommendations for specific BCI components
- Invasive and Noninvasive BCIs expands on recommendations for these two types
- Financial and Business Issues features relevant recommendations
- Ethics includes ethical recommendations
- Project Summaries each end with recommendations from other projects
- Surveys of Stakeholders has recommendations from researchers and different user groups, and the videos contains interviews asking stakeholders for recommendations on some issues

Summary

This section contains three one-page summaries of ten issues. The first seven issues are problems with BCIs themselves, whereas the last three are more general challenges for the BCI community. The three summaries discuss challenges, trends, and a five year view. The ten issues were developed through extensive discussions at different workshops, and are generally consistent with views from other groups. Supporting references and discussion can be found in Nijholt et al., 2011. The funding recommendations, presented in the preceding section, tend to follow the current trends. The section ends with two additional one-page summaries: disruptive technologies and a conclusion.

First, we present comments from very well-established BCI researchers. Andrea Kübler summed up modern issues and challenges: “BCI technology provides many new opportunities for basic scientific and clinical research. The neurofeedback bubble burst in the 1970s because of excess hype elicited unrealistic expectations, and bad reporting. However, nowadays our knowledge on the possibilities of neurofeedback is sound and we have to go along the same path for BCIs that face a similar risk. BCIs are currently at the cutting edge of being transfered to broader clinical and home application which both are big challenges in BCI research. BCIs have to be straight forward to apply and set up and important steps have been taken in the past years. BCIs gain attention also for healthy users with respect to entertainment and cognitive enhancement and more importantly for rehabilitation after stroke, which consitutes a major burden of today's societies. To fully exploit the potential of BCI with this respect to clinical application and application in healthy users, we need to maintain funding and attention for BCIs as assistive and rehabilitative technologies. Patients should not be forgotten and be offered the potential of BCI.”

Gert Pfurtscheller said: “"BCI technology could be very useful for basic scientific and medical research in many areas, including the study of motor functions, intentionality and decision making, attention and effort, and other condition. For the improvement of the performance of a motor imagery-based BCI three points needs further research: the priming of the motor system through the ideomotor effect (the influencing of an action by the idea), the enhancement of mental effort by focused attention and the impact of slow cortical excitabilitiy fluctuations in the resting brain on BCI training.”

> “It still feels like yesterday. But it isn’t.”

Perhaps the most poignant comment came from Jacques Vidal, the inventor of BCIs. Professor Vidal gave the keynote address at the FBNCI workshop in Graz in September 2011, returning to visit the BCI community after being away for literally over 30 years. After a captivating talk about the early days of BCI research, Vidal said: “It still feels like yesterday. But it isn’t.”

Challenges

Reliability: Any user should be able to use any BCI, in any realworld setting, any time, with minimal preparation, maintenance, discomfort, embarrassment, inconvenience, and cleaning. Many factors may impair performance, including fatigue, changes in the user's brain within or across days, background activity, or movements such as fasciculations, spasms, fidgeting, or swallowing.

Proficiency: There is no "universal BCI" that any person can use. This problem exists across all BCI approaches (P300, SSVEP, ERD) and may be worse with patients. There is little understanding of why people cannot use a BCI or how to best predict BCI illiteracy. Hence, many users only learn they cannot use a certain BCI after using it, possibly with training, which can be discouraging.

Bandwidth: BCIs are very low bandwidth communication systems. Users can typically only convey one of a few different signals, once every few seconds, with errors. Tools to correct errors, complete words, or let users select goals instead of individual processes are rarely used in BCIs.

Convenience: Typical gel-based BCIs require about 20 minutes of preparation. An expert is usually needed, and the hair must be washed later. Turning a BCI on and off is challenging. Some BCIs only operate in synchronous mode, meaning that the user can only communicate when the BCI is ready.

Support: Most laypeople cannot use a BCI without expert help. An expert needs help to identify, buy, setup, configure, maintain, repair and upgrade the BCI.

Training: While some BCIs require little or no training, other BCIs require weeks or even months. There may be little progress early in training, and many training paradigms are poorly designed.

Utility: Most BCIs can do only one thing, such as spell. Most BCIs are designed with little consideration of what each user wants to accomplish with the BCI. If a BCI does allow control of different devices and applications, there needs to be a central interface to switch between them.

Image: Many news stories about BCIs are inaccurate, and science fiction often presents BCIs as insidious and overly intrusive. Increasing commercial pressures could lead companies or individuals to overhype BCIs and their capabilities. Most BCI hardware is not cosmetically appealing, and interfaces are difficult to learn and use. People will not buy a system they think is ineffective, dangerous, Orwellian, unpopular, ugly, confusing, or boring.

Standards: The BNCI community needs more canon. There is little agreement on file formats, data interchange protocols, ethical procedures, media reporting guidelines, bit rate reporting guidelines, terms and definitions, and benchmarks to compare different systems.

Infrastructure: Free online resources could lower the barriers to entry and development. These include improved software platforms, better documentation and support, data and processing tools, and a searchable database of articles, IP, events, and groups.

Trends

Reliability: Improved sensors (including practical electrodes), high impedance amplifiers, and noise reduction software can help make BCIs work in more environments. Groups are focusing more on clinical validation and integrating BCI hardware and software with existing devices.

Proficiency: Two trends can improve proficiency. Improved signal processing can reduce illiteracy and reduce the training time needed to attain proficiency. Hybrid BCIs could allow users to switch to a different type of input that works better. Also, basic research efforts are helping to identify the causes of illiteracy, which could lead to further reductions and help find the right BCI for each user. Recent work has shown that more people are proficient with BCIs based on evoked potentials.

Bandwidth: Bandwidth continues to improve through improved signal processing, new stimuli and tasks, and improved interfaces and environments. Hybrid BCIs can provide an additional control signal, increased accuracy, and/or reduce selection time. Shared control, context awareness, and error correction improve effective bandwidth.

Convenience: Active electrodes require less preparation time and hassle than conventional passive electrodes, although gel is still required. Practical electrodes, including dry and water-based electrodes, could considerably reduce preparation time, and washing the hair or electrodes is no longer necessary. Wireless BCIs will become more common, particularly in commercial systems, eliminating the inconvenience of cables. Invasive BCIs could be available on demand.

Support: Many research groups are developing support tools. Commercial sales will also increase online support, at least for those products. Practical electrodes require considerably less support, since they typically do not require help to set up or clean the system.

Training: The BCI approach that requires the most extensive training (slow cortical potentials) is no longer used. Groups are reducing training time through new signal processing tools, more immersive training environments, and better incorporation of basic gaming and feedback principles. The trend toward BCIs for rehabilitation could raise many new issues and challenges with training.

Utility: many groups continue to produce BCIs that can do new things, but most BCIs still only allow people to do one thing with a single application or device. Groups within our H3 research cluster are beginning to produce tools to switch between applications.

Image: There is a greater focus on design-centered approaches, driven largely by commercial interests and increased interaction with relevant professionals. Dissemination is getting more prevalent but does not show any new trends; mechanisms such as journals, conferences, workshops, expositions, and the news media are all well established.

Standards and infrastructure: The trend generally entails proposing improvements rather than implementing them. New file formats, terms and definitions, bit rate reporting guidelines, software platforms, and other contributions have been published, but it is too early to assess adoption. A “BCI Society” or steering board consisting of highly respected established researchers could propose and develop various standards, guidelines, terms and definitions, tools, and other resources.

Five Year View

Reliability and Proficiency: “BCI illiteracy” will not be completely solved in the near future. However, matching the right BCI to each user will become easier thanks to basic research that identifies personality factors or neuroimaging data to predict which BCI approach will be best for each user. Hybrid BCIs will make it much easier to switch between different types of inputs, which will considerably improve reliability and reduce illiteracy.

Bandwidth: There will be substantial but not groundbreaking improvements in noninvasive BCIs within the next five years. Invasive BCIs show more potential for breakthroughs, although translating major improvements to new invasive BCIs for human use will take more time. Matching the right BCI to each user will also improve the mean bandwidth. Tools to increase the effective bandwidth, such as ambient intelligence, error correction and context awareness, will progress considerably.

Convenience: BCIs will become moderately more convenient. New headwear will more seamlessly integrate sensors with other head-mounted devices and clothing. However, BCIs will not at all become transparent devices within five years.

Support: Expectations are mixed. Various developments will reduce the need for expert help. In five years, there will be a lot more material available online and through other sources to support both experts and end users. Simple games are already emerging that require no expert help. On the other hand, support will remain a problem for many serious applications, especially with patients. In five years, most end users who want to use a BCI, particularly for demanding communication and control tasks, will still need help.

Training: Two trends will continue. First, BCI flexibility will improve, making it easier to choose a BCI that requires no training. Second, due to improved signal processing and experimentation, BCIs that do require training will require less training.

Utility: This is an area of considerable uncertainty. It will be easier to switch between BCI applications and adapt to new applications. However, it is too early to say whether BCIs for rehabilitation will gain traction, which would greatly increase utility.

Image: Unfortunately, many people will either not know about BCIs or have unrealistic and overly negative opinions about them. Inaccurate and negative portrayals in science fiction and news media will continue unchecked. We are concerned that the “bubble will burst”, meaning that excess hype and misrepresentation could lead to a backlash against BCI research, similar to the neurofeedback backlash that began in the late 1970s. This could hamstring public funding, sales, and research.

Standards: We anticipate modest progress in the next five years. At least, numerous technical standards will be established, including reporting guidelines. Ethical guidelines will probably also proceed well. We think the disagreement over the exact definition of a BCI will only grow, and cannot be stopped with any reasonable amount of funding. We are helping to form a BCI Society.

Infrastructure: We also anticipate modest progress. Many software tools will improve, and improved online support will advise people on the best systems and walk people through setup and troubleshooting. Infrastructure development depends heavily on outside funding.

Potential Disruptive Technologies

> "BCIs show great promise for rehabilitation of many conditions."

Rehabilitation: BCIs are typically viewed as communication and control devices. However, recent work has adapted BCI technology for rehabilitation, also called neuromodulation or functional improvement. Different groups have begun exploring BCIs to treat symptoms of stroke, autism, psychopathy, and attentional disorders. One prominent researcher in this space, Niels Birbaumer, said that "BCIs show great promise for rehabilitation of many conditions.[93]" The next five years should reveal which of these directions is most promising. If a BCI can produce a substantial, reliable functional improvement, then the potential applications and end users of BCIs could grow dramatically. Using a BCI might increase motor plasticity and thereby help the brain remap itself, and/or BCI technology could be used to analyze the changes in brain activity during stroke and recovery and thereby facilitate therapy.

The real impact of such a device depends heavily on the development of competing technologies. For example, a BCI that can help most people regain most motor function after stroke is less appealing if a new drug or simpler therapy becomes available. Practical electrodes are helpful but not vital. If a BCI could provide substantially better stroke rehabilitation than any other available method, then these new BCIs could be quite disruptive even if they require gel-based electrodes and expert help.

Practical electrodes: BNCI sensors need to become more transparent. A "plug and play" sensor system would considerably accelerate BCI adoption. The field is moving toward a device as wearable as a baseball cap, glasses, or headphones, probably integrated with these or other head-mounted objects or clothing, with the same signal quality as conventional gel-based systems. Systems like these will emerge and gain significant adoption in the next five years.

Invasive BCI sensors are also becoming more practical. Smaller and less reactive electrodes, longer testing with different electrode types (especially ECoG in humans), and other factors could substantially increase the appeal of invasive BCIs. In the next five years, improved sensors will continue to yield benefits in key factors such as safety, recording quality over years of use, and power requirements. Because of the understandably longer delays inherent in invasive BCI development with humans, many advances with invasive BCI sensors will need longer than five years to significantly impact people.

---

[93] Source: email from Niels Birbaumer dated 21 Dec 2011, reprinted with permission

Conclusion

How should BCIs change? Today, most BCIs are cumbersome standalone systems, which use a single type of input to allow one healthy user to control a boring application in a laboratory test. BCIs need to become transparent integrated tools that can use different types of signals to allow any user to accomplish different goals with an immersive, usable interface, any time in any location or situation. Burdens such as training the system or user, mounting or washing bulky caps and wires, customizing various parameters to each user, downloading new applications or updates, switching between applications, correcting errors or spelling out low-level actions to attain a goal, synchronizing messages or commands with cues presented by the system, learning to use confusing and unnatural software, and troubleshooting impede wider BCI adoption and need to be minimized.

While all of these changes will not occur within five years, some trends will advance the state of the art toward that goal. BCIs will be hybridized with other tools to convey information, including BNCIs based on other physiological signals and conventional interfaces like keyboards, mice, and joysticks. Intelligent software will incorporate information about the system, user, and ambient environment to help users focus on goals instead of processes, present information more effectively, reduce errors, and facilitate natural interaction. Well-designed interfaces, with appropriately immersive graphics and consideration of end user preferences and expectations, will also make future BNCIs more natural and intuitive. Practical electrodes will improve convenience, reliability, and appearance. Improved signal processing and basic research will make more users proficient with BCIs, help match the right BCI to each user, and help identify why some people cannot use some BCIs.

Many changes are also necessary to improve the BCI infrastructure. Despite the tremendous progress in BCI research – indeed, because of it – there is growing fragmentation amongst different entities. With so many new people getting involved in BCI research, from different disciplines and sectors, maintaining adequate and effective communication becomes increasingly challenging. The BCI and BNCI communities do not interact with each other enough, nor with related disciplines. Universal standards, terms, ethical and reporting guidelines, and other canon need to be established, which will require support for workshops, online discussion forums, background research, and coordination. Software platforms, documentation, troubleshooting guides, repositories of data and signal processing tools, and other improvements need to be supported to reduce barriers to entry and accelerate research, especially with new groups. In addition to communication within the research communities, dissemination to many outside groups needs to improve. The general public generally does not know about or understand BCIs, which could be countered through videos, online resources, demonstrations, talks, positive media representation, and other means. Funding could be critical in many of these infrastructural improvements. Otherwise, many improvements will not occur or result from the efforts of a single group, and thus be heavily biased.

Overall, it is a critical, dynamic, and exciting time for BCI research. At least modest progress is likely in many facets of BCIs, and some disruptive technologies such as practical electrodes and rehabilitation could substantially increase BCI adoption. With BCI in the limelight, any news – positive or negative, accurate or not – could have a much greater impact than just a few years ago. While some directions are hard to predict, it's safe to expect that BCIs, and the general perception of them, will change considerably over the next five years.

Appendix I: Invasive and Non-invasive BCIs

This appendix is intended to facilitate decisions regarding funding directions. It is directed primarily at European Commission officials who are considering how much funding to provide for new projects with two types of BCIs, invasive and/or non-invasive. This document may also be of value to other funding agencies (governmental, commercial, nonprofit, and other), companies and analysts, scientists, media, doctors, current or potential BCI users, students, and the public at large. There is some overlap with other roadmap sections, particularly the funding recommendations.

Relative Distribution of Invasive and Noninvasive BCIs Today

Most BCIs today are noninvasive. This is apparent through journal publications, adoption by patients, and business activities. However, invasive BCIs have been gaining attention over the last several years, and will probably represent a greater percentage of overall BCI R&D over the next five years.

Academia

Within the academic literature, most BCIs are noninvasive. Mason et al. (2007) surveyed numerous BCI articles and found that 83% of all BCIs rely on the EEG. 12% used implanted electrodes, and 5% used ECoG. The distribution has not changed dramatically since then. ECoG BCIs gained some traction over other invasive approaches, and noninvasive non-EEG BCIs, which constituted less than 1% of all BCIs in the 2007 paper, have become slightly more prevalent.

Patients

Within the patient community, figures are not available. As best we can estimate, the number of end users who regularly rely on a noninvasive BCI for communication worldwide – that is, who use it as an assistive technology – is on the scale of dozens rather than hundreds. We do not know of any patients who rely on an invasive BCI outside of laboratory experiments. Note that ECoG based BCIs are not really used as long-term assistive technologies, since ECoG papers typically use patients who have an ECoG grid temporarily implanted for other purposes such as seizure detection (e.g., Brunner et al., 2011[94]).

This reflects an improvement over only a few years ago, when only a handful of patients had access to BCIs. In September 2011, Jonathan Wolpaw and his colleague Theresa Vaughan presented work with their large-scale effort to work with patients, and researchers in Michigan and Pittsburgh are also gearing up for a large scale patient effort. While this is still preliminary, it reflects real progress in terms of getting BCIs to the people who need them most.

---

[94] This article was also published in an open access journal called “Frontiers in Neuroscience” and is available for free from the journal website. The reference is doi: 10.3389/fnins.2011.00005.

Business

Within the business community, there has been a major increase in noninvasive BCI sales recently. Most buyers are healthy users interested in a BCI for fun and entertainment instead of assistive technology or critical communication. Companies focused on invasive BCIs have not done as well, although this may change as new applications and opportunities develop in the next five to seven years[95].

Advantages and Disadvantages: Invasive vs. Noninvasive BCIs

There are many different reasons why users might prefer one BCI over another. Of course, price and performance (as measured by information throughput) are important measures (Schalk, 2008), but many other factors are often neglected (Allison, 2010). Figure 74 presents key factors in BCI adoption. We do not compare invasive vs. noninvasive BCIs on each of these factors, and in many cases, there is no meaningful or clearly proven difference.

For example, "training" is meaningless because both invasive and non-invasive BCIs may or may not require training. Users may prefer a BCI because it requires less attention, or produces less distraction or fatigue, than an alternative BCI. This topic needs to be further researched, especially with invasive BCIs. It would be premature to state that either type produces less fatigue or distraction.

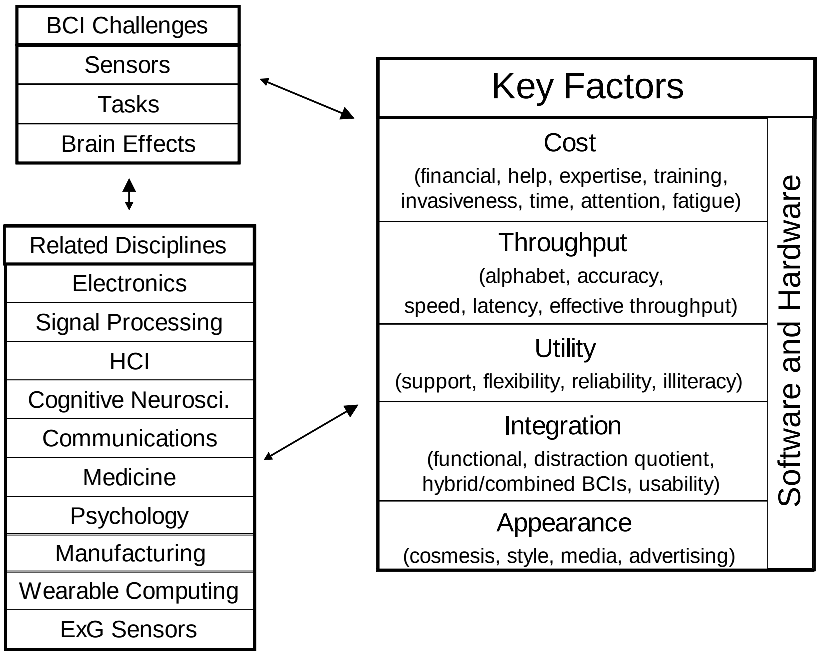


Figure 74: Key factors that may influence a buyer's decision about which BCI to purchase (from Allison, 2010). These factors interact with major challenges and related disciplines.

---

[95] Please see "Financial and Business Issues".

Cost

The cost of a BCI can be measured in many ways. The financial cost is the most obvious, and invasive BCIs are more expensive primarily due to the need for neurosurgery to implant the electrode apparatus. While some non-invasive BCIs cost less than US$100, such as the Star Wars Force Trainer based on the Neurosky chip, such systems may not have the number of electrodes and signal quality of more expensive laboratory systems. Such systems cost considerably more, such as about $6000 from TMSi or €14000 from g.tec. Invasive BCIs, including surgery and associated costs, cost in the high tens of thousands.

Another major cost is the need for help to use the system. A BCI that requires a caretaker to help with various tasks can substantially burden the user and caretaker, and may only be available on a caretaker's schedule. If expert help is needed, then costs increase considerably. Any time that is spent purchasing, assembling, maintaining, updating, and repairing a BCI system also constitutes a cost. On these axes, each approach has relative merits. Invasive BCIs require a tremendous initial cost. The neurosurgery and recovery process takes several days and requires highly trained experts. However, invasive BCIs could then be available on demand, any time, without any additional preparation. While the long-term viability of invasive BCIs is a concern, and some electrodes may be lost over time, work has shown that invasive BCIs can still provide useful functions within a few years of implantation. With a noninvasive BCI, the user must place an electrode mechanism on the head whenever he or she wants to use the BCI. With many systems, a carer must prepare the electrode cap with a procedure involving electrode gel, which typically takes at least 20 minutes. The hair and cap must be washed afterward. Active electrodes may require less time, and practical noninvasive electrodes that do not require gel could reduce the need for help considerably.

The surgery necessary to implant invasive electrodes is often misunderstood. At a plenary session of the 2010 International BCI conference, Eric Leuthardt, a neurosurgeon with a strong history in invasive BCI research, stood up and spoke about this issue. He reported that implanting an electrode system for an invasive BCI, particularly an ECoG BCI, is fairly trivial compared to most other neurosurgical procedures in terms of time, cost, and risk. Dr. Leuthardt's comments were verified by Phillip Kennedy, who has been involved in invasive BCI research even longer.

There has also been some enthusiasm for less invasive BCIs. Newer sensors and improved procedures could result in procedures that require smaller burrholes, and invasive BCI implantation could become an outpatient procedure. We expect that less invasive electrodes will be developed within five years, but will require more than five years to hit the market due to the need for testing and validation. In any case, neurosurgery is never a casual procedure. Anyone considering an invasive BCI should discuss risks and issues with their doctors.

Invasive BCIs may also entail other costs just by their nature. Some people may not wish to use a BCI because they do not feel comfortable with surgical procedures or implanted devices. Others may be poor candidates for surgery for various reasons.

Ethical issues are also a major factor. The FBNCI and TOBI projects have both been exploring views on this topic, and the picture is complex. Some people feel that neurosurgery is only considered ethical if the user needs a BCI and has no viable alternate means of communication or control. In workshops or surveys that the FBNCI project coordinated, about half of key stakeholders in BCI research said that invasive BCI surgery may be comparable to other cosmetic surgeries such as liposuction, breast implants, or nonessential eye surgery to improve vision. In a survey of likely end users, Huggins et al. (2011) found that patients' acceptance of invasive BCIs depended largely on the duration of the recovery.

Throughput

Misperceptions about the relative throughput of invasive vs. noninvasive BCIs are common, even among experts. Many persons who work with invasive technologies believe that invasive BCIs offer people dramatically greater information throughput than noninvasive options. There have also been some very high profile predictions regarding the limitations of noninvasive BCIs that have been addressed in later publications[96].

This misperception is so prevalent that it was emphasized during a keynote address at the Fifth International BCI Conference in Graz, Austria. Jonathan Wolpaw posted a slide stating that "Right now, Sept 24, 2011, there is no evidence that implanted BCIs are substantially more capable than non-invasive BCIs." However, as we note below, this is likely to change within the next five years.

> "Right now, Sept 24, 2011, there is no evidence that implanted BCIs are substantially more capable than non-invasive BCIs."

Until very recently, the fastest BCI in the published literature for human subjects has been noninvasive. The first publication that described a working online BCI, Vidal (1973), was by definition the fastest. Sutter et al. (1992) did not adequately report throughput, but was probably the fastest until (at least) Gao et al. (2003), which presented peak throughput over 60 bits per minute. The same lab developed a new record of "92.8 +/-14.1 bits/min" (Bin et al., 2008). Brunner et al. (2011) described an ECoG BCI with a peak rate of 113 bits per minute. In another paper from the Gao lab, Bin et al. (2011) described slightly better performance - as did Volosyak (2011), although this article contains critical flaws in their calculation of information transfer rate (ITR). During a visit with the Gao lab in July 2011, she and the other authors of their 2011 study presented ideas to further improve ITR, and hence further improvements may emerge soon.

Carmena et al. (2003), and associated media publicity from that group, described an invasive BCI for two dimensional cursor control (in monkey subjects) and argued that such a feat was not feasible for a non invasive BCI. The following year, Wolpaw and McFarland (2004) presented a noninvasive BCI for two dimensional cursor control in human subjects. They explicitly compared performance to an invasive BCI, and showed that their system offered at least comparable performance. Hochberg et al. (2006) presented an invasive BCI that went slightly beyond 2D control and argued that noninvasive BCIs were limited to 2D control. McFarland et al. (2008) demonstrated a noninvasive BCI that could emulate a mouse, with two dimensions plus a click. The article explicitly addressed prior articles arguing against the potential of noninvasive BCIs:

The drive to develop invasive BCI methods is based in part on the widespread conviction (Fetz 1999, Chapin 2000, Nicolelis 2001, Konig and Verschure 2002, Donoghue 2002) that only invasive BCIs will

---

[96] The reason we do not include any claims in the reverse direction – that is, noninvasive BCI researchers highlighting limitations of invasive BCIs in publications – is that we do not know of any.

be able to provide users with realtime multidimensional sequential control of a robotic arm or a neuroprosthesis. Nevertheless, in an early study (Wolpaw and McFarland 1994) we showed that a noninvasive BCI that uses scalp recorded EEG activity (i.e. sensorimotor rhythms) can provide humans with multidimensional movement control. A later study (Wolpaw and McFarland 2004) showed that a noninvasive EEG-based BCI that incorporates an adaptive algorithm and other technical improvements can give humans multidimensional movement control comparable in movement time, precision and accuracy to the control achieved by invasive BCIs in monkeys (Serruya et al 2002, Taylor et al 2002, Carmena et al 2003) or humans (Hochberg et al 2006).

McFarland et al. (2010) presented the first BCI that allowed people to control a cursor in three dimensions. Notably, it was noninvasive, although prior work with invasive BCIs showed three-dimensional control in animals (e.g., Taylor et al., 2002). McFarland et al. (2010) stated that their demonstration of non-invasive control further eroded any claims about the upper limitations of noninvasive BCIs.

We also anticipate that the next five years will see substantial improvements in bandwidth for both invasive and noninvasive systems. However, dramatic advancements are more likely within invasive BCIs, particularly beyond five years. The two main reasons are that invasive BCIs are further away from realizing the full potential of invasive electrodes, and the greater potential for progress within invasive sensors (Millán and Carmena, 2010). Within noninvasive BCIs, most research is focused on practical sensors, with disappointingly little progress in technologies that would be practical for BCIs and provide richer information (Wolpaw et al., 2006). Invasive sensors, on the other hand, could provide a richer signal in many ways.

One example of a task in which invasive BCIs may ultimately prove superior is prosthetic control. Noninvasive BCIs are useful for prosthesis control (Horki et al., 2011; Ortner et al., 2011). However, simultaneously controlling many degrees of freedom, with the ease and fluidity of natural movement, may be easier with invasive BCIs, because they might be able to provide much finer details of the numerous individual commands involved in advanced prosthetic control.

This raises another issue relating to throughput, which is the prospect of BCIs that combine invasive and noninvasive technology. While this notion was proposed in Wolpaw et al. (2002), it has not yet been implemented. One limitation of invasive sensors is that they are often placed in only one or a few brain regions. ECoG BCIs may offer a broader distribution, but implanted electrode grids that measure the entire brain are not the norm in invasive BCI research. Furthermore, adding new electrodes is nontrivial. A BCI might use invasive sensors in hand and arm motor areas to sense fine details of control, and use noninvasive sensors over other areas for other tasks.

Utility

What can a user do with a BCI? Flexibility refers to the number of different applications that a BCI can support. This could also be a deciding factor; a BCI that offers fantastic wheelchair control may be of limited value to someone who wants to surf the web. Ideally, BCIs should allow people to add new applications or switch between them with minimal or no support. On this axis, noninvasive BCIs are at somewhat of an advantage due largely to the much greater number of available systems, which often explore different applications. However, Hochberg et al. (2006) showed a flexible invasive BCI for many applications, and universal software platforms such as BCI2000 (Schalk and Mellinger, 2010) make it relatively easy to make applications available to any BCI with little or no support. Hence, we expect that any difference in BCI utility will fade over the next five years.

Two other issues are reliability and illiteracy. The former term refers to the universal, on-demand operability of a BCI. Invasive BCIs are at some advantage here because EEG sensors may be vulnerable to environmental noise in some situations, whereas invasive sensors are effectively shielded by the skull. This advantage will also fade over the next five years; there have already been some validations of EEG BCIs under very noisy conditions (Scherer et al., 2008; Allison et al., 2010; Blankertz et al., 2010). “Illiteracy” refers to the unfortunate phenomenon that a minority of users cannot use some subtypes of different BCIs (Allison and Neuper, 2010; Vidaurre and Blankertz, 2010). We are unaware of studies that explore this phenomenon in invasive BCIs, and hence cannot compare them to noninvasive BCIs. Future research should assess illiteracy further.

Integration

People who use a BCI may want to do other things and wear other devices. Both invasive and noninvasive BCIs require some device on or protruding from the head that could make it difficult or impossible to use other head mounted devices such as an eye tracker or headphones. We anticipate considerable progress integrating both types of BCIs, especially noninvasive BCIs. Recent commercial noninvasive systems, such as devices from Neurosky, already combine a BCI with headphones. There is no reason invasive BCIs could not also be integrated with hardware.

Integration with other software, and other functions, is also an important issue. So is the prospect of hybridizing a BCI with another device, allowing more than one communication and control mechanism. There is little difference between invasive and noninvasive BCIs on these axes.

Appearance

Cosmesis refers to the cosmetic appearance of the BCI. This is very much a judgment call. Some users may not want to be seen with devices protruding from their heads, others may not care or simply wear a hat, and others may more strongly dislike a full electrode cap required for some EEG BCI applications. We anticipate very strong progress in cosmesis in the next five years because of the recent emergence of strong commercial efforts, for example, from the computer gaming domain. Academic BCI researchers, and companies that supplied them, were under relatively little pressure to develop cosmetically appealing BCIs. There will also be strong progress developing diverging styles that may appeal to different people.

BCI adoption may be heavily influenced by media and public perception. A single high-profile story describing a very negative event, such as a BCI triggering a seizure or an infection resulting from improper surgery, could hamper BCI development for years – even if the story is not accurate. We also anticipate a strong risk that the “bubble will burst” within five years, producing a backlash against BCIs akin to the demise of neurofeedback in the late 1970s. Many factors exacerbate this risk, such as the excessive hype about BCIs, absence of formal guidelines and standards that explicitly prevent false claims about what a BCI is, extremely sloppy reporting in numerous articles, and negative portrayals of BCIs in science fiction.

It is difficult to say whether the risk of a media backlash is more likely for invasive versus noninvasive BCIs. On the one hand, invasive BCIs, by their very nature, may seem more intrusive or intimidating to some people. On the other hand, noninvasive BCIs are being distributed much more broadly, increasing the chance that a user will have a negative incident that is (or is reported to be) caused by a BCI.

Stakeholder Cohesion

As noted above, the published literature does include some disagreements between invasive and noninvasive BCI researchers. The topic of invasive vs. noninvasive BCIs is a popular topic for debate at conferences and other events. Competition for funding, attention, and making history will continue over the next five years.

On the other hand, these disagreements in the literature and at conferences are very much in the minority. For the most part, invasive and noninvasive BCI researchers have tremendous mutual respect and enjoy seeing progress from colleagues. The debates are generally congenial, mutually supportive, and undramatic. The Utrecht BCI 2011 conference focused on these two sensor approaches and highlighted the camaraderie among both groups. Senior researchers from both camps joined together for a very engaging conference. The Future BNCI project coordinated several satellite events featuring a broad mix of researchers, including a workshop, museum tour, dinner meeting, and numerous surveys and interviews.

Recommendations for Funding and Joint Research Agendas

Fund invasive and noninvasive BCI research

In many ways, the Seventh Framework of the European Commission has made excellent funding decisions that have strongly impacted BCI research and European dominance. The surge in funding for European noninvasive BCI research has unquestionably paid off in many ways, as measured by publications, new technologies, patients helped, improved infrastructures, etc. Furthermore, this decision occurred while the US reduced BCI research funding, leaving the EC in a dominant position.

On the other hand, the EC has provided very little support for invasive BCI research. This has been a mistake. The US has remained the definite leader in invasive BCI technology over the last several years, and this is not likely to change within five years. Indeed, the US Army very recently announced a new grant of $18.5 million to a group led by Professor Moon at San Diego State University focusing on invasive BCIs. In addition to funding issues, animal research is more difficult in the EC than the US for other reasons. For example, ethical approvals can be more difficult, and protestors can be more disruptive.

We conclude that both invasive and non-invasive research should be funded with the Eighth Framework. We addressed numerous arguments for the superiority of one approach, and explained why they are flawed or miss the point. A comparison of numerous factors in BCI adoption, which are often ignored in other analyses, shows that each approach has significant advantages in various factors. There are many reasons why people who are provided with a fair and objective overview of their choices might choose either approach. Ultimately, there will be two user groups for BCIs: people who could use invasive BCIs, and people who cannot, due to reasons such as cost, cosmesis, or ethical factors. It would be premature to abandon either direction (Millán and Carmena, 2010).

Moreover, the classic line between invasive and noninvasive BCIs is becoming increasingly blurry. Technologies such as ECoG (Leuthardt et al., 2008; P. Brunner et al., 2011) offer a less invasive option than depth electrodes (Hochberg et al., 2006; Schwartz et al., 2010). Improved invasive electrode designs, better electronics that require less size and power, and other factors could reduce the time, risk, cost, and ethical concerns of surgery (Shain, 2011).

Recognize distinct issues

Call text should reflect some directions that are more important for invasive BCIs only. Biocompatibility is a much greater concern with invasive BCIs. Invasive sensors must provide a clean signal for many years. When a noninvasive sensor stops providing a good signal, it can be easily replaced. There is a greater need to explore different brain signals that could be used with invasive BCIs as well, both for active control and for rehabilitation. This is largely a basic science issue, and there is considerable promise in using invasive BCI technology to learn more about fundamental issues in brain function (Schalk et al., 2008; Vansteensel et al., 2010; Miller et al., 2011).

In addition to scientific and technical needs, there are also somewhat different infrastructural needs. While evaluation metrics should be strongly encouraged for all BCIs, we recommend supporting a project that develops them for invasive BCIs, such as signal loss, surgery requirements, etc. Insurance and reimbursal issues differ for invasive BCIs because of the increased cost, need for surgery, and other factors. A project should focus on improving or creating standards, ethical guidelines, and certifications focused on invasive BCIs.

Expectations should also be different. Spinoff companies that focus on invasive BCIs are quite challenging. If the EU wants to encourage invasive BCI companies, then support should be provided for overcoming the necessary regulatory efforts. Invasive BCI projects should not be expected to work with as many end users, and may require more time and flexibility for ethical approvals.

Appendix II: Funding Mechanisms for BNCI Projects

Funding for BNCI projects are available through four general mechanisms: A) international funding[97], B) national funding, C) private funding (such as societies) and D) industrial funding. The following table summarizes the potential funding resources for starting or continuing innovative research in BNCI fields as well as for bringing the BNCI devices from the laboratory to the market. To this end, we encourage researchers & startup companies to identify appropriate funding mechanisms from the following suggested list[98].

Apart from conventional funding from various national and international organizations[99] listed in the table, researchers are also advised to talk with the appropriate candidates from industry. Importantly, such collaborative funds would lead to faster and more market and user inclined outcomes with practical implications. The recent connection between the CNBI laboratory of EPFL with Nissan for designing futuristic car interfaces is one such example[100]. Another fruitful example is the collaboration of the BBCI team of the Technical University in Berlin with Daimler-Chrysler, visible through a video[101] and an article[102].

This document is certainly not meant as an exhaustive list of all sources that might fund BNCI research. Instead, it is meant to provide some examples of common sources so readers have an appreciation of different options. Also, many BNCI research efforts are funded through sources that focus primarily on other directions, such as robotics or assistive technology. Furthermore, many funding possibilities through industry or private sources are not advertised, and are often developed through personal contacts.

---

[97] For international funding, there is often an eligibility criterion, which can be found on the corresponding website of the funding organization. This criterion may sometimes restrict the investigator's working location.

[98] This is a partial list made based on communication with several researchers in the field. Industrial sources are not included because they change quickly and are often not advertised.

[99] The table listed in this document is only a partial list compiled from several BCI researchers. The following web-sites list more funding opportunities across the globe

1. https://researchfunding.duke.edu
2. http://www.research-in-germany.de/
3.

[100] http://actu.epfl.ch/news/nissan-teams-up-with-epfl-for-futurist-car-interfa/

[101] http://www.youtube.com/watch?feature=player_embedded&v=kkKoMQwQ0yA

[102] http://iopscience.iop.org/1741-2552/8/5/056001

Table 16: Examples of potential national and international funding mechanisms for BNCI projects.

	Fund name	*Scope*	*Web-page*	*Research areas*	*Notes*
			A. International funding		
1	EU funding	EU	http://cordis.europa.eu/fp7/		Health http://cordis.europa.eu/fp7/health/ ICT http://cordis.europa.eu/fp7/ict/ FET http://cordis.europa.eu/fp7/ict/programme/fet_en.html Some example projects are: TOBI, FutureBNCI, BrainAble, Better, Decoder, BackHome, TREMOR, BRAIN, REHABCI, BRAINNIGHT, MINDWALKER, CODEC, OPPORTUNITY, HIVE, QFATIGUE, etc.
2	EU Research Council (ERC) grants	International	http://erc.europa.eu/	Basic & applied sciences	A variety of schemes are available. Grants are available for single persons. Some example projects listed are here: http://erc.europa.eu/projects-and-results
3	EU Flagship projects	International	http://ec.europa.eu/europe2020/tools/flagship-initiatives/index_en.htm	“Science beyond fiction” themes.	Examples: The human brain project, for brain interfaces: http://www.humanbrainproject.eu/index.html Robot companions http://www.robotcompanions.eu Future of medicine http://www.itfom.eu/
4	Centro para del Desarrollo	National (Spain) and	http://www.cdti.es/	Energy and environment Biomedical.	

	Technologico Industrial	International		Industrial Technologies.	
4	Eurostars	International	http://www.eurostars-eureka.eu/	The overview of the last cut-offs shows that any kind of innovative technology has its place in Eurostars.	The main participant of any Eurostars consortium must be an R&D SME in order to satisfy the Eurostars eligibility criteria. Usually consortia are set up with R&D SMEs, SMEs and Research Institutes and Universities.
5	Ambient Assisted Living	Available across Europe, but national funding rules applied.	http://www.aal-europe.eu/	1. ICT based solutions for prevention and management of chronic conditions of elderly people, 2. ICT based solutions for advancement of social interaction of elderly people, 3. Self- serve society	Example projects can be found in this document. http://www.aal-europe.eu/projects/AALCatalogueV3.pdf
6	Joint programming		http://ec.europa.eu/research/era/areas/programming/joint_programming_en.htm	1. Neurodegenerative Diseases/Alzheimer's 2. Agriculture, food security and climate change 3. A healthy diet for a healthy life 4. Cultural heritage & global change 5. Urban Europe 6. CliK'EU More years, better lives 7. Antimicrobial resistance 8. Water challenges 9. Healthy & productive seas and oceans	
7	Joint Technology Initiatives	Europe	http://cordis.europa.eu/fp7/jtis/ind-jti_en.html	Supports trans-national cooperation in key areas where research and technological development can contribute to European competitiveness and quality of life.	Some example are: • Innovative Medicines Initiative (IMI) • Embedded Computing Systems (ARTEMIS) • Aeronautics and Air Transport (Clean Sky)

					- Nanoelectronics Technologies 2020 (ENIAC) - Fuel Cells and Hydrogen (FCH)
B. National funding					
1	Swiss national foundation (SNF)	Switzerland	http://www.snf.ch/	A wide range of research funding schemes, which are open to scientists and academics of any nationality working in Switzerland.	Single projects, programs for young careers, infrastructure and communication. Funding available also for predefined research topics covered under (1) National Centres of Competence in Research (NCCRs) (2) National Research Programs (NRPs)
2	Austrian Science Fund (FWF)	Austrian	http://www.fwf.ac.at/	Basic sciences	
3	Deutsche Forschungsgemeinschaft (DFG)	Germany	http://www.dfg.de	Basic sciences	
4	Fonds National de la Recherche Scientifique	Belgium	http://www2.frs-fnrs.be/		
5	SmartMix	Netherlands	http://www.agentschapnl.nl/programmas-regelingen/smart-mix-supports-innovators	Economic, civil-societal and cultural innovation	Braingain (http://www.nici.ru.nl/cgi-brain/index.cgi), Other: http://www.agentschapnl.nl/programmas-regelingen/projecten-smart-mix Currently this funding is closed.
6	Generalitat de Catalunya	Catalonia (Spain)	http://www.acc10.cat/ACC1O/cat/	It is a general funding for business projects in the domain of industrial	This Catalan funding offers loans for innovation, industrialization and

				research and experimental developments carried out in Catalonia, which involve the development of improved or novel products.	internationalization.
7	Ministro de Industria, Turismo y Comercio	Spain	http://www.mityc.es/	Foreign trade, Telecommunications, Information society, Energy, Industry, Tourism.	
8	Ministro de Ciencia e Innovation	Spain	http://www.micinn.es/	Strategic industrial research, large-scale and long-range scientific and technical projects	Several grants available. One such recent example is the INNOPORNTA grant, which funded 7 large research projects in Spain.
			C. Private funding and societies		
1	Wings of life	International	http://www.wingsforlife.com/	Spinal cord injury. More specifically, (i) neuronal and glial protection, (ii) Remyelination, (iii) Regeneration/Plasticity, (iv) Neuroreconstructive therapies and (iv) Compensatory approach to SCI	It performs/promotes basic and clinical research related to spinal cord injury. Both, individual as well as project grants are available. Some example projects are listed here: http://www.wingsforlife.com/en/research/research-projects/
2	ALS Hope Foundation	International	http://alshopefoundation.org/	Basic and clinical research related to ALS.	The Foundation has encouraged collaborations across Institutions by supporting multi-center clinical trials and research planning meetings that involve a consortium of investigators.

Appendix III: Follow-up Plan

The Future BNCI project officially ended on 31 December 2011. Hence, no more project funds are available, and since the project completed all of its goals, there will be no remaining deliverables. However, the FBNCI project team has decided to continue or extend some elements of the project. This section summarizes our status as of the end of the project and our follow up plan.

Roadmap

Status: This roadmap was completed on time.

Plan: All partners will still be responsible for publicizing the roadmap and responding to comments when possible. For example, in addition to the TOBI workshop below, Mr. Dunne will announce the roadmap through the HCC website and a summer school. The roadmap may be updated later. TOBI will take over primary responsibility for any redevelopment of the roadmap. There is one exception – Uni Twente will take over the Ethics section.

Ethics section

Status: The Ethics section of the roadmap was also completed on time.

Plan: U Twente will take over primary responsibility for developing any updates to the Ethics Section. Dr. Femke Nijboer will lead a **new Veni project devoted to Ethics**, and thus she will update and extend the material in the Ethics section through this project.

Workshop

Status: FBNCI completed all required workshops, but is interested in further dissemination.

Plan: At least EPFL and TUG will be at the TOBI 2012 workshop in Würzburg, where we will give a talk about the roadmap and follow-up issues such as the BCI Society. EPFL will host another workshop in 2013 that will also follow up on some FBNCI issues.

Website

Status: The website at future-bnci.org is currently physically hosted at U Twente, and the Project Coordinator has been primarily responsible for updating the content. This has included updating news items on the front page, uploading new roadmap sections as developed, and posting on the discussion forum.

Plan: U Twente will continue to host the website, but TOBI will be primarily responsible for updating the content. Dr. Nijboer will update the ethics material. Some material will be moved to other sites. **We also encourage roadmap comments in the Discussion Forum on our website.**

Book

Status: The FBNCI project was responsible for developing a book through Springer Publishing. The chapters were sent to the publisher ahead of schedule. **The book will be published in early 2012**.

Plan: Prof. Nijholt at U Twente and the Project Coordinator will remain primarily responsible for any remaining work on the book.

Videos

Status: FBNCI developed many videos, such as interviews of stakeholders, recordings of lectures, and a representation video of the Utrecht 2011 conference.

Plan: We hope to start a **60 minute documentary** about BCI research around the world. The new videos could help further some aims of FBNCI, such as presenting research to the general public. We have already secured agreements from several top groups to host our film team and pay for some travel and production costs.

BCI Society

Status: FBNCI has been pushing hard for this Society. Several people are interested and have discussed it online and in special workshops at two BCI conferences in 2011.

Plan: We will continue pushing for a BCI Society through various means.

New EU or other projects

Status: FBNCI just ended.

Plan: This roadmap recommends additional funding for CSAs, but FP8 will be too late for any continuity with FBNCI. We **may be open** to earlier options to continue some elements of FBNCI. Overall, however, coordination and support actions such as these should involve different groups of people at different times, and many colleagues in the BNCI community would be highly qualified. We hope the next project team enjoys their project as much as we have!

Contributors

This roadmap was only possible through ongoing intensive collaboration with a myriad of different stakeholders within the BNCI research community. Many people contributed in a wide variety of ways, such as writing text, proofreading, discussing case scenarios and major issues at workshops, providing links or references, introducing new contacts, sharing helpful research findings, and/or participating in interviews. We are very grateful to the contributors described below.

Many contributors changed institutions during the project. The affiliation below lists each contributor's primary institutional affiliation during their contribution. In addition, each contributor was only allowed to list a primary affiliation. Many contributors have one or more additional affiliations that are not presented below.

In addition, we wish to thank the Seventh Framework of the European Commission for funding our project. We also thank the many EC officials who contributed to our project supervision, including our Project Officer, Marion Le-Louarn, and other staff including Ilias Iakovidis, Francois Junique, Jan Komarek, Orsolya Molnar, Luis Santos, Mika Somppi, Paul Timmers, and Benedicte Vasseur. We are also grateful to our project reviewers, Anastasios Bezerianos, Marco Congedo, and Patric Salomon for their many helpful comments and, in the case of Dr. Congedo, participation in one of our workshops.

Of course, with any document of this magnitude, some differences of opinion are inevitable. We were generally surprised by the overall accord we encountered, but some points were controversial. Please note that this roadmap does not necessarily reflect the views of any particular entity, including any of its authors, contributors, funding sources, or institutions. However, any errors in this contributor list are the sole responsibility of the Project Coordinator, who apologizes in advance for any mistakes.

The research leading to these results has received funding from the European Union Seventh Framework Programme FP7/2007-2013 under grant agreement 248320.

Table 17: FBNCI team members.

Last Name	First Name	Primary Institution	Country
Allison	Brendan	Graz University of Technology	Austria
Bradacs	Eva	Graz University of Technology	Austria
Cester	Iván	Starlab	Spain
Deuse	Lisa	Karl Franzens University	Austria
Dunne	Stephen	Starlab	Spain
Garipelli	Gangadhar	Ecole Polytechnique Fédérale de Lausanne	Switzerland
Grissmann	Sebastian	Graz University of Technology	Austria
Haring	Raphaela	Graz University of Technology	Austria
Hondorp	Hendri	University of Twente	Netherlands
Leeb	Robert	Ecole Polytechnique Fédérale de Lausanne	Switzerland
Millán	José	Ecole Polytechnique Fédérale de Lausanne	Switzerland
Müller-Putz	Gernot	Graz University of Technology	Austria
Neuper	Christa	University of Graz	Austria
Neuper	Markus	University of Graz	Austria
Nijboer	Femke	University of Twente	Netherlands
Nijholt	Anton	University of Twente	Netherlands
Packwood	Lynn	University of Twente	Netherlands
Poel	Mannes	University of Twente	Netherlands
Riera	Alejandro	Starlab Barcelona S.L.	Spain
Schellnast	Harald	Graz University of Technology	Austria
Soria-Frisch	Aureli	Starlab Barcelona S.L.	Spain
Tschernegg	Melanie	Karl Franzens University	Austria
Valjamae	Aleksander	Graz University of Technology	Austria
Viñas	David	Starlab Barcelona S.L.	Spain
Whitmer	Diane	Starlab Barcelona S.L.	Spain

Table 18: FBNCI Advisory Board.

Last Name	First Name	Primary Institution	Country
Aersten	Ad	Albert-Ludwigs University	Germany
Blankertz	Benjamin	Berlin Institute of Technology	Germany
Cincotti	Febo	Santa Lucia Foundation	Italy
Edlinger	Günter	Guger Technologies OEG	Austria
Garcia	Gary	Philips	Netherlands
Hochberg	Leigh	Brown University	U.S.A.
Hoogerwerf	Evert-Jan	AIAS Bologna Onlus	Italy
Kübler	Andrea	University Würzburg	Germany
Pons	Jose	CSIC	Spain
Sullivan	Thomas	Neurosky	U.S.A.
Wolpaw	Jonathan	Wadsworth Center	U.S.A.

Table 19: Additional contributors.

Last Name	First Name	Primary Institution	Country
Aarnoutse	Erik	UMC Utrecht	Netherlands
Acedo	Javier	Starlab Barcelona S.L.	Spain
Albajes	Anton	Starlab Barcelona S.L.	Spain
Arroyo	Jorge	University of Barcelona	Spain
Bauernfeind	Günther	Graz University of Technology	Austria
Biasiucci	Andrea	Ecole Polytechnique Fédérale de Lausanne	Switzerland
Birbaumer	Niels	Eberhard Karls University of Tübingen	Germany
Blain	Stefanie	University of Michigan	U.S.A.
Bonnet	Laurent	INRIA	France
Brook	Tansy	Neurosky	U.S.A.
Brunner	Clemens	Graz University of Technology	Austria
Carmichael	Clare	Abilitynet	U.K.
Cichocki	Andrzej	RIKEN Institute	Japan
Clauzel	Guillaume	Graz University of Technology	Austria
Collinger	Jennifer	University of Pittsburgh	U.S.A.
Daly	Ian	Graz University of Technology	Austria
de la Vega	Julita	Guger Technologies OEG	Austria
Desain	Peter	Radboud University Nijmegen	Netherlands
Donoghue	John	Brown University	U.S.A.
Erp, van	Jan	TNO	Netherlands
Espinosa	Arnau	Universitat Pompeu Fabra	Spain
Farina	Dario	University of Göttingen	Germany
Ferrante	Simona	Politecnico di Milano	Italy
Friedrich	Lisa	Karl Franzens University	Austria
Garten	Ariel	InteraXon	Canada
Gao	Shangkai	Tsinghua University	China
Gonzalez	Mar	University of Barcelona	Spain
Grozea	Cristian	Frauhofer Institute FIRST	Germany
Gruebler	Gerd	Johannes Gutenberg University	Germany
Guan	Cuntai	Institute for Infocomm Research (I2R)	Singapore
Guerrero	José María	Infoseg	Spain
Guger	Christoph	Guger Technologies OEG	Austria
Gupta	Disha	Wadsworth Center	U.S.A.
Gürkök	Hayrettin	University of Twente	Netherlands
Heiden, van der	Linda	University of Tübingen	Germany
Hill	Jeremy	Wadsworth Center	U.S.A.
Hoogendorn	Leo	TMS International BV	Netherlands
Huggins	Jane	University of Michigan	U.S.A.
Ibañez	David	Starlab Barcelona S.L.	Spain
Ilkovitz	Michel	Space Applications Services NV	Belgium
Jin	Jing	East China University of Science and Tech.	China
Jung	Tzyy-Ping	University of California, San Diego	U.S.A.
Kaiser	Vera	Graz University of Technology	Austria
Kennedy	Philip	Neural Signals Inc.	U.S.A.
Kerick	Scott	US Army Research Laboratory	U.S.A.

Kleih	Sonja	University of Würzburg	Germany
Krusienski	Dean	Pennsylvania State University	U.S.A.
Laar, van de	Bram	University of Twente	Netherlands
Lance	Brent	US Army Research Laboratory	U.S.A.
Lecuyer	Anatole	INRIA	France
Leotta	Francesco	Fondazione Santa Lucia	Italy
López	María	BitBrain technologies	Spain
Lotte	Fabien	Institute for Infocomm Research (I2R)	Singapore
Makeig	Scott	University of California, San Diego	U.S.A.
Malavasi	Massimiliano	Emilia Romagna’s Regional Center for AT	Italy
Malechka	Tatsiana	University of Bremen	Germany
Martini	Matteo	University of Barcelona	Spain
Maselli	Antonella	University of Barcelona	Spain
Mattia	Donatella	Santa Lucia Foundation	Italy
Mattout	Jeremie	INSERM Lyon	France
McCullagh	Paul	University of Ulster	U.K.
McDowell	Kaleb	US Army Research Laboratory	U.S.A.
McFarland	Dennis	Wadsworth Center	U.S.A.
Mealla	Sebastian	MTG-UPF	Spain
Miller	Kai	University of Washington	U.S.A.
Minguez	Javier	University of Zaragoza	Spain
Miralles	Felip	Bdigital	Spain
Mühl	Christian	University of Twente	Netherlands
Mullen	Tim	University of California, San Diego	U.S.A.
Navarro	Agustin	Bdigital	Spain
Onishi	Akinari	RIKEN Institute	Japan
Orero	Pilar	CAIAC-UAB	Spain
Ortner	Rupert	Guger Technologies OEG	Austria
Pape	Anna-Antonia	Knowledge Media Research Institute	Germany
Parker	Stefan	Kompetenznetzwerk KI-I	Austria
Pedrocchi	Alessandra	Politecnico di Milano	Italy
Perez	Dani	IDIBAPS	Spain
Perrin	Margaux	INSERM Lyon	France
Peuscher	Jan	TMS International BV	Netherlands
Pfurtscheller	Gert	Graz University of Technology (Emeritus)	Austria
Plass-Oude Bos	Danny	University of Twente	Netherlands
Pons	Didac	CAIAC-UAB	Spain
Puglesi	Cecilia	Independent graphic artist	Spain
Pun	Thierry	University of Geneva	Switzerland
Putz	Veronika	Guger Technologies OEG	Austria
Ramsey	Nick	University of Utrecht	Netherlands
Renard	Yann	OpenVibe	France
Rickert	Jörn	Albert-Ludwigs-University Freiburg	Germany
Riera	Alejandro	Starlab Barcelona S.L.	Spain
Rocon	Eduardo	Consejo Superior de Investigaciones	Spain
Ruf	Carolin	University of Tübingen	Germany
Ruffini	Giulio	Starlab Barcelona S.L.	Spain

Rupp	Rüdiger	Orthopaedic Hospital of Heidelberg University	Germany
Sanchez	Gaetan	INSERM Lyon	France
Sanmarti	Anna	Independent filmmaker	Spain
Sarnacki	William	Wadsworth Center	U.S.A.
Schalk	Gerwin	Wadsworth Center	U.S.A.
Scherer	Reinhold	Graz University of Technology	Austria
Schwartz	Christina	Albert-Ludwigs-University Freiburg	Germany
Sefer	Ana Branka	University of Zagreb	Croatia
Sellers	Eric	East Tennessee State University	U.S.A.
Sergeeva	Julia	MindGames	U.S.A.
Torrellas	Sergi	Bdigital	Spain
Valbuena	Diana	University of Bremen	Germany
Vallis	Georgios	Starlab Barcelona S.L.	Spain
Vaughan	Theresa	Wadsworth Center	U.S.A.
Vidal	Jacques	University of California, Los Angeles (Emeritus)	U.S.A.
Vidaurre	Carmen	Berlin Institute of Technology	Germany
Vlek	Rutger	University of Nijmegen	Netherlands
Wagner	Isabella	Karl Franzens University	Austria
Wang	Xingyu	East China University of Science and Tech.	China
Ware	Melanie	University of Ulster	U.K.
Weiss	Christoph	Fachhochschule Technikum Wien	Austria
Wolpaw	Elizabeth	Wadsworth Center	U.S.A.
Wriessneggar	Selina	Graz University of Technology	Austria
Zander	Thorsten	Max Planck Institute for Intelligent Systems	Germany
Zschusschen	Corona	University of Twente	Netherlands

Glossary

Amyotrophic lateral sclerosis (ALS): This is a progressive nervous system disorder. People lose the ability to control their muscles, often until they lose all voluntary muscle control.

Asynchronous: In this mode of BCI operation, users do not need to pace themselves according to external cues. For example, some BCIs allow users to move an avatar left, right, or forward by imagining left hand, right hand, or foot movement at any time.

Autoregressive (AR) modeling: This is a signal processing technique often used in BCI research.

Bit rate: This measures the amount of information sent within a certain time period. It is also called information transfer rate (ITR).

Brain-Computer Interface: A system that allows users to communicate via direct measures of brain activity.

Brain-Machine Interface: An alternate term for BCI. Some authors use this term to refer only to invasive BCIs.

Completely locked-in state (CLIS): A state in which a person has lost all ability to control any muscles. Even small eye movements or other facial movements are impossible.

Deep brain stimulator (DBS): An invasive device to directly stimulate brain activity. While these devices are not BCIs, they are an example of successful neurotechnology, and could be combined with BCIs in future technologies.

Dependent: A type of BCI in which some muscle activity is necessary, even though the BCI reads direct measures of brain activity. For example, the user might need to control gaze to produce the brain activity signals needed for control.

Electrocardiogram (ECG): A recording of the heart’s electrical activity.

Electrocorticogram (ECoG): A recording of the brain's electrical activity from an invasive sensor placed under the skull on the surface of the brain.

Electroencephalogram (EEG): A record of the brain's electrical activity from a noninvasive sensor (electrode) placed on the surface of the head.

Electromyogram (EMG): A recording of electrical activity from the muscles.

Electrooculogram (EOG): A recording of the eyes' electrical activity.

Event-related desynchronization and synchronization (ERD/S): These terms refer to changes in electrical power in certain frequencies that occur in the brain during various cognitive tasks. ERD/S changes are associated with motor imagery.

Functional electrical stimulation (FES): A method of directly stimulating muscles. This technique can help people grasp objects or perform other tasks if the connection between the brain and the muscles is damaged.

Functional Magnetic Resonance Imaging (fMRI): A technique to use MRI to study the brain's function. This differs from MRIs used to analyze structure, such as an MRI to identify a tumor or injury.

Functional Near Infrared Spectroscopy (fNIRS): A technique to measure brain activity using NIRS. This technique measures blood flow instead of electrical or magnetic activity.

Human-computer interface (HCI): A tool to let people interact with computers.

Hybrid: A communication system in which users can communicate using a BCI and another means of conveying information, such as another BCI, EMG switch, or keyboard.

Implanted: See invasive.

Independent: A BCI that does not require any movement from the user in any way.

Independent component analysis (ICA): This is a signal processing technique often used in BCI research. It is conceptually similar to principal component analysis (PCA), but component vectors do not need to be orthogonal to each other.

Invasive: A type of BCI or sensor that requires surgery to implant the recording device.

Information transfer rate (ITR): See bit rate.

Interleaved: See sequential.

Linear discriminant analysis (LDA): This is a signal processing technique often used in BCI research. This method can distinguish different classes of data, such as EEG activity corresponding to "move left" or "move right".

Locked-in state (LIS): A state in which people have little or no control of voluntary movements and hence are "locked in" to their bodies

Magnetoencephalogram (MEG): This is a technique to monitor the brain's magnetic activity.

Motor imagery (MI): The imagination of movement, typically without actually performing the same movement. Motor imagery is commonly used to communicate through BCIs.

Magnetic resonance imaging (MRI): This is a tool to measure the brain that can be very powerful. However, it requires a very expensive and bulky magnetic field.

Near infrared spectroscopy (NIRS): This is a tool to study the brain by reflecting light off the surface of the brain. The light travels through the skull, so this is a noninvasive technique.

Neuromodulation: Here, this refers to changing brain activity in potentially helpful ways, such as recovery from stroke.

No-control state: A period during which a person does not wish to communicate with or through a communication system. During these times, the system needs to remain dormant but available.

P300: A type of brainwave that develops about 300 milliseconds after some events. The P300 is often used in BCIs. While the P300 can be elicited by other modalities, most BCIs that rely on P300s use visual stimuli, such as flashes of rows of letters.

Sequential: This is a type of hybrid BCI in which users do not simultaneously perform two or more tasks to elicit the activity needed for control.

Simultaneous: This is a type of hybrid BCI in which users simultaneously perform two or more tasks to elicit the activity needed for control.

Slow cortical potential (SCP): A shift in EEG activity that was commonly used in BCIs. It is no longer common because it typically requires extensive training before users gain control.

Synchronous: In BCI research, this means that a user can only communicate at specific times specified by the system. For example, in some ERD BCIs, the user must either relax or imagine movements during specific trials lasting several seconds each.

Steady-state visual-evoked potential (SSVEP): A type of brainwave that is elicited by rapidly oscillating visual stimuli, such as a strobelight, LED, or monitor display. SSVEPs are often used in BCIs.

Virtual reality (VR): An immersive, typically graphically rich environment designed to make people feel they are in another setting.

Visual evoked potential (VEP): A brainwave that is produced after observing a visual event, such as a photo appearing or light flashing. Different VEPs are often used in BCIs.

References

Abbott, A., & Weydt, P. (2000). Frustration grows over EU grant application procedures. *Nature*, *404*(6779), 695. doi:10.1038/35008229.

Allison, B. Z. (2010). Toward Ubiquitous BCIs. In B. Graimann, B. Z. Allison, & G. Pfurtscheller (Eds.), *Brain-Computer Interfaces*. Springer Berlin Heidelberg. doi:10.1007/978-3-642-02091-9_19.

Allison, B. Z. (2011). Trends in BCI research: progress today, backlash tomorrow? XRDS: Crossroads, The ACM Magazine for Students, 18(1), 18-22. doi:10.1145 /2000775.2000784.

Allison, B. Z., & Neuper, C. (2010). Could Anyone Use a BCI? *Brain-computer interfaces* (pp. 35–54). Springer.

Allison, B. Z., & Pineda, J. A. (2003). ERPs evoked by different matrix sizes: implications for a brain computer interface (BCI) system. *IEEE transactions on neural systems and rehabilitation engineering*, *11*(2), 110-113. doi:10.1109/TNSRE.2003.814448.

Allison, B. Z., Brunner, C., Altstätter, C., Wagner, I. C., Grissmann, S. & Neuper, C. (in review). A hybrid ERD / SSVEP BCI for continuous simultaneous two dimensional cursor control. *Journal of Neuroscience Methods*.

Allison, B. Z., Brunner, C., Kaiser, V., Müller-Putz, G. R., Neuper, C., & Pfurtscheller, G. (2010). Toward a hybrid brain-computer interface based on imagined movement and visual attention. *Journal of neural engineering*, *7*(2), 26007. doi:10.1088/1741-2560/7/2/026007.

Allison, B. Z., Leeb, R., Brunner, C., Müller-Putz, G. R., Bauernfeind, G., Kelly, J. W., & Neuper, C. (2012). Toward smarter BCIs: extending BCIs through hybridization and intelligent control. *Journal of neural engineering*, *9*(1), 013001. doi:10.1088/1741-2560/9/1/013001.

Allison, B. Z., Neuper, C., Tan, D. S., & Nijholt, A. (2010). Could anyone use a BCI? *Brain-Computer Interfaces*. (D. S. Tan & A. Nijholt, Eds.). London: Springer London. doi:10.1007/978-1-84996-272-8.

Allison, B. Z., Wolpaw, E. W., & Wolpaw, J. R. (2007). Brain-computer interface systems: progress and prospects. *Expert Review of Medical Devices*, *4*(4), 1-12. Expert Reviews. doi10.1586/17434440.4.4.463

Andersen, P. M., Borasio, G. D., Dengler, R., Hardiman, O., Kollewe, K., Leigh, P. N., Pradat, P.-F., et al. (2005). EFNS task force on management of amyotrophic lateral sclerosis: guidelines for diagnosing and clinical care of patients and relatives. *European journal of neurology*, *12*(12), 921-938. doi:10.1111/j.1468-1331.2005.01351.x.

Andersen, R. A., Hwang, E. J., & Mulliken, G. H. (2010). Cognitive neural prosthetics. *Annual review of psychology*, *61*, 169-190. doi:10.1146/annurev.psych.093008.100503.

Andersen, R. A., Musallam, S., & Pesaran, B. (2004). Selecting the signals for a brain-machine interface. *Current opinion in neurobiology*, *14*(6), 720-726. doi:10.1016/j.conb.2004.10.005

Andrianopoulos, A., Ardizzone, C., Argyropoulos, N., Athanassoglou, S., Barache, M., Barbançon, A., Bauwens, J., et al. (2006). *European Citizens ' Meeting of Minds European Citizens ' Panel* (p. 105).

Ang, K. K., Guan, C., Chua, K. S., Ang, B. T., Kuah, C., Wang, C., Phua, K. S., et al. (2011). A large clinical study on the ability of stroke patients to use an EEG-based motor imagery brain-computer interface. *Clinical EEG and Neuroscience*, 253–258.

Arthur, W. B. (2011). *The Nature of Technology: What It Is and How It Evolves* (Reprint., p. 256). Free Press.

Barth, D. S., Sutherling, W., & Beatty, J. (1986). Intracellular currents of interictal penicillin spikes: evidence from neuromagnetic mapping. *Brain research*, *368*(1), 36-48.

Bauernfeind G, Scherer R, Pfurtscheller G, Neuper C. (2011). Single-trial classification of antagonistic oxyhemoglobin responses during mental arithmetic. *Med Biol Eng Comput* 49(9):979-84.

Bayliss, J. D. (2003). Use of the evoked potential P3 component for control in a virtual apartment. *IEEE transactions on neural systems and rehabilitation engineering*, *11*(2), 113-116. doi:10.1109/TNSRE.2003.814438

Bayliss, J. D., & Ballard, D. H. (2000). Single Trial P300 Recognition in a Virtual Environment. *Neurocomputing, 32-33,* 637-642.

Bayliss, J. D., Inverso, S. A., & Tentler, A. (2004). Changing the P300 Brain Computer Interface. *CyberPsychology & Behavior*, *7*(6), 694-704.

Becerra, J., Fernández, T., Roca-Stappung, M., Díaz-Comas, L., Galán, L., Bosch, J., Espino, M., et al. (2011). Neurofeedback in Healthy Elderly Human Subjects with Electroencephalographic Risk for Cognitive Disorder. *Journal of Alzheimer's disease: JAD*. doi:10.3233/JAD-2011-111055

Benaron, D. A., Hintz, S. R., Villringer, A., Boas, D., Kleinschmidt, A., Frahm, J., Hirth, C., et al. (2000). Noninvasive functional imaging of human brain using light. *Journal of cerebral blood flow and metabolism*, *20*(3), 469-477. doi:10.1097/00004647-200003000-00005

Bensch, M., Karim, A. A., Mellinger, J., Hinterberger, T., Tangermann, M., Bogdan, M., Rosenstiel, W., et al. (2007). Nessi: an EEG-controlled web browser for severely paralyzed patients. *Computational intelligence and neuroscience*. doi:10.1155/2007/71863

Biasiucci, A., Chavarriaga, R., Hamner, B., Leeb, R., Pichiorri, F., De Vico Fallani, F., Mattia, D., et al. (2011). Combining discriminant and topographic information in BCI: Preliminary results on stroke patients. *Neural Engineering (NER), 2011 5th International IEEE/EMBS Conference on*, 290-293. doi:10.1109/NER.2011.5910544

Birbaumer, N., & Cohen, L. G. (2007). Brain-computer interfaces: communication and restoration of movement in paralysis. *The Journal of physiology*, *579*(Pt 3), 621-636. doi:10.1113/jphysiol.2006.125633

Birbaumer, N., Ghanayim, N., Hinterberger, T., Iversen, I., Kotchoubey, B., Kübler, A., Perelmouter, J., et al. (1999). A spelling device for the paralysed. *Nature*, *398*(6725), 297-298. doi:10.1038/18581

Birbaumer, N., Weber, C., Neuper, C., Buch, E., Haapen, K., & Cohen, L. G. (2006). Physiological regulation of thinking: brain-computer interface (BCI) research. *Progress in brain research*, *159*, 369-391. doi:10.1016/S0079-6123(06)59024-7

Blankertz, B., Dornhege, G., Schäfer, C., Krepki, R., Kohlmorgen, J., Müller, K.-R., Kunzmann, V., et al. (2003). Boosting bit rates and error detection for the classification of fast-paced motor commands based on single-trial EEG analysis. *IEEE transactions on neural systems and rehabilitation engineering*, *11*(2), 127-131. doi:10.1109/TNSRE.2003.814456

Blankertz, B., Müller, K.-R., Curio, G., Vaughan, T. M., Schalk, G., Wolpaw, J. R., Schlögl, A., et al. (2004). The BCI Competition 2003: progress and perspectives in detection and discrimination of EEG single trials. *IEEE transactions on bio-medical engineering*, *51*(6), 1044-1051. doi:10.1109/TBME.2004.826692

Blankertz, B., Tangermann, M., Vidaurre, C., Fazli, S., Sannelli, C., Haufe, S., Maeder, C., et al. (2010). The Berlin Brain-Computer Interface: Non-Medical Uses of BCI Technology. *Frontiers in neuroscience*, *4*, 1-17. doi:10.3389/fnins.2010.00198

Blankertz, B., Tomioka, R., Lemm, S., Kawanabe, M., & Müller, K.-R. (2008). Optimizing Spatial filters for Robust EEG Single-Trial Analysis. *IEEE Signal Processing Magazine*, *25*(1), 41-56. Citeseer. doi:10.1109/MSP.2008.4408441

Boeck, D. (2010). Responsive environment for brainwaves. Retrieved from http://www.staalhemel.com/

Borenstein, J., & Koren, Y. (1991). The vector field histogram—fast obstacle avoidance for mobile robots. *IEEE transactions on robotics and automation*, *7*(3), 278-288. Institute of Electrical and Electronics Engineers.

Brunner, C., Allison, B. Z., Altstätter, C., & Neuper, C. (2011). A comparison of three brain-computer interfaces based on event-related desynchronization, steady state visual evoked potentials, or a hybrid approach using both signals. *Journal of neural engineering*, *8*(2), 025010. doi:10.1088/1741-2560/8/2/025010

Brunner, C., Allison, B. Z., Krusienski, D. J., Kaiser, V., Müller-Putz, G. R., Pfurtscheller, G., & Neuper, C. (2010). Improved signal processing approaches in an offline simulation of a hybrid brain-computer interface. *Journal of neuroscience methods*, *188*(1), 165-173. doi:10.1016/j.jneumeth.2010.02.002

Buch, E., Weber, C., Cohen, L. G., Braun, C., Dimyan, M. A., Ard, T., Mellinger, J., et al. (2008). Think to move: a neuromagnetic brain-computer interface (BCI) system for chronic stroke. *Stroke*, *39*(3), 910-917. doi:10.1161/STROKEAHA.107.505313

Cajochen, C., Kräuchi, K., von Arx, M. A., Möri, D., Graw, P., & Wirz-Justice, A. (1996). Daytime melatonin administration enhances sleepiness and theta/alpha activity in the waking EEG. *Neuroscience letters*, *207*(3), 209-213.

Caria, A., Veit, R., Sitaram, R., Lotze, M., Weiskopf, N., Grodd, W., & Birbaumer, N. (2007). Regulation of anterior insular cortex activity using real-time fMRI. *NeuroImage*, *35*(3), 1238-1246. doi:10.1016/j.neuroimage.2007.01.018

Caria, A., Weber, C., Brötz, D., Ramos, A., Ticini, L. F., Gharabaghi, A., Braun, C., et al. (2011). Chronic stroke recovery after combined BCI training and physiotherapy: a case report. *Psychophysiology*, *48*(4), 578-582. doi:10.1111/j.1469-8986.2010.01117.x

Carlson, T., & Demiris, Y. (2008). Human-wheelchair collaboration through prediction of intention and adaptive assistance. *Robotics and Automation, 2008. ICRA 2008. IEEE International Conference on*, 3926-3931. doi:10.1109/ROBOT.2008.4543814

Carlson, T., Leeb, R., Monnard, G., Al-Khodairy, A., & del R. Millán, J. (in press). Driving a BCI Wheelchair: A Patient Case Study. *Proc. TOBI workshop 3*.

Carmena, J. M., Lebedev, M. A., Crist, R. E., O'Doherty, J. E., Santucci, D. M., Dimitrov, D. F., Patil, P. G., et al. (2003). Learning to control a brain-machine interface for reaching and grasping by primates. *PLoS biology*, *1*(2), 193-208. doi:10.1371/journal.pbio.0000042

Cester, I., Llobera, J., & Soria-Frisch, A. (2009). *BCI classification, OVR approach*.

Chanel, G., Kronegg, J., Grandjean, D., & Pun, T. (2006). Emotion assessment: Arousal evaluation using EEG's and peripheral physiological signals. *Lecture notes in computer science*, *4105*, 530-537. Springer.

Chapin, J. K., Moxon, K. A., Markowitz, R. S., & Nicolelis, M. A. L. (1999). Real-time control of a robot arm using simultaneously recorded neurons in the motor cortex. *Nature neuroscience*, *2*(7), 664-670. doi:10.1038/10223

Cherubini, A., Oriolo, G., Macrí, F., Aloise, F., Cincotti, F., & Mattia, D. (2008). A multimode navigation system for an assistive robotics project. *Autonomous Robots*, *25*(4), 383-404. doi:10.1007/s10514-008-9102-y

Chi, Y. M., Deiss, S. R., & Cauwenberghs, G. (2009). Non-contact Low Power EEG/ECG Electrode for High Density Wearable Biopotential Sensor Networks. *2009 Sixth International Workshop on Wearable and Implantable Body Sensor Networks* (pp. 246-250). IEEE. doi:10.1109/BSN.2009.52

Cisek, P., & Kalaska, J. F. (2004). Neural correlates of mental rehearsal in dorsal premotor cortex. *Nature*, *431*(7011), 993-996. doi:10.1038/nature03005

Clausen, J. (2008). Moving minds: ethical aspects of neural motor prostheses. *Biotechnology journal*, *3*(12), 1493-1501. doi:10.1002/biot.200800244

Clausen, J. (2009). Man, machine and in between. *Nature*, *457*(7233), 1080-1081. doi:10.1038/4571080a

Clausen, J. (2010). Ethical brain stimulation - neuroethics of deep brain stimulation in research and clinical practice. *The European journal of neuroscience*, *32*(7), 1152-1162. doi:10.1111/j.1460-9568.2010.07421.x

Cohen, D. (1968). Magnetoencephalography: evidence of magnetic fields produced by alpha-rhythm currents. *Science (New York, N.Y.)*, *161*(843), 784-786.

Collinger, J.L., Boninger, M.L., Bruns, T., Curley, K., Wang, W., Weber, D.J. (In Review). Functional Priorities, Assistive Technology, and Brain-Computer Interfaces after Spinal Cord Injury. *Journal of Rehabilitation Research and Development.*

Congedo, M., Goyat, M., Tarrin, N., Ionescu, G., Varnet, L., Rivet, B., Phlypo, R., et al. (2011). “Brain Invaders”: a prototype of an open-source P300-based video game working with the OpenViBE platform. In G. R. Müller-Putz, R. Scherer, M. Billinger, A. Kreilinger, V. Kaiser, & C. Neuper (Eds.), *Proceedings of the 5th International Brain-Computer Interface Conference* (pp. 1-6). Verlag der Technischen Universitaet Graz.

Coyle, D. (2009). Neural network based auto association and time-series prediction for biosignal processing in brain-computer interfaces. *IEEE Computational Intelligence Magazine*, *4*(4), 47-59. doi:10.1109/MCI.2009.934560

Coyle, D., Prasad, G., & McGinnity, T. M. (2005). A time-series prediction approach for feature extraction in a brain-computer interface. *IEEE transactions on neural systems and rehabilitation engineering*, *13*(4), 461-467. doi:10.1109/TNSRE.2005.857690

Coyle SM, Ward TE, Markham CM. Brain-computer interface using a simplified functional near-infrared spectroscopy system. J Neural Eng. 2007 Sep;4(3):219-26.

Coyle, D., Satti, A., Prasad, G., & McGinnity, T. M. (2008). Neural time-series prediction preprocessing meets common spatial patterns in a brain-computer interface. *Proceedings of the Annual International Conference of the IEEE Engineering in Medicine and Biology Society,* 2626-2629. doi:10.1109/IEMBS.2008.4649739

Coyle, S., Ward, T., Markham, C., & McDarby, G. (2004). On the suitability of near-infrared (NIR) systems for next-generation brain-computer interfaces. *Physiological measurement*, *25*(4), 815-822.

Cutrell, E., & Tan, D. S. (2008). BCI for passive input in HCI. *Proceedings of CHI* (Vol. 8, pp. 1-3). Citeseer.

Danóczy, M., Fazli, S., Grozea, C., Müller, K.-R., & Popescu, F. (2008). Brain2robot: A grasping robot arm controlled by gaze and asynchronous EEG BCI. *Proc. 4th Int. BCI Workshop & Train. Course*.

DeCharms, R. C., Maeda, F., Glover, G. H., Ludlow, D., Pauly, J. M., Soneji, D., Gabrieli, J. D. E., et al. (2005). Control over brain activation and pain learned by using real-time functional MRI. *Proceedings of the National Academy of Sciences of the United States of America*, *102*(51), 18626-18631. doi:10.1073/pnas.0505210102

Donchin, E., Spencer, K. M., & Wijesinghe, R. (2000). The mental prosthesis: assessing the speed of a P300-based brain-computer interface. *IEEE transactions on rehabilitation engineering*, *8*(2), 174-179.

Donoghue, J. P. (2008). Bridging the brain to the world: a perspective on neural interface systems. *Neuron*, *60*(3), 511-521. doi:10.1016/j.neuron.2008.10.037

Dornhege, G., & del R. Millán, J. (2007). *Toward Brain-Computer Interfacing*. (G. Dornhege, J. del R. Millán, T. Hinterberger, D. J. McFarland, & K.-R. Müller, Eds.). MIT Press.

Duda, R. O., Hart, P. E., & Stork, D. G. (2000). *Pattern Classification* (2nd ed., p. 654). Wiley-Interscience.

Editorial. Neuroethics needed. (2006). *Nature*, *441*(7096), 907. doi:10.1038/441907a

Editorial. A maturing European Research Council. (2010). *Nature cell biology*, *12*(4), 307. Nature Publishing Group. doi:10.1038/ncb0410-307

Eliassen JC, Boespflug EL, Lamy M, Allendorfer J, Chu WJ, Szaflarski JP. Brain-mapping techniques for evaluating poststroke recovery and rehabilitation: a review. *Top Stroke Rehabil.* 2008 Sep-Oct;15(5):427-50.

Farwell, L. A., & Donchin, E. (1991). The Truth Will Out: Interrogative Polygraphy ("Lie Detection") With Event-Related Brain Potentials. *Psychophysiology*, *28*(5), 531-547. doi:10.1111/j.1469-8986.1991.tb01990.x

Fazli, S., Popescu, F., Danóczy, M., Blankertz, B., Müller, K.-R., & Grozea, C. (2009). Subject-independent mental state classification in single trials. *Neural networks*, *22*(9), 1305-1312. doi:10.1016/j.neunet.2009.06.003

Fazli, S., Mehnert. J., Steinbrink, J., Curio, G., Villringer, A., Müller, K-R., & Blankertz, B. (2012). Enhanced performance by a hybrid NIRS-EEG brain computer interface. Neuroimage, 59(1):519-29.

Fenton, A., & Alpert, S. (2008). Extending Our View on Using BCIs for Locked-in Syndrome. *Neuroethics*, *1*(2), 119-132. Springer Netherlands. doi:10.1007/s12152-008-9014-8

Ferrez, P. W., & Millán, J. D. R. (2005). You are wrong!: automatic detection of interaction errors from brain waves. *IJCAI'05 Proceedings of the 19th international joint conference on Artificial intelligence* (pp. 1413-1418). Edinburgh, UK: Morgan Kaufmann Publishers Inc.

Ferrez, P. W., & del R. Millán, J. (2008). Error-related EEG potentials generated during simulated brain-computer interaction. *IEEE transactions on bio-medical engineering*, *55*(3), 923-929. doi:10.1109/TBME.2007.908083

Fetz, E. E. (1969). Operant conditioning of cortical unit activity. *Science*, *163*(870), 955-958.

Finke, A., Lenhardt, A., & Ritter, H. (2009). The MindGame: a P300-based brain-computer interface game. *Neural networks*, *22*(9), 1329-1333. doi:10.1016/j.neunet.2009.07.003

Flemisch, O., Adams, A., Conway, S. R., Goodrich, K. H., Palmer, M. T., & Schutte, P. C. (2003). *The H-Metaphor as a guideline for vehicle automation and interaction*.

Furuhashi, T. (2001). Fusion of fuzzy/neuro/evolutionary computing for knowledge acquisition. *Proceedings of the IEEE*, *89*(9), 1266-1274. Institute of Electrical and Electronics Engineers.

Galán, F., Nuttin, M., Lew, E., Ferrez, P. W., Vanacker, G., Philips, J., & del R. Millán, J. (2008). A brain-actuated wheelchair: asynchronous and non-invasive Brain-computer interfaces for continuous control of robots. *Clinical neurophysiology*, *119*(9), 2159-2169. doi:10.1016/j.clinph.2008.06.001

Gangadhar, G., Chavarriaga, R., & del R. Millán, J. (2009). Fast recognition of anticipation-related potentials. *IEEE transactions on bio-medical engineering*, *56*(4), 1257-1260. doi:10.1109/TBME.2008.2005486

Ganguly, K., & Carmena, J. M. (2009). Emergence of a stable cortical map for neuroprosthetic control. *PLoS biology*, *7*(7). doi:10.1371/journal.pbio.1000153

Gao, X., Xu, D., Cheng, M., & Gao, S. (2003). A BCI-based environmental controller for the motion-disabled. *IEEE transactions on neural systems and rehabilitation engineering*, *11*(2), 137-140. doi:10.1109/TNSRE.2003.814449

George, L., & Lécuyer, A. (2010). An overview of research on “passive” brain-computer interfaces for implicit human-computer interaction. *International Conference on Applied Bionics and Biomechanics (ICABB)*. Venice, Italy.

Georgopoulos, A. P., Kalaska, J. F., Caminiti, R., & Massey, J. T. (1982). On the relations between the direction of two-dimensional arm movements and cell discharge in primate motor cortex. *The Journal of neuroscience, 2*(11), 1527-1537.

Gerson, A. D., Parra, L. C., & Sajda, P. (2006). Cortically coupled computer vision for rapid image search. *IEEE transactions on neural systems and rehabilitation engineering*, *14*(2), 174-179. doi:10.1109/TNSRE.2006.875550

Gevins, A., Leong, H., Du, R., Smith, M. E., Le, J., DuRousseau, D., Zhang, J., et al. (1995). Towards measurement of brain function in operational environments. *Biological psychology*, *40*(1-2), 169-186.

Grimes, D., Tan, D. S., Hudson, S. E., Shenoy, P., & Rao, R. P. N. (2008). Feasibility and pragmatics of classifying working memory load with an electroencephalograph. *Proceeding of the twenty-sixth annual CHI conference on Human factors in computing systems - CHI ’08*. New York, New York, USA: ACM Press. doi:10.1145/1357054.1357187

Groenegress, C., Holzner, C., Guger, C., & Slater, M. (2010). Effects of P300-Based BCI Use on Reported Presence in a Virtual Environment. *Presence: Teleoperators and Virtual Environments*, *19*(1), 1-11. doi:10.1162/pres.19.1.1

Grosse-Wentrup, M., Mattia, D., & Oweiss, K. (2011). Using brain-computer interfaces to induce neural plasticity and restore function. *Journal of neural engineering*, *8*(2), 025004. doi:10.1088/1741-2560/8/2/025004

Gruis, K. L., Wren, P. A., & Huggins, J. E. (2011). Amyotrophic lateral sclerosis patients’ self-reported satisfaction with assistive technology. *Muscle & nerve*, *43*(5), 643-647. doi:10.1002/mus.21951

Grübler, G. (2010). Shared Control - Shared Responsibility? *TOBI Workshop 2010*. Rome, Italy.

Grübler, G. (2011). Beyond the responsibility gap. Discussion note on responsibility and liability in the use of brain-computer interfaces. *AI & SOCIETY*, *26*(4), 377-382. Springer London. doi:10.1007/s00146-011-0321-y

Guger, C., Edlinger, G., Harkam, W., Niedermayer, I., & Pfurtscheller, G. (2003). How many people are able to operate an EEG-based brain-computer interface (BCI)? *IEEE transactions on neural systems and rehabilitation engineering*, *11*(2), 145-147. doi:10.1109/TNSRE.2003.814481

Guger, C., Leeb, R., Friedman, D., Vinayagamoorthy, V., Edlinger, G., & Slater, M. (2010). Controlling Virtual Environments by Thoughts. *Zeitschrift für Funktionsdiagnostik des Nervensystems*, *37*, 40-41.

Gürkök, H., Plass-Oude Bos, D., van de Laar, B. L. A., Nijboer, F., & Nijholt, A. (2011). User Experience Evaluation in BCI: Filling the Gap. *International Journal of Bioelectromagnetism*, *13*(3), 54-55. International Society for Bioelectromagnetism.

Halder, S., Agorastos, D., Veit, R., Hammer, E.-M., Lee, S., Varkuti, B., Bogdan, M., et al. (2011). Neural mechanisms of brain-computer interface control. *NeuroImage*, *55*(4), 1779-1790. doi:10.1016/j.neuroimage.2011.01.021

Hamadicharef, B., Haihong, Z., Cuntai, G., Chuanchu, W., Kok Soon, P., Keng Peng, T., & Kai Keng, A. (2009). Learning EEG-based spectral-spatial patterns for attention level measurement. *Circuits and Systems, 2009. ISCAS 2009. IEEE International Symposium on*, 1465-1468. doi:10.1109/ISCAS.2009.5118043

Hammon, P. S., Makeig, S., Poizner, H., Todorov, E., & de Sa, V. R. (2008). Predicting Reaching Targets from Human EEG. *Signal Processing Magazine, IEEE*, *25*(1), 69-77. doi:10.1109/MSP.2008.4408443

Haselager, P., Vlek, R., Hill, J., & Nijboer, F. (2009). A note on ethical aspects of BCI. *Neural Networks*, *22*(9), 1352-1357. Elsevier Ltd.

Hatsopoulos, N. G., Joshi, J., & O'Leary, J. G. (2004). Decoding continuous and discrete motor behaviors using motor and premotor cortical ensembles. *Journal of neurophysiology*, *92*(2), 1165-1174. doi:10.1152/jn.01245.2003

Herman, P., Prasad, G., McGinnity, T. M., & Coyle, D. (2008). Comparative analysis of spectral approaches to feature extraction for EEG-based motor imagery classification. *IEEE transactions on neural systems and rehabilitation engineering*, *16*(4), 317-326. doi:10.1109/TNSRE.2008.926694

Herrmann, C. S. (2001). Human EEG responses to 1-100 Hz flicker: resonance phenomena in visual cortex and their potential correlation to cognitive phenomena. *Experimental brain research. Experimentelle Hirnforschung. Expérimentation cérébrale*, *137*(3-4), 346-353.

Hinterberger, T., Pulvermacher, C., & Gendera, O. (2007). Braindance. Retrieved from http://www.interactivebrain.de/braindance.htm

Hochberg, L. R., & Donoghue, J. P. (2006). Sensors for brain-computer interfaces. *IEEE engineering in medicine and biology magazine: the quarterly magazine of the Engineering in Medicine & Biology Society*, *25*(5), 32-38.

Hoedlmoser, K., Pecherstorfer, T., Gruber, G., Anderer, P., Doppelmayr, M., Klimesch, W., & Schabus, M. (2008). Instrumental conditioning of human sensorimotor rhythm (12-15 Hz) and its impact on sleep as well as declarative learning. *Sleep*, *31*(10), 1401-1408.

Hoogerwerf, A. C., & Wise, K. D. (1994). A three-dimensional microelectrode array for chronic neural recording. *IEEE transactions on bio-medical engineering*, *41*(12), 1136-1146. doi:10.1109/10.335862

Huggins, J. E., Wren, P. A., & Gruis, K. L. (2011). What would brain-computer interface users want? Opinions and priorities of potential users with amyotrophic lateral sclerosis. *Amyotrophic lateral sclerosis*, *12*(5), 318-324. doi:10.3109/17482968.2011.572978

Hwang, E. J., & Andersen, R. A. (2009). Brain control of movement execution onset using local field potentials in posterior parietal cortex. *The Journal of neuroscience, 29*(45), 14363-14370. doi:10.1523/JNEUROSCI.2081-09.2009

Ijzerman, M. J., Stoffers, T. S., Groen, in ’t F. A. C. G., Klatte, M. A. P., Snoek, G. J., Vorsteveld, J. H. C., Nathan, R. H., et al. (1996). The NESS Handmaster othosis. *Journal of Rehabilitation Sciences*, *9*, 86-89.

Ihme, K., Zander, T. O., & Martin, J.-C. (2011). What You Expect Is What You Get? Potential Use of Contingent Negative Variation for Passive BCI Systems in Gaze-Based HCI. In S. D’Mello, A. Graesser, B. Schuller, & J.-C. Martin (Eds.), *Affective Computing and Intelligent Interaction* (Vol. 6975, pp. 447-456). Berlin, Heidelberg: Springer Berlin Heidelberg. doi:10.1007/978-3-642-24571-8

Iturrate, I., Antelis, J. M., Kübler, A., & Minguez, J. (2009). A Noninvasive Brain-Actuated Wheelchair Based on a P300 Neurophysiological Protocol and Automated Navigation. *IEEE Transactions on Robotics*, *25*(3), 614-627. doi:10.1109/TRO.2009.2020347

Jeannerod, M. (2001). Neural simulation of action: a unifying mechanism for motor cognition. *NeuroImage*, *14*(1 Pt 2), 103-109. doi:10.1006/nimg.2001.0832

Jin, J., Allison, B. Z., Sellers, E. W., Brunner, C., Horki, P., Wang, X., & Neuper, C. (2011). An adaptive P300-based control system. *Journal of neural engineering*, *8*(3), 036006. doi:10.1088/1741-2560/8/3/036006

John, M. S. (2003). DARPA augmented cognition technical integration experiment (TIE), (December). Retrieved from http://oai.dtic.mil/oai/oai?verb=getRecord&metadataPrefix=html&identifier=ADA420147

Jung, T. P., Makeig, S., Stensmo, M., & Sejnowski, T. J. (1997). Estimating alertness from the EEG power spectrum. *IEEE transactions on bio-medical engineering*, *44*(1), 60-69. doi:10.1109/10.553713

Kachenoura, A., Albera, L., Senhadji, L., & Comon, P. (2008). ICA: a potential tool for bci systems. *Signal Processing Magazine, IEEE*, *25*(1), 57-68. doi:10.1109/MSP.2008.4408442

Kaiser, V., Kreilinger, A., Müller-Putz, G. R., & Neuper, C. (2011). First Steps Toward a Motor Imagery Based Stroke BCI: New Strategy to Set up a Classifier. *Frontiers in neuroscience*, *5*, 1-10. doi:10.3389/fnins.2011.00086

Kanoh S, Murayama YM, Miyamoto K, Yoshinobu T, Kawashima R. (2009). A NIRS-based brain-computer interface system during motor imagery: system development and online feedback training. *Conf Proc IEEE Eng Med Biol Soc. 2009;*594-7.

Karim, A. A., Hinterberger, T., Richter, J., Mellinger, J., Neumann, N., Flor, H., Kübler, A., et al. (2006). Neural internet: Web surfing with brain potentials for the completely paralyzed. *Neurorehabilitation and neural repair*, *20*(4), 508-515. doi:10.1177/1545968306290661

Keith, M. W., & Hoyen, H. (2002). Indications and future directions for upper limb neuroprostheses in tetraplegic patients: a review. *Hand clinics*, *18*(3), 519-528.

Kelly, S. P., Lalor, E. C., Reilly, R. B., & Foxe, J. J. (2005). Visual spatial attention tracking using high-density SSVEP data for independent brain-computer communication. *IEEE transactions on neural systems and rehabilitation engineering*, *13*(2), 172-178. doi:10.1109/TNSRE.2005.847369

Kennedy, P. R., & Bakay, R. A. (1998). Restoration of neural output from a paralyzed patient by a direct brain connection. *Neuroreport*, *9*(8), 1707-1711.

Kennedy, P. R., Bakay, R. A., Moore, M. M., Adams, K., & Goldwaithe, J. (2000). Direct control of a computer from the human central nervous system. *IEEE transactions on rehabilitation engineering*, *8*(2), 198-202.

Kiernan, M. C., Vucic, S., Cheah, B. C., Turner, M. R., Eisen, A., Hardiman, O., Burrell, J. R., et al. (2011). Amyotrophic lateral sclerosis. *Lancet*, *377*(9769), 942-955. doi:10.1016/S0140-6736(10)61156-7

Kilgore, K. L., Peckham, P. H., Keith, M. W., Thrope, G. B., Wuolle, K. S., Bryden, A. M., & Hart, R. L. (1997). An implanted upper-extremity neuroprosthesis. Follow-up of five patients. *The Journal of bone and joint surgery. American volume*, *79*(4), 533-541.

Kipke, D. R., Vetter, R. J., Williams, J. C., & Hetke, J. F. (2003). Silicon-substrate intracortical microelectrode arrays for long-term recording of neuronal spike activity in cerebral cortex. *IEEE transactions on neural systems and rehabilitation engineering*, *11*(2), 151-155. doi:10.1109/TNSRE.2003.814443

Kleih, S. C., Kaufmann, T., Zickler, C., Halder, S., Leotta, F., Cincotti, F., Aloise, F., et al. (2011). Out of the frying pan into the fire--the P300-based BCI faces real-world challenges. *Progress in brain research*, *194*, 27-46. doi:10.1016/B978-0-444-53815-4.00019-4

Kleih, S. C., Riccio, A., Mattia, D., Schreuder, M., Tangermann, M., Zickler, C., & Kübler, A. (2011). Motivation affects performance in a P300-Brain-Computer Interface. *International Journal of Bioelectromagnetism*, *13*(1), 46-47.

Kohlmorgen, J., Dornhege, G., Braun, M., Blankertz, B., Müller, K.-R., Curio, G., Hagemann, K., et al. (2007). Improving human performance in a real operating environment through real-time mental workload detection. In G. Dornhege, J. del R. Millán, T. Hinterberger, D. J. McFarland, & K.-R. Müller (Eds.), *Toward Brain-Computer Interfacing* (pp. 409–422). MIT Press.

Kübler, A., Neumann, N., Kaiser, J., Kotchoubey, B., Hinterberger, T., & Birbaumer, N. (2001). Brain-computer communication: self-regulation of slow cortical potentials for verbal communication. *Archives of physical medicine and rehabilitation*, *82*(11), 1533-1539.

Kübler, A., Neumann, N., Wilhelm, B., Hinterberger, T., & Birbaumer, N. (2004). Predictability of Brain-Computer Communication. *Journal of Psychophysiology*, *18*(2-3), 121-129. doi:10.1027/0269-8803.18.23.121

Kübler, A., Nijboer, F., Mellinger, J., Vaughan, T. M., Pawelzik, H., Schalk, G., McFarland, D. J., et al. (2005). Patients with ALS can use sensorimotor rhythms to operate a brain-computer interface. *Neurology*, *64*(10), 1775-1777. doi:10.1212/01.WNL.0000158616.43002.6D

Kübler, A. & Müller, K.-R. (2007). An introduction to brain computer interfacing. In G. Dornhege, J. del R. Millán, T. Hinterberger, D. J. McFarland, & K.-R. Müller (Eds.), *Toward Brain-Computer Interfacing* (pp. 1-26). Boston: MIT Press.

Lalor, E. C., Kelly, S. P., Finucane, C., & Burke, R. (2005). Steady-state VEP-based brain-computer interface control in an immersive 3D gaming environment. *EURASIP journal on Signal Processing*, 3156-3164.

Lebedev, M. A., & Nicolelis, M. A. L. (2006). Brain-machine interfaces: past, present and future. *Trends in neurosciences*, *29*(9), 536-546. doi:10.1016/j.tins.2006.07.004

Lecuyer, A., Lotte, F., Reilly, R. B., Leeb, R., Hirose, M., & Slater, M. (2008). Brain-Computer Interfaces, Virtual Reality, and Videogames. *Computer*, *41*(10), 66-72. IEEE Computer Society.

Lee, E. C., Woo, J. C., Kim, J. H., Whang, M., & Park, K. R. (2010). A brain-computer interface method combined with eye tracking for 3D interaction. *Journal of neuroscience methods*, *190*(2), 289-298. doi:10.1016/j.jneumeth.2010.05.008

Lee, J.-H., Ryu, J., Jolesz, F. A., Cho, Z.-H., & Yoo, S.-S. (2009). Brain-machine interface via real-time fMRI: preliminary study on thought-controlled robotic arm. *Neuroscience letters*, *450*(1), 1-6. doi:10.1016/j.neulet.2008.11.024

Leeb, R., Al-Khodairy, A., Biasiucci, A., Perdikis, S., Tavella, M., Tonin, L., Carlson, T., et al. (2011). Are we ready? Issues in transferring BCI technology from experts to users. *Proceedings of the 5th International Brain-Computer Interface Conference*, 352-355.

Leeb, R., Friedman, D., Müller-Putz, G. R., Scherer, R., Slater, M., & Pfurtscheller, G. (2007). Self-paced (asynchronous) BCI control of a wheelchair in virtual environments: a case study with a tetraplegic. *Computational intelligence and neuroscience*. doi:10.1155/2007/79642

Leeb, R., Gubler, M., Tavella, M., Miller, H., & del R. Millán, J. (2010). On the road to a neuroprosthetic hand: a novel hand grasp orthosis based on functional electrical stimulation. *Proceedings of the Annual International Conference of the IEEE Engineering in Medicine and Biology Society,* 146-149. doi:10.1109/IEMBS.2010.5627412

Leeb, R., Keinrath, C., Friedman, D., Guger, C., Scherer, R., Neuper, C., Garau, M., et al. (2006). Walking by Thinking: The Brainwaves Are Crucial, Not the Muscles! *Presence: Teleoperators and Virtual Environments*, *15*(5), 500-514. doi:10.1162/pres.15.5.500

Leeb, R., Lee, F., Keinrath, C., Scherer, R., Bischof, H., & Pfurtscheller, G. (2007). Brain-computer communication: motivation, aim, and impact of exploring a virtual apartment. *IEEE transactions on neural systems and rehabilitation engineering*, *15*(4), 473-482. doi:10.1109/TNSRE.2007.906956

Leeb, R., Sagha, H., Chavarriaga, R., & del R. Millán, J. (2011). A hybrid brain-computer interface based on the fusion of electroencephalographic and electromyographic activities. *Journal of neural engineering*, *8*(2), 025011. doi:10.1088/1741-2560/8/2/025011

Leuthardt, E. C., Schalk, G., Wolpaw, J. R., Ojemann, J. G., & Moran, D. W. (2004). A brain-computer interface using electrocorticographic signals in humans. *Journal of neural engineering*, *1*(2), 63-71. doi:10.1088/1741-2560/1/2/001

Levine, S. P., Huggins, J. E., BeMent, S. L., Kushwaha, R. K., Schuh, L. A., Rohde, M. M., Passaro, E. A., et al. (2000). A direct brain interface based on event-related potentials. *IEEE transactions on rehabilitation engineering:*, *8*(2), 180-185.

Li, Y., Long, J., Yu, T., Yu, Z., Wang, C., Zhang, H., & Guan, C. (2010). A hybrid BCI system for 2-D asynchronous cursor control. *Proceedings of the Annual International Conference of the IEEE Engineering in Medicine and Biology Society,* 4205-4208. doi:10.1109/IEMBS.2010.5627394

Lin, C.-T., Ko, L.-W., & Shen, T.-K. (2009). Computational intelligent brain computer interaction and its applications on driving cognition. *IEEE Computational Intelligence Magazine*, *4*(4), 32-46. doi:10.1109/MCI.2009.934559

Logroscino, G., Traynor, B. J., Hardiman, O., Chiò, A., Mitchell, D., Swingler, R. J., Millul, A., et al. (2010). Incidence of amyotrophic lateral sclerosis in Europe. *Journal of neurology, neurosurgery, and psychiatry*, *81*(4), 385-390. doi:10.1136/jnnp.2009.183525

Lotte, F., & Renard, Y. (2008). Self-Paced Brain-Computer Interaction with Virtual Worlds: A Quantitative and Qualitative Study "Out of the Lab." *4th international Brain Computer Interface Workshop and Training Course*. Graz.

Lotte, F., Congedo, M., Lécuyer, A., Lamarche, F., & Arnaldi, B. (2007). A review of classification algorithms for EEG-based brain-computer interfaces. *Journal of neural engineering*, *4*(2), R1-R13. doi:10.1088/1741-2560/4/2/R01

Lotte, F., van Langhenhove, A., Lamarche, F., Ernest, T., Renard, Y., Arnaldi, B., & Lécuyer, A. (2010). Exploring Large Virtual Environments by Thoughts Using a Brain–Computer Interface Based on Motor Imagery and High-Level Commands. *Presence: Teleoperators and Virtual Environments*, *19*(1), 54-70. doi:10.1162/pres.19.1.54

Mehring, C., Nawrot, M. P., Cardosa de Oliveira, S., Vaadia, E., Schulze-Bonhage, A., Aersten, A., & Ball, T. (2004). Comparing information about arm movement direction in single channels of local and epicortical field potentials from monkey and human motor cortex. *Journal of physiology*, *98*(4-6), 498-506. Elsevier.

Mangold, S., Keller, T., Curt, A., & Dietz, V. (2005). Transcutaneous functional electrical stimulation for grasping in subjects with cervical spinal cord injury. *Spinal cord*, *43*(1), 1-13. doi:10.1038/sj.sc.3101644

Martinez, P., Bakardjian, H., & Cichocki, A. (2007). Fully online multicommand brain-computer interface with visual neurofeedback using SSVEP paradigm. *Computational intelligence and neuroscience*. doi:10.1155/2007/94561

Mason, S. G., Bashashati, A., Fatourechi, M., Navarro, K. F., & Birch, G. E. (2007). A comprehensive survey of brain interface technology designs. *Annals of biomedical engineering*, *35*(2), 137-169. doi:10.1007/s10439-006-9170-0

Matthews, R., McDonald, N. J., Anumula, H., Woodward, J., Turner, P. J., Steindorf, M. A., Chang, K., et al. (2007). Novel hybrid bioelectrodes for ambulatory zero-prep EEG measurements using multi-channel wireless EEG system. *FAC'07 Proceedings of the 3rd international conference on Foundations of augmented cognition*, 137-146.

Maynard, E. M., Hatsopoulos, N. G., Ojakangas, C. L., Acuna, B. D., Sanes, J. N., Normann, R. A., & Donoghue, J. P. (1999). Neuronal interactions improve cortical population coding of movement direction. *The Journal of neuroscience: the official journal of the Society for Neuroscience*, *19*(18), 8083-8093.

Maynard, E. M., Nordhausen, C. T., & Normann, R. A. (1997). The Utah intracortical Electrode Array: a recording structure for potential brain-computer interfaces. *Electroencephalography and clinical neurophysiology*, *102*(3), 228-239.

McFarland, D. J., Sarnacki, W. A., & Wolpaw, J. R. (2010). Electroencephalographic (EEG) control of three-dimensional movement. *Journal of neural engineering*, *7*(3). doi:10.1088/1741-2560/7/3/036007

Mehring, C., Rickert, J., Vaadia, E., Cardosa de Oliveira, S., Aertsen, A., & Rotter, S. (2003). Inference of hand movements from local field potentials in monkey motor cortex. *Nature neuroscience*, *6*(12), 1253-1254. doi:10.1038/nn1158

Miller, K. J., DenNijs, M., Shenoy, P., Miller, J. W., Rao, R. P. N., & Ojemann, J. G. (2007). Real-time functional brain mapping using electrocorticography. *NeuroImage*, *37*(2), 504-507. doi:10.1016/j.neuroimage.2007.05.029

Millán, J. D. R. (2003). Adaptive brain interfaces. *Communications of the ACM*, *46*(3), 74-80. doi:10.1145/636772.636773

Millán, J., Renkens, F., Mouriño, J., & Gerstner, W. (2004). Brain-actuated interaction. *Artificial Intelligence*, *159*(1-2), 241-259. doi:10.1016/j.artint.2004.05.008

Millán, J., Renkens, F., Mouriño, J., & Gerstner, W. (2004). Noninvasive brain-actuated control of a mobile robot by human EEG. *IEEE transactions on bio-medical engineering*, *51*(6), 1026-1033. doi:10.1109/TBME.2004.827086

Millán, J., Ferrez, P. W., Galán, F., Lew, E., & Chavarriaga, R. (2008). Non-Invasive Brain-Machine Interaction. *Int Journal Pattern Recognition and Artificial Intelligence*, *22*(5), 959–972.

Millán, J., Galán, F., Vanhooydonck, D., Lew, E., Philips, J., & Nuttin, M. (2009). Asynchronous non-invasive brain-actuated control of an intelligent wheelchair. *Proceedings of the Annual International Conference of the IEEE Engineering in Medicine and Biology Society*, 3361-3364. doi:10.1109/IEMBS.2009.5332828

Millán, J., & Carmena, J. M. (2010). Invasive or Noninvasive: Understanding Brain-Machine Interface Technology [Conversations in BME]. *Engineering in Medicine and Biology Magazine, IEEE*, *29*(1), 16-22. doi:10.1109/MEMB.2009.935475

Millán, J., Rupp, R., Müller-Putz, G. R., Murray-Smith, R., Giugliemma, C., Tangermann, M., Vidaurre, C., et al. (2010). Combining Brain-Computer Interfaces and Assistive Technologies: State-of-the-Art and Challenges. *Frontiers in neuroscience*, *4*(September), 1-15. doi:10.3389/fnins.2010.00161

Miranda, E. R., Magee, W. L., Wilson, J. J., Eaton, J., & Palaniappan, R. (2011). Brain-Computer Music Interfacing (BCMI): From Basic Research to the Real World of Special Needs. *Music and Medicine*, *3*(3), 134-140. SAGE Publications. doi:10.1177/1943862111399290

Mitchell, T. M., Shinkareva, S. V., Carlson, A., Chang, K.-M., Malave, V. L., Mason, R. A., & Just, M. A. (2008). Predicting human brain activity associated with the meanings of nouns. *Science (New York, N.Y.)*, *320*(5880), 1191-1195. doi:10.1126/science.1152876

Mitzdorf, U. (1985). Current source-density method and application in cat cerebral cortex: investigation of evoked potentials and EEG phenomena. *Physiological reviews*, *65*(1), 37-100.

Molina, G. G., Tsoneva, T., & Nijholt, A. (2009). Emotional brain-computer interfaces. *3rd International Conference on Affective Computing and Intelligent Interaction and Workshops,* pp. 1–9. IEEE. doi:10.1109/ACII.2009.5349478

Muehlemann, T., Haensse, D., & Wolf, M. (2008). Wireless miniaturized in-vivo near infrared imaging. *Optics express*, *16*(14), 10323-10330.

Mugler, E. M., Bensch, M., Halder, S., Rosenstiel, W., Bogdan, M., Birbaumer, N., & Kübler, A. (2008). Control of an internet browser using the P300 event-related potential. *Control*, *10*(1), 56-63.

Mugler, E. M., Ruf, C. A., Halder, S., Bensch, M., & Kübler, A. (2010). Design and implementation of a P300-based brain-computer interface for controlling an internet browser. *IEEE transactions on neural systems and rehabilitation engineering*, *18*(6), 599-609. doi:10.1109/TNSRE.2010.2068059

Musallam, S., Corneil, B. D., Greger, B., Scherberger, H., & Andersen, R. A. (2004). Cognitive control signals for neural prosthetics. *Science*, *305*(5681), 258-262. American Association for the Advancement of Science.

Mühl, C., Heylen, D., & Nijholt, A. (2009). Affective Brain-Computer Interfaces: Preface. *ACII 2009: Affective Computing & Intelligent Interaction*.

Müller, K.-R., & Blankertz, B. (2006). Toward noninvasive brain-computer interfaces. *Signal Processing Magazine, IEEE*, *23*(5), 128-126. doi:10.1109/MSP.2006.1708426

Müller, K.-R., Tangermann, M., Dornhege, G., Krauledat, M., Curio, G., & Blankertz, B. (2008). Machine learning for real-time single-trial EEG-analysis: from brain-computer interfacing to mental state monitoring. *Journal of neuroscience methods*, *167*(1), 82-90. doi:10.1016/j.jneumeth.2007.09.022

Müller-Putz, G. R., Breitwieser, C., Cincotti, F., Leeb, R., Schreuder, M., Leotta, F., Tavella, M., et al. (2011). Tools for Brain-Computer Interaction: A General Concept for a Hybrid BCI. *Frontiers in neuroinformatics*, *5*(November), 30. doi:10.3389/fninf.2011.00030

Müller-Putz, G. R., Scherer, R., & Pfurtscheller, G. (2007). Control of a two-axis artificial limb by means of a pulse width modulated brain switch. *European Conference for the Advancement of Assistive Technology*.

Müller-Putz, G. R., Scherer, R., Pfurtscheller, G., & Neuper, C. (2010). Temporal coding of brain patterns for direct limb control in humans. *Frontiers in neuroscience*, *4*. doi:10.3389/fnins.2010.00034

Müller-Putz, G. R., Scherer, R., Pfurtscheller, G., & Rupp, R. (2005). EEG-based neuroprosthesis control: a step towards clinical practice. *Neuroscience letters*, *382*(1-2), 169-174. doi:10.1016/j.neulet.2005.03.021

Münßinger, J. I., Halder, S., Kleih, S. C., Furdea, A., Raco, V., Hösle, A., & Kübler, A. (2010). Brain Painting: First Evaluation of a New Brain-Computer Interface Application with ALS-Patients and Healthy Volunteers. *Frontiers in neuroscience*, *4*, 182. doi:10.3389/fnins.2010.00182

Myrden AJB, Kushki A, Sejdic´ E, Guerguerian A-M, Chau T (2011). A Brain-Computer Interface Based on Bilateral Transcranial Doppler Ultrasound. *PLoS ONE* 6(9): e24170. doi:10.1371/journal.pone.0024170

Nijholt, A., Tan, D. S., Pfurtscheller, G., Brunner, C., del R. Millán, J., Allison, B. Z., Graimann, B., et al. (2008). Brain-Computer Interfacing for Intelligent Systems. *IEEE intelligent systems*, *23*(3), 72-79. IEEE Computer Society.

Nijholt, A., Allison, B.Z., and Jacob, R.K. (2011). Brain-Computer Interaction: Can Multimodality Help? *Proceedings of the 13th International Conference on Multimodal Interaction*, H. Bourlard, T.S. Huang, E. Vidal, D. Gatica-Perez, L.-P. Morency, N. Sebe (Eds.), ACM Digital Library, ISBN 978-4503-0641-6, 35-39.

Negueruela, C., Broschart, M., Menon, C., & del R. Millán, J. (2010). Brain–computer interfaces for space applications. *Personal and Ubiquitous Computing*, *15*(5), 527-537. doi:10.1007/s00779-010-0322-8.

Neuper, C., & Pfurtscheller, G. (2010). Neurofeedback Training for BCI Control. In B. Graimann, G. Pfurtscheller, & B. Z. Allison (Eds.), *Brain-Computer Interfaces* (pp. 65-78). Berlin, Heidelberg: Springer Berlin Heidelberg. doi:10.1007/978-3-642-02091-9.

Neuper, Christa, & Pfurtscheller, Gert. (2010). Neurofeedback Training for BCI Control. *Brain-Computer Interfaces*. doi:10.1007/978-3-642-02091-9_4.

Nicolelis, M. A. L., Baccala, L. A., Lin, R. C., & Chapin, J. K. (1995). Sensorimotor encoding by synchronous neural ensemble activity at multiple levels of the somatosensory system. *Science (New York, N.Y.)*, *268*(5215), 1353-1358.

Nicolelis, M. A. L., Dimitrov, D. F., Carmena, J. M., Crist, R. E., Lehew, G., Kralik, J. D., & Wise, S. P. (2003). Chronic, multisite, multielectrode recordings in macaque monkeys. *Proceedings of the National Academy of Sciences of the United States of America*, *100*(19), 11041-11046. doi:10.1073/pnas.1934665100

Nicolelis, M. A. L., Ghazanfar, A. A., Faggin, B. M., Votaw, S., & Oliveira, L. M. (1997). Reconstructing the engram: simultaneous, multisite, many single neuron recordings. *Neuron*, *18*(4), 529-537.

Nijboer, F., Allison, B. Z., Dunne, S., Plass-Oude Bos, D., Nijholt, A., Haselager, P., Müller-Putz, G. R., et al. (2011). A Preliminary Survey on the Perception of Marketability of Brain-Computer Interfaces and Initial Development of a Repository of BCI Companies. In G. R. Müller-Putz, R. Scherer, M. Billinger, A. Kreilinger, A.Kreilinger, V. Kaiser, & C. Neuper (Eds.), *Proceedings of the 5th Int. Brain-Computer Interface Conference* (p. 4). Graz: Verlag der Technischen Universitaet Graz.

Nijboer, F., Carmien, S. P., Leon, E., Morin, F. O., Koene, R. A., & Hoffmann, U. (2009). Affective brain-computer interfaces: Psychophysiological markers of emotion in healthy persons and in persons with amyotrophic lateral sclerosis. *Affective Computing and Intelligent Interaction and Workshops, 2009. ACII 2009. 3rd International Conference on*, 1-11. doi:10.1109/ACII.2009.5349479

Nijboer, F., Clausen, J., Allison, B. Z., & Haselager, P. (2011). Researchers' opinions about ethically sound dissemination of BCI research to the public media. *International Journal of Bioelectromagnetism*, *13*(3), 108-109. International Society for Bioelectromagnetism.

Nijboer, F., Clausen, J., Allison, B. Z., & Haselager, P. (2011). The Asilomar Survey: Stakeholders' Opinions on Ethical Issues Related to Brain-Computer Interfacing. *Neuroethics*, 1-38. Springer Netherlands. doi:10.1007/s12152-011-9132-6

Nijboer, F., Sellers, E. W., Mellinger, J., Jordan, M. A., Matuz, T., Furdea, A., Halder, S., et al. (2008). A P300-based brain-computer interface for people with amyotrophic lateral sclerosis. *Clinical neurophysiology*, *119*(8), 1909-1916. doi:10.1016/j.clinph.2008.03.034

Nijholt, A. (2009). BCI for Games: A `State of the Art' Survey. In S. M. Stevens & S. J. Saldamarco (Eds.), *ICEC '08 Proceedings of the 7th International Conference on Entertainment Computing* (Vol. 5309, pp. 225-228). Berlin, Heidelberg: Springer Berlin Heidelberg. doi:10.1007/978-3-540-89222-9

Nijholt, A. (2011). Towards Multimodal, Multi-Party, and Social Brain-Computer Interfacing. *Proceedings 4th International ICST Conference on Intelligent Technologies for Interactive Entertainment (INTETAIN 2011)*. Genoa, Italy: Springer-Verlag, Berlin.

Nijholt, A., Plass-Oude Bos, D., & Reuderink, B. (2009). Turning shortcomings into challenges: Brain–computer interfaces for games. *Entertainment Computing*, *1*(2), 85-94. International Federation for Information Processing. doi:10.1016/j.entcom.2009.09.007

Nijholt, A., Tan, D. S., Allison, B. Z., del R. Millán, J., & Graimann, B. (2008). Brain-computer interfaces for hci and games. *Proceeding of the twenty-sixth annual CHI conference extended abstracts on Human factors in computing systems - CHI '08*. New York, New York, USA: ACM Press. doi:10.1145/1358628.1358958

Nijholt, A., Allison, B.Z., & Jacob, R.K. (2011). Brain-Computer Interaction: Can Multimodality Help? In: Proceedings 13th International Conference on Multimodal Interaction, H. Bourlard, T.S. Huang, E. Vidal, D. Gatica-Perez, L.-P. Morency, N. Sebe (Eds.), ACM Digital Library, ISBN 978-4503-0641-6, 35-39.

Noirhomme, Q., Kitney, R. I., & Macq, B. (2008). Single-trial EEG source reconstruction for brain-computer interface. *IEEE transactions on bio-medical engineering*, *55*(5), 1592-1601. doi:10.1109/TBME.2007.913986

Nunez, P., & Srinivasan, R. (2006). *Electric Fields of the Brain: The Neurophysics of EEG, 2nd Edition* (2nd ed.). Oxford University Press, USA.

Nussbaum, G., Veigl, C., Acedo, J., Barton, Z., Diaz, U., Drajsajtl, T., Garcia, A., et al. (2011). AsTeRICS - Towards a Rapid Integration Construction Set for Assistive Technologies. *AAATE conference 2011*. Maastricht, The Netherlands.

Oehler, M., Neumann, P., Becker, M., Curio, G., & Schilling, M. (2008). Extraction of SSVEP signals of a capacitive EEG helmet for human machine interface. *Proceedings of the Annual International Conference of the IEEE Engineering in Medicine and Biology Society*, 4495-4498. doi:10.1109/IEMBS.2008.4650211

Okada, Y. (1983). Neurogenesis of evoked magnetic fields. In S. H. Williamson, G. L. Romani, L. Kaufman, & I. Modena (Eds.), *Biomagnetism: an Interdisciplinary Approach* (pp. 399-408). New York: Plenum Press.

Panicker, R. C., Puthusserypady, S., & Sun, Y. (2011). An asynchronous P300 BCI with SSVEP-based control state detection. *IEEE transactions on bio-medical engineering*, *58*(6), 1781-1788. doi:10.1109/TBME.2011.2116018

Parra, L. C., Spence, C. D., Gerson, A. D., & Sajda, P. (2003). Response error correction--a demonstration of improved human-machine performance using real-time EEG monitoring. *IEEE transactions on neural systems and rehabilitation engineering*, *11*(2), 173-177. doi:10.1109/TNSRE.2003.814446

Patil, P. G., Carmena, J. M., Nicolelis, M. A. L., & Turner, D. A. (2004). Ensemble recordings of human subcortical neurons as a source of motor control signals for a brain-machine interface. *Neurosurgery*, *55*(1), 27-38.

Perdikis, S., Leeb, R., Liboni, N., Coincenot, L., Giugliemma, C., & del R. Millán, J. (2010). BCI for Augmenting Communication Capabilities of. *Proceedings of the TOBI Workshop 2010: Integrating Brain-Computer Interfaces with Conventional Assistive Technology* (p. 17).

Pesaran, B., Musallam, S., & Andersen, R. A. (2006). Cognitive neural prosthetics. *Current biology□: CB*, *16*(3), R77-80. doi:10.1016/j.cub.2006.01.043

Pesaran, B., Pezaris, J. S., Sahani, M., Mitra, P. P., & Andersen, R. A. (2002). Temporal structure in neuronal activity during working memory in macaque parietal cortex. *Nature neuroscience*, *5*(8), 805-811. doi:10.1038/nn890

Pfurtscheller, G. (1981). Central beta rhythm during sensorimotor activities in man. *Electroencephalography and clinical neurophysiology*, *51*(3), 253-264.

Pfurtscheller, G., & Neuper, C. (1994). Event-related synchronization of mu rhythm in the EEG over the cortical hand area in man. *Neuroscience letters*, *174*(1), 93-96.

Pfurtscheller, G., & Neuper, C. (2006). Future prospects of ERD/ERS in the context of brain-computer interface (BCI) developments. *Progress in Brain Research*, *159*, 433-437. Elsevier.

Pfurtscheller, G., Müller-Putz, G. R., Pfurtscheller, J., Gerner, H. J., & Rupp, R. (2003). “Thought”-control of functional electrical stimulation to restore handgrasp in a patient with tetraplegia. *Neuroscience Letters*, *351*, 33–36.

Pfurtscheller, G., Müller-Putz, G. R., Scherer, R., & Neuper, C. (2008). Rehabilitation with Brain-Computer Interface Systems. *Computer*, *41*(10), 58-65. doi:10.1109/MC.2008.432

Pfurtscheller, G., Neuper, C., Andrew, C., & Edlinger, G. (1997). Foot and hand area mu rhythms. *International journal of psychophysiology*, *26*(1-3), 121-135.

Pfurtscheller, G., Solis-Escalante, T., Ortner, R., Linortner, P., & Müller-Putz, G. R. (2010). Self-paced operation of an SSVEP-Based orthosis with and without an imagery-based “brain switch:” a feasibility study towards a hybrid BCI. *IEEE transactions on neural systems and rehabilitation engineering*, *18*(4), 409-14. IEEE. doi:10.1109/TNSRE.2010.2040837

Piccione, F., Giorgi, F., Tonin, P., Priftis, K., Giove, S., Silvoni, S., Palmas, G., et al. (2006). P300-based brain computer interface: reliability and performance in healthy and paralysed participants. *Clinical neurophysiology*, *117*(3), 531-537. doi:10.1016/j.clinph.2005.07.024

Pichiorri, F., Cincotti, F., De Vico Fallani, F., Pisotta, I., Morone, G., Molinari, M., & Mattia, D. (2011). Towards a brain computer interface-based rehabilitation: from bench to bedside. In Gernot R. Müller-Putz, R. Scherer, M. Billinger, A. Kreilinger, V. Kaiser, & C. Neuper (Eds.), *Proceedings of the 5th Int. Brain-Computer Interface Conference* (pp. 268–271). Graz, Austria: Verlag der Technischen Universität Graz.

Pineda, J. A., Brang, D., Hecht, E., Edwards, L., Carey, S., Bacon, M., Futagaki, C., et al. (2008). Positive behavioral and electrophysiological changes following neurofeedback training in children with autism. *Research in Autism Spectrum Disorders*, *2*(3), 557-581. Elsevier. doi:10.1016/j.rasd.2007.12.003

Pineda, J. A., Silverman, D. S., Vankov, A., & Hestenes, J. (2003). Learning to control brain rhythms: making a brain-computer interface possible. *IEEE transactions on neural systems and rehabilitation engineering, 11*(2), 181-184. doi:10.1109/TNSRE.2003.814445

Pistohl, T., Ball, T., Schulze-Bonhage, A., Aertsen, A., & Mehring, C. (2008). Prediction of arm movement trajectories from ECoG-recordings in humans. *Journal of neuroscience methods*, *167*(1), 105-114. doi:10.1016/j.jneumeth.2007.10.001

Plass-Oude Bos, D., Gürkök, H., van de Laar, B. L. A., Nijboer, F., & Nijholt, A. (2011). User Experience Evaluation in BCI: Mind the Gap! *International Journal of Bioelectromagnetism*, *13*(3), 48-49. International Society for Bioelectromagnetism.

Plass-Oude Bos, D., Reuderink, B., De Laar, B. V., Gürkök, H., Mühl, C., Poel, M., Nijholt, A., et al. (2010). Brain-computer interfacing and games. In D. S. Tan & A. Nijholt (Eds.), *Brain-Computer Interfaces. Applying our Minds to Human-Computer Interaction* (pp. 149-178). London: Springer London. doi:10.1007/978-1-84996-272-8

Pope, A. T., Bogart, E. H., & Bartolome, D. S. (1995). Biocybernetic system evaluates indices of operator engagement in automated task. *Biological psychology*, *40*(1-2), 187-95.

Posse, S., Fitzgerald, D., Gao, K., Habel, U., Rosenberg, D., Moore, G. J., & Schneider, F. (2003). Real-time fMRI of temporolimbic regions detects amygdala activation during single-trial self-induced sadness. *NeuroImage*, *18*(3), 760-768.

Power SD, Falk TH, Chau T. (2010). Classification of prefrontal activity due to mental arithmetic and music imagery using hidden Markov models and frequency domain near-infrared spectroscopy. *Journal of Neural Engineering* 7(2):26002.

Prance, R. J., Clark, T. D., & Prance, H. (2006). Room temperature induction magnetometers. In C. A. Grimes, E. C. Dickey, & M. V. Pishko (Eds.), *Encyclopedia of Sensors Vol. 10* (pp. 1-12). Valencia, CA: American Scientific Publishers.

Qin, J., Li, Y., & Sun, W. (2007). A semisupervised support vector machines algorithm for BCI systems. *Computational intelligence and neuroscience*. doi:10.1155/2007/94397

Quian Quiroga, R., Reddy, L., Kreiman, G., Koch, C., & Fried, I. (2005). Invariant visual representation by single neurons in the human brain. *Nature*, *435*(7045), 1102-1107. Nature Publishing Group.

Racine, E., Waldman, S., Rosenberg, J., & Illes, J. (2010). Contemporary neuroscience in the media. *Social science & medicine (1982)*, *71*(4), 725-733. doi:10.1016/j.socscimed.2010.05.017

Rebsamen, B., Guan, C., Zhang, H., Wang, C., Teo, C., Ang, M. H., & Burdet, E. (2010). A brain controlled wheelchair to navigate in familiar environments. *IEEE transactions on neural systems and rehabilitation engineering*, *18*(6), 590-598. doi:10.1109/TNSRE.2010.2049862

Riccio, A., Leotta, F., Bianchi, L., Aloise, F., Zickler, C., Hoogerwerf, E.-J., Kübler, A., et al. (2011). Workload measurement in a communication application operated through a P300-based brain-computer interface. *Journal of neural engineering*, *8*(2). doi:10.1088/1741-2560/8/2/025028

Rickert, J., Cardosa de Oliveira, S., Vaadia, E., Aertsen, A., Rotter, S., & Mehring, C. (2005). Encoding of movement direction in different frequency ranges of motor cortical local field potentials. *The Journal of neuroscience*, *25*(39), 8815-8824. doi:10.1523/JNEUROSCI.0816-05.2005

Roger, V. L., Go, A. S., Lloyd-Jones, D. M., Adams, R. J., Berry, J. D., Brown, T. M., Carnethon, M. R., et al. (2011). Executive Summary: Heart Disease and Stroke Statistics--2011 Update: A Report From the American Heart Association. *Circulation*, *123*(4), 459-463. doi:10.1161/CIR.0b013e31820c7a50

Ron-Angevin, R., Díaz-Estrella, A., & Velasco-Alvarez, F. (2009). A two-class brain computer interface to freely navigate through virtual worlds. *Biomedizinische Technik. Biomedical engineering*, *54*(3), 126-133. doi:10.1515/BMT.2009.014

Roy, C. S., & Sherrington, C. S. (1890). On the Regulation of the Blood-supply of the Brain. *The Journal of physiology*, *11*(1-2), 85-158.

Ruiz, S., Lee, S., Soekadar, S. R., Caria, A., Veit, R., Kircher, T., Birbaumer, N., et al. (2011). Acquired self-control of insula cortex modulates emotion recognition and brain network connectivity in schizophrenia. *Human brain mapping*. doi:10.1002/hbm.21427

Ryu, S. I., & Shenoy, K. V. (2009). Human cortical prostheses: lost in translation? *Neurosurgical focus*, *27*(1), E5. doi:10.3171/2009.4.FOCUS0987

Saha, K., & Hurlbut, J. B. (2011). Research ethics: Treat donors as partners in biobank research. *Nature*, *478*(7369), 312-313. doi:10.1038/478312a

Sannelli, C., Dickhaus, T., Halder, S., Hammer, E.-M., Müller, K.-R., & Blankertz, B. (2010). On optimal channel configurations for SMR-based brain-computer interfaces. *Brain topography*, *23*(2), 186-193. doi:10.1007/s10548-010-0135-0

Sannelli, C., Vidaurre, C., Müller, K.-R., & Blankertz, B. (2010). Common spatial pattern patches - an optimized filter ensemble for adaptive brain-computer interfaces. *Proceedings of the Annual International Conference of the IEEE Engineering in Medicine and Biology Society Conference*, 4351-4354. doi:10.1109/IEMBS.2010.5626227

Santhanam, G., Ryu, S. I., Yu, B. M., Afshar, A., & Shenoy, K. V. (2006). A high-performance brain-computer interface. *Nature*, *442*(7099), 195-198. doi:10.1038/nature04968

Schalk, G. (2008). Brain-computer symbiosis. *Journal of neural engineering*, *5*(1), P1-P15. doi:10.1088/1741-2560/5/1/P01

Schalk, G., Kubánek, J., Miller, K. J., Anderson, N. R., Leuthardt, E. C., Ojemann, J. G., Limbrick, D., et al. (2007). Decoding two-dimensional movement trajectories using electrocorticographic signals in humans. *Journal of neural engineering*, *4*(3), 264-275. doi:10.1088/1741-2560/4/3/012

Schalk, G., Miller, K. J., Anderson, N. R., Wilson, J. A., Smyth, M. D., Ojemann, J. G., Moran, D. W., et al. (2008). Two-dimensional movement control using electrocorticographic signals in humans. *Journal of neural engineering*, *5*(1), 75-84. doi:10.1088/1741-2560/5/1/008

Schalk, G., Wolpaw, J. R., McFarland, D. J., & Pfurtscheller, G. (2000). EEG-based communication: presence of an error potential. *Clinical neurophysiology*, *111*(12), 2138-44.

Scherberger, H. (2009). Neural control of motor prostheses. *Current opinion in neurobiology*, *19*(6), 629-633. doi:10.1016/j.conb.2009.10.008

Scherberger, H., Jarvis, M. R., & Andersen, R. A. (2005). Cortical local field potential encodes movement intentions in the posterior parietal cortex. *Neuron*, *46*(2), 347-354. doi:10.1016/j.neuron.2005.03.004

Scherer, M. J. (2000). *Living in the State of Stuck: How Assistive Technology Impacts the Lives of People with Disabilities* (3rd ed., p. 212). Brookline Books; 3rd edition.

Scherer, Reinhold, Friedrich, E. C. V., Allison, B. Z., Pröll, M., Chung, M., Cheung, W., Rao, R. P. N., et al. (2011). Non-invasive brain-computer interfaces: enhanced gaming and robotic control. *Lecture Notes in Computer Science 6691:362-269,* Springer-Verlag Berlin.

Scherer, Reinhold, Lee, F., Schlögl, A., Leeb, R., Bischof, H., & Pfurtscheller, G. (2008). Toward self-paced brain-computer communication: navigation through virtual worlds. *IEEE transactions on bio-medical engineering*, *55*(2 Pt 1), 675-682. doi:10.1109/TBME.2007.903709

Scherer, Reinhold, Müller-Putz, G. R., & Pfurtscheller, G. (2007). Self-initiation of EEG-based brain-computer communication using the heart rate response. *Journal of Neural Engineering*, *4*(4), L23-29. doi:10.1088/1741-2560/4/4/L01

Scherer, Reinhold, Müller-Putz, G. R., Neuper, C., Graimann, B., & Pfurtscheller, G. (2004). An asynchronously controlled EEG-based virtual keyboard: improvement of the spelling rate. *IEEE transactions on bio-medical engineering*, *51*(6), 979-984. doi:10.1109/TBME.2004.827062

Scherer, Reinhold, Schlögl, A., Lee, F., Bischof, H., Jansa, J., & Pfurtscheller, G. (2007). The self-paced graz brain-computer interface: methods and applications. *Computational intelligence and neuroscience*. doi:10.1155/2007/79826

Schermer, M. (2009). The Mind and the Machine. On the Conceptual and Moral Implications of Brain-Machine Interaction. *Nanoethics*, *3*(3), 217-230. doi:10.1007/s11569-009-0076-9

Schmidt, E. A., Kincses, W. E., Schrauf, M., Haufe, S., Schubert, R., & Curio, G. (2009). ASSESSING DRIVERS ' VIGILANCE STATE DURING MONOTONOUS DRIVING. *PROCEEDINGS of the Fourth International Driving Symposium on Human Factors in Driver Assessment, Training and Vehicle Design*.

Schmidt, E. M. (1980). Single neuron recording from motor cortex as a possible source of signals for control of external devices. *Annals of biomedical engineering*, *8*(4-6), 339-349.

Sellers, E. W., Krusienski, D. J., McFarland, D. J., Vaughan, T. M., & Wolpaw, J. R. (2006). A P300 event-related potential brain-computer interface (BCI): the effects of matrix size and inter stimulus interval on performance. *Biological psychology*, *73*(3), 242-252. doi:10.1016/j.biopsycho.2006.04.007

Sellers, E. W., Turner, P. J., Sarnacki, W. A., Mcmanus, T., Vaughan, T. M., & Matthews, R. (2009). A novel dry electrode for brain-computer interface. In J. A. Jacko (Ed.), *Human-Computer Interaction. Novel Interaction Methods and Techniques* (Vol. 5611, pp. 623-631). Berlin, Heidelberg: Springer Berlin Heidelberg. doi:10.1007/978-3-642-02577-8

Serruya, M. D., Hatsopoulos, N. G., Paninski, L., Fellows, M. R., & DONOGHUE, J. P. (2002). Instant neural control of a movement signal. *Nature*, *416*, 141-142.

Seymour, T. L., Seifert, C. M., Shafto, M. G., & Mosmann, A. L. (2000). Using Response Time Measures to Assess “Guilty Knowledge.” *Journal of Applied Psychology*, *85*(1), 37-30.

Shinkareva, S. V., Mason, R. A., Malave, V. L., Wang, W., Mitchell, T. M., & Just, M. A. (2008). Using FMRI brain activation to identify cognitive states associated with perception of tools and dwellings. *PloS one*, *3*(1). doi:10.1371/journal.pone.0001394

Silvoni, S., Ramos-Murguialday, A., Cavinato, M., Volpato, C., Cisotto, G., Turolla, A., Piccione, F., et al. (2011). Brain-Computer Interface in Stroke: a Review of Progress. *Journal of Clinical EEG & Neuroscience*, 245–252.

Silvoni, S., Volpato, C., Cavinato, M., Marchetti, M., Priftis, K., Merico, A., Tonin, P., et al. (2009). P300-Based Brain-Computer Interface Communication: Evaluation and Follow-up in Amyotrophic Lateral Sclerosis. *Frontiers in neuroscience*, *3*. doi:10.3389/neuro.20.001.2009

Song, Y.-K., Patterson, W. R., Bull, C. W., Beals, J., Hwang, N., Deangelis, A. P., Lay, C., et al. (2005). Development of a chipscale integrated microelectrode/microelectronic device for brain implantable neuroengineering applications. *IEEE transactions on neural systems and rehabilitation engineering*, *13*(2), 220-226. doi:10.1109/TNSRE.2005.848337

Sorger, B., Dahmen, B., Reithler, J., Gosseries, O., Maudoux, A., Laureys, S., & Goebel, R. (2009). Another kind of “BOLD Response”: answering multiple-choice questions via online decoded single-trial brain signals. *Progress in brain research*, *177*, 275-292. doi:10.1016/S0079-6123(09)17719-1

Stam, C., & van Dijk, B. W. (2002). Synchronization likelihood: an unbiased measure of generalized synchronization in multivariate data sets. *Physica D: Nonlinear Phenomena*, *163*(3-4), 236-251. doi:10.1016/S0167-2789(01)00386-4

Su, Y., Qi, Y., Luo, J.-xun, Wu, B., Yang, F., Li, Y., Zhuang, Y.-ting, et al. (2011). A hybrid brain-computer interface control strategy in a virtual environment. *Journal of Zhejiang University SCIENCE C*, *12*(5), 351-361. Zhejiang University Press, co-published with Springer. doi:10.1631/jzus.C1000208

Tamburrini, G. (2009). Brain to Computer Communication: Ethical Perspectives on Interaction Models. *Neuroethics*, *2*(3), 137-149. Springer Netherlands. doi:10.1007/s12152-009-9040-1

Tan, D. S., & Nijholt, A. (2010). Brain-Computer Interfaces and Human-Computer Interaction. In: D. S. Tan & A. Nijholt (Eds.), *Brain-Computer Interfaces and Human-Computer Interaction. Applying our Minds to Human-Computer Interaction,* 3-19. London: Springer.

Tangermann, M., Krauledat, M., Grzeska, K., Sagebaum, M., Blankertz, B., Vidaurre, C., & Müller, K.-R. (2009). Playing pinball with non-invasive BCI. *Advances in Neural Information Processing Systems*, *21*, 1641-1648.

Tavella, M., Leeb, R., Rupp, R., & del R. Millán, J. (2010). Towards natural non-invasive hand neuroprostheses for daily living. *Proceedings of the Annual International Conference of the IEEE Engineering in Medicine and Biology Society,* 126-129. doi:10.1109/IEMBS.2010.5627178

Taylor, D. M., Tillery, S. I. H., & Schwartz, A. B. (2002). Direct cortical control of 3D neuroprosthetic devices. *Science (New York, N.Y.)*, *296*(5574), 1829-1832. doi:10.1126/science.1070291

Thorsen, R., Spadone, R., & Ferrarin, M. (2001). A pilot study of myoelectrically controlled FES of upper extremity. *IEEE transactions on neural systems and rehabilitation engineering*, *9*(2), 161-168. doi:10.1109/7333.928576

Tonin, L., Leeb, R., Tavella, M., Zander, T. O., & del R. Millán, J. (2010). The role of shared-control in BCI-based telepresence. *Systems Man and Cybernetics (SMC), 2010 IEEE International Conference on*, 1462-1466. doi:10.1109/ICSMC.2010.5642338

Townsend, G., LaPallo, B. K., Boulay, C. B., Krusienski, D. J., Frye, G. E., Hauser, C. K., Schwartz, N. E., et al. (2010). A novel P300-based brain-computer interface stimulus presentation paradigm: moving beyond rows and columns. *Clinical neurophysiology*, *121*(7), 1109-1120. doi:10.1016/j.clinph.2010.01.030

Trejo, L. J., Kochavi, R., & Kubitz, K. (2005). EEG-based estimation of cognitive fatigue. *Proceedings of the SPIE* (Vol. 5797, pp. 1-11).

Trejo, L. J., Kramer, A. F., & Arnold, J. A. (1995). Event-related potentials as indices of display-monitoring performance. *Biological psychology*, *40*(1-2), 33-71.

Truccolo, W., Friehs, G. M., Donoghue, J. P., & Hochberg, L. R. (2008). Primary motor cortex tuning to intended movement kinematics in humans with tetraplegia. *The Journal of neuroscience*, *28*(5), 1163-1178. doi:10.1523/JNEUROSCI.4415-07.2008

Valbuena, D., Sugiarto, I., & Gräser, A. (2008). Spelling with the Bremen brain computer interface and the integrated SSVEP. *Proc 4th Intl. Brain-Computer Interface Workshop and Training Course*. Graz.

van Est, R., Stemerding, D., van Keulen, I., Geesink, I., & Schuijff, M. (2010). *Bio-engineering (in) the 21st Century. Reproduction*.

van de Laar, B. L. A., Nijboer, F., Gürkök, H., Plass-Oude Bos, D., & Nijholt, A. (2011). User Experience Evaluation in BCI: Bridge the Gap. *International Journal of Bioelectromagnetism*, *13*(3), 157-158. International Society for Bioelectromagnetism.

Vanhooydonck, D., Demeester, E., Nuttin, M., & Van Brussel, H. (2003). Shared Control for Intelligent Wheelchairs: an Implicit Estimation of the User Intention. *Proceedings of the ASER '03 1 st International Workshop on Advances in Service Robotics* (pp. 176–182).

Vansteensel, M. J., Hermes, D., Aarnoutse, E. J., Bleichner, M. G., Schalk, G., van Rijen, P. C., Leijten, F. S. S., et al. (2010). Brain-computer interfacing based on cognitive control. *Annals of Neurology*, *67*(6), 809-816. doi:10.1002/ana.21985

Velliste, M., Perel, S., Spalding, M. C., Whitford, A. S., & Schwartz, A. B. (2008). Cortical control of a prosthetic arm for self-feeding. *Nature*, *453*(7198), 1098-1101. doi:10.1038/nature06996

Vialatte, F. B., Solé-Casals, J., Dauwels, J., Maurice, M., & Cichocki, A. (2009). Bump time-frequency toolbox: a toolbox for time-frequency oscillatory bursts extraction in electrophysiological signals. *BMC neuroscience*, *10*. doi:10.1186/1471-2202-10-46

Vidaurre, C., & Blankertz, B. (2010). Towards a cure for BCI illiteracy. *Brain topography*, *23*(2), 194-198. Springer New York. doi:10.1007/s10548-009-0121-6

Vidaurre, C., Sannelli, C., Müller, K.-R., Blankertz, B., Graña Romay, M., Corchado, E., & Garcia Sebastian, M. (2010). Machine-Learning Based Co-adaptive Calibration: A Perspective to Fight BCI Illiteracy. In M. Graña Romay, E. Corchado, & M. T. Garcia Sebastian (Eds.), *Hybrid Artificial Intelligence Systems* (Vol. 6076, pp. 413-420). Berlin, Heidelberg: Springer Berlin Heidelberg. doi:10.1007/978-3-642-13769-3

Viventi, J., Kim, D.-H., Vigeland, L., Frechette, E. S., Blanco, J. A., Kim, Y.-S., Avrin, A. E., et al. (2011). Flexible, foldable, actively multiplexed, high-density electrode array for mapping brain activity in vivo. *Nature Neuroscience*, *14*(12), 1599 - 1605. doi:10.1038/nn.2973

Vogel, G. (2005). European research. A framework for change? *Science, 308*(5720), 342-344. doi:10.1126/science.308.5720.342

Walter, S. (2009). Locked-in Syndrome, BCI, and a Confusion about Embodied, Embedded, Extended, and Enacted Cognition. *Neuroethics*, *3*(1), 61-72. Springer Netherlands. doi:10.1007/s12152-009-9050-z

Wang, Y., Wang, R., Gao, X., Hong, B., & Gao, S. (2006). A practical VEP-based brain-computer interface. *IEEE transactions on neural systems and rehabilitation engineering : a publication of the IEEE Engineering in Medicine and Biology Society*, *14*(2), 234-239. doi:10.1109/TNSRE.2006.875576

Weiskopf, N., Mathiak, K., Bock, S. W., Scharnowski, F., Veit, R., Grodd, W., Goebel, R., et al. (2004). Principles of a brain-computer interface (BCI) based on real-time functional magnetic resonance imaging (fMRI). *IEEE transactions on bio-medical engineering*, *51*(6), 966-970. doi:10.1109/TBME.2004.827063

Weiskopf, N., Veit, R., Erb, M., Mathiak, K., Grodd, W., Goebel, R., & Birbaumer, N. (2003). Physiological self-regulation of regional brain activity using real-time functional magnetic resonance imaging (fMRI): methodology and exemplary data. *NeuroImage*, *19*(3), 577-586.

Wessberg, J., Stambaugh, C. R., Kralik, J. D., Beck, P. D., Laubach, M., Chapin, J. K., Kim, J., et al. (2000). Real-time prediction of hand trajectory by ensembles of cortical neurons in primates. *Nature*, *408*(6810), 361-365. Macmillian Magazines Ltd.

White, J. R., Levy, T., Bishop, W., & Beaty, J. D. (2010). Real-time decision fusion for multimodal neural prosthetic devices. *PloS one*, *5*(3). doi:10.1371/journal.pone.0009493

Williamson, J., Murray-Smith, R., Blankertz, B., Krauledat, M., & Müller, K.-R. (2009). Designing for uncertain, asymmetric control: Interaction design for brain–computer interfaces. *International Journal of Human-Computer Studies*, *67*(10), 827-841. doi:10.1016/j.ijhcs.2009.05.009

Wills, S. A., & MacKay, D. J. C. (2006). DASHER--an efficient writing system for brain-computer interfaces? *IEEE transactions on neural systems and rehabilitation engineering*, *14*(2), 244-246. doi:10.1109/TNSRE.2006.875573

Wolpaw, J. R. (2007). Brain-computer interfaces as new brain output pathways. *The Journal of physiology*, *579*(Pt 3), 613-619. doi:10.1113/jphysiol.2006.125948

Wolpaw, J. R., & McFarland, D. J. (2004). Control of a two-dimensional movement signal by a noninvasive brain-computer interface in humans. *Proceedings of the National Academy of Sciences of the United States of America*, *101*(51), 17849-17854. doi:10.1073/pnas.0403504101

Wolpaw, J. R., Birbaumer, N., McFarland, D. J., Pfurtscheller, G., & Vaughan, T. M. (2002). Brain-computer interfaces for communication and control. *Clinical neurophysiology*, *113*(6), 767-791.

Wolpaw, J. R., Loeb, G. E., Allison, B. Z., Donchin, E., do Nascimento, O. F., Heetderks, W. J., Nijboer, F., et al. (2006). BCI Meeting 2005--workshop on signals and recording methods. *IEEE transactions on neural systems and rehabilitation engineering*, *14*(2), 138-141. doi:10.1109/TNSRE.2006.875583

Wolpaw, J. R., McFarland, D. J., Neat, G. W., & Forneris, C. A. (1991). An EEG-based brain-computer interface for cursor control. *Electroencephalography and clinical neurophysiology*, *78*(3), 252-259.

Wolpaw, J., & Wolpaw, E. W. (2012). Brain computer interfaces: Something new under the sun. In J. Wolpaw & E. W. Wolpaw (Eds.), *Brain-Computer Interfaces: Principles and Practice* (pp. 3-14). Oxford: Oxford Univ Press.

Worrell, G. A., Gardner, A. B., Stead, S. M., Hu, S., Goerss, S., Cascino, G. J., Meyer, F. B., et al. (2008). High-frequency oscillations in human temporal lobe: simultaneous microwire and clinical macroelectrode recordings. *Brain*, *131*(Pt 4), 928-937. doi:10.1093/brain/awn006

Wu, W., Gao, X., & Gao, S. (2005). One-Versus-the-Rest(OVR) Algorithm: An Extension of Common Spatial Patterns(CSP) Algorithm to Multi-class Case. *Proceedings of the Annual International Conference of the IEEE Engineering in Medicine and Biology Society, 3*, 2387-2390. doi:10.1109/IEMBS.2005.1616947

Xu, N., Gao, X., Hong, B., Miao, X., Gao, S., & Yang, F. (2004). BCI Competition 2003--Data set IIb: enhancing P300 wave detection using ICA-based subspace projections for BCI applications. *IEEE Transactions on Biomedical Engineering*, *51*(6), 1067-1072. IEEE. doi:10.1109/TBME.2004.826699

Yoo, S.-S., & Jolesz, F. A. (2002). Functional MRI for neurofeedback: feasibility study on a hand motor task. *Neuroreport*, *13*(11), 1377-1381.

Yoo, S.-S., Fairneny, T., Chen, N.-K., Choo, S.-E., Panych, L. P., Park, H., Lee, S.-Y., et al. (2004). Brain-computer interface using fMRI: spatial navigation by thoughts. *Neuroreport*, *15*(10), 1591-1595.

Zander, T. O., & Kothe, C. (2011). Towards passive brain-computer interfaces: applying brain-computer interface technology to human-machine systems in general. *Journal of neural engineering*, *8*(2). doi:10.1088/1741-2560/8/2/025005

Zander, T. O., Kothe, C., Jatzev, S., & Gaertner, M. (2010). Enhancing Human-Computer Interaction with Input from Active and Passive Brain-Computer Interfaces. In D. S. Tan & A. Nijholt (Eds.), *BrainComputer Interfaces* (pp. 181-199). London: Springer London. doi:10.1007/978-1-84996-272-8

Zhang, D., Wang, Y., Gao, X., Hong, B., & Gao, S. (2007). An algorithm for idle-state detection in motor-imagery-based brain-computer interface. *Computational intelligence and neuroscience*. doi:10.1155/2007/39714

Zickler, C., Di Donna, V., Kaiser, V., Al-Khodairy, A., Kleih, S. C., Kübler, A., Malavasi, M., et al. (2009). BCI Applications for People with Disabilities: Defining User Needs and User Requirements. *AAATE*.

Zickler, C., Riccio, A., Leotta, F., Hillian-Tress, S., Halder, S., Holz, E., Staiger-Sälzer, P., et al. (2011). A Brain-Computer Interface as Input Channel for a Standard Assistive Technology Software. *Journal of Clinical EEG & Neuroscience*.