Chapter 1
Recent and Upcoming BCI Progress: Overview, Analysis, and Recommendations

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1.1 Introduction

Brain–computer interfaces (BCIs) let people communicate without using muscular activity. BCIs have been developed primarily as communication devices for people who cannot move because of conditions like Lou Gehrig's disease. However, recent advancements like practical electrodes, usable and adaptive software, and reduced cost have made BCIs appealing to new user groups. People with mild to moderate disabilities might benefit from BCIs, which were previously so cumbersome and technically demanding that other assistive communication technologies were preferable. Simple and cheap BCIs have gained attention among a much larger market: healthy users.

Right now, healthy people who use BCIs generally do so for fun. These types of BCIs will gain wider adoption, but not as much as the next generation of field BCIs and similar systems, which healthy people will use because they consider them useful. These systems could provide useful communication in situations

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when conventional means such as keyboards or game controllers are unavailable or inadequate. Future BCIs will go beyond communication in different ways, such as monitoring error, alertness, frustration, or other cognitive and emotive states to facilitate human–computer interaction (HCI). The hardware, software, and functionality afforded by BCIs will be more effectively integrated with any devices that the user already wears or carries. BCIs that contribute to rehabilitation or functional improvement could go further beyond communication and make BCIs appealing to far more users, such as persons with stroke, autism, or attentional disorders. The next 5 years will help resolve which of these areas are promising.

The BCI community also faces growing challenges. Because BCIs are generally not well known or understood, many end users and others may have unrealistic expectations or fears. Groups might unnecessarily conduct research that was already done, or miss opportunities from other disciplines or research projects. In addition to developing and sharing knowledge about BCIs, we also need practical infrastructural issues like terms, definitions, standards, and ethical and reporting guidelines. The appeal of the brand "BCI" could encourage unjustified boasting, unscrupulous reporting in the media or scientific literature, products that are not safe or effective, or other unethical practices. The acronym is already used much more broadly than it was just 5 years ago, such as to refer to devices that write to the brain or literally read minds [8, 23].

On the other hand, several key advances cannot be ignored. With improved flexibility and reliability, new applications, dry electrodes that rely on gold and composites rather than gel, practical software, and growing public appeal, we could be on the verge of a Golden Age of BCI research. Key performance indicators like sales, cost, and dependence on support should reflect substantial progress in the next 5 years. While the spirit of camaraderie and enthusiasm should remain strong within the BCI community, the BCIs in 5 years will be significantly better in many ways. This sentimental elan was captured best by Jacques Vidal, the inventor of BCIs, who gave a lecture after many years of retirement at a workshop that we authors hosted in Graz, Austria in September 2011. "It still feels like yesterday," he said, "but it isn't."

1.2 Overview of This Book

AQ2 This book is divided into four sections. These sections are structured around the four components of a BCI (Fig. 1.1). Articles about BCIs generally describe four components, which are responsible for:

1. Directly measuring brain activity
2. Identifying useful information from that activity
3. Implementing messages or comments through devices or applications
4. Providing an application interface or operating environment.

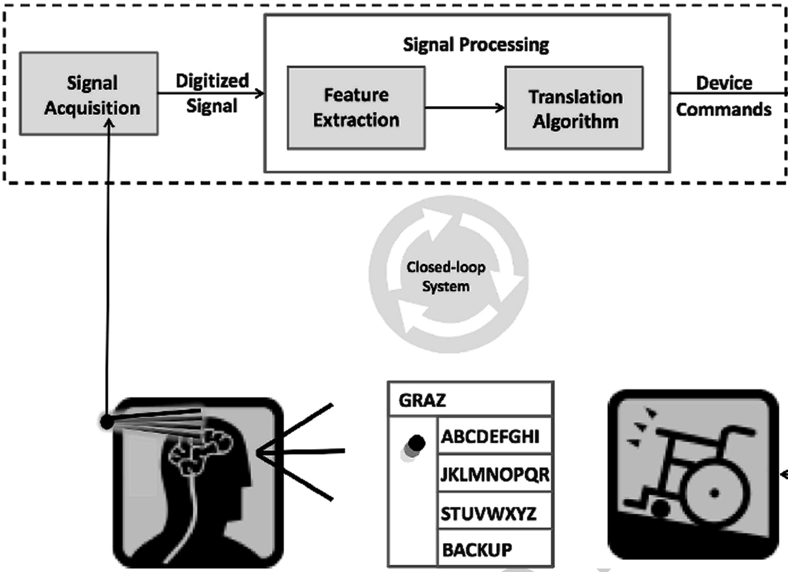

Fig. 1.1 The components of any BCI system from [2]. The different sections of this book are structured around these different components

In this book, the first two components are jointly addressed in the first section. The second section discusses the devices and applications that implement user commands, and the third covers interfaces and environments. The last section addresses practical issues that span all the components of a BCI.

1.2.1 Overview of Part

In this first part of the book we start at the beginning, with the signals, the sensors used to capture those signals and the signal processing techniques used to extract information. The majority of recent BCI research and development, particularly in Europe and Asia, has been based on electroencephalogram (EEG) activity, recorded using resistive electrodes with conductive gel. This is the BCI standard and sufficient for many purposes. However, many researchers, including those involved in writing this book, feel that much more can be done in terms of usability, robustness and performance if we look beyond the standard platform.

The term hybrid-BCI is used in various ways, as discussed in Chap. 18 of this book and some recent articles [3,21]. Chapter 2 discusses hybrid sensor systems that combine different technologies that measure brain activity. Here we see an example of a hybrid optical–electrical sensor system providing functional near-infrared spectroscopy (fNIRS) and EEG in a single system. The resulting "compound" signal provides information on neural activity and haemodynamic response in coincident brain areas. There are many possible hybrid systems but for practical and useful BCI systems, for use in daily life, we must look at mobility and cost. Here, too, such systems show promise.

A consequence of such hybrid systems is the need for some sort of data fusion to make sense of these compound signals is a coherent way. In Chap. 3, we have a critical review of classifier ensembles and their use in BCI applications. This Machine Learning approach is ideally suited to hybrid systems and to BCI in general as it copes particularly well with variable data sources such as physiological signals.

For many EEG based BCI approaches, the focus has moved to performance enhancement in recent years. Independent component analysis (ICA) continues to provide improvements in three important and practical aspects, as discussed in Chap. 4. The chapter discusses artifact removal, improved SNR and optimal electrode selection, and how these techniques might be implemented in real-time. Such improvements are essential if we are to move from the lab into real world scenarios.

Finally we look at the world of invasive sensors, where chronic BCI makes sense for some applications [17]. While there are many different points of view on whether the perceived advantages justify the procedures necessary to implant such electrodes, and on whether this is as risky or invasive as often perceived, there can be no doubt that some groups are making significant steps towards wholly and long term implantable Electrocorticogram (ECoG) BCIs. Chapter 5 talks about the short term possibilities for such systems and what they might look like.

1.2.2 Overview of Part

Recording the brain signals, applying sophisticated signal processing and machine learning methods to classify different brain patterns is only the beginning of establishing a new communication channel between the human brain and a machine. In this Part , the focus is on how to provide new devices and applications for different users, a challenge that goes beyond simple control tasks.

The first chapter in this section (Chap. 6) by Leeb and Millán gives an overview on current devices and application scenarios for various user groups [18]. Up to now, typical BCI applications require a very good and precise control channel to achieve performances comparable to users without a BCI. However, current day BCIs offer low throughput information and are insufficient for the full dexterous control of such complex applications. Techniques like shared control can enhance the interaction, yielding performance comparable to systems without a BCI [9, 26]. With shared control the user is giving high-level commands at a fairly slow pace (e.g., directions of a wheelchair) and the system is executing fast and precise low-level interactions (e.g., obstacle avoidance) [7,27]. Chapter 6 also includes examples of how the performance of such applications can be improved by novel hybrid BCIs architectures [3,22], which are a synergetic combination of a BCI with other residual input channels.

The impact and usage of Brain–Computer interfaces for the neurological rehabilitation to lessen motor impairment and for the restoration and recovery of hand motor functions is discussed by Mattia and colleagues in Chap. 7. On the one hand, BCI systems can be utilized to bypass central nervous system injury by controlling neuroprosthetics for patients' arms to manage reach and grasp functional activities in peripersonal space [20]. On the other, BCI technology can encourage motor training and practice by offering an on-line feedback about brain signals associated with mental practice, motor intention and other neural recruitment strategies, and thus helping to guide neuroplasticity associated with post-stroke motor impairment and its recovery [6].

Brain–Computer Interfaces are no longer only used by healthy subjects under controlled conditions in laboratory environments, but also by patients, controlling applications in their homes under real-world settings [18]. But which types of applications are useful for them and how much they can influence the applications already during the development cycle, so that they are tailored? Holz and co-authors discuss the different aspects of user involvement and the roles that users could or should have in the design and development of BCI driven assistive applications. Their focus is on BCI applications in the field of communication, access to ICT and environmental control, typical areas where assistive technology solutions can make the difference between participation and exclusion. User-centered design is an important principle gaining attention within BCI research, and this issue is addressed from an application interface perspective in Chap. 11.

The next chapter by Quek and colleagues addresses similar issues. Here, the focus is on how new BCI applications have to be designed to go beyond basic BCI control and isolated intention detection events. Such a design process for the overall system comprises finding a suitable control metaphor, respecting neuro-ergonomic principles, designing visually aesthetic feedback, dealing with the learnability of the system, creating an effective application structure (navigation), and exploring the power of social aspects of an interactive BCI system. Designing a human-machine system also involves eliciting a user's knowledge, preferences, requirements and priorities. In order not to overload end users with evaluation tasks and to take into account issues specific to BCI, techniques and processes from other fields that aim to acquire these must be adapted for applications that use BCI [29].

The last chapter of this part is focused on an emerging application field. Recently BCIs have gained interest among the virtual reality (VR) community, since they have appeared as promising interaction devices for virtual environments [12]. These implicit interaction techniques are of great interest for the VR community. For example, users might imagine movement of their hands to control a virtual hand, or navigate through houses or museums by your thoughts alone or just by looking at some highlighted objects [13, 16]. Furthermore, VR can provide an excellent testing ground for procedures that could be adapted to real world scenarios. Patients with disabilities can learn to control their movements or perform specific tasks in a virtual environment (VE). Lotte and co-authors provide several studies which highlight these interactions.

1.2.3 Overview of Part

While the term “BCI” has three words, the “interface” part has not received enough attention. Sensors to detect brain activity are making great strides, with dry electrodes that are increasingly cheap and effective. Pattern classification has long been an active research area, with numerous articles and data analysis competitions. But, especially in the early days of BCI research, relatively few BCI articles focused on improved usability, immersive and natural environments, evaluating user experience, user-centered interface design, accounting for the needs of special user populations, and other issues relating to the human–computer interaction (HCI) side of BCIs [1, 2, 10, 11, 19].

Part summarizes progress and issues in application interfaces and operating environments for BCIs. The first chapter reviews how to evaluate users’ experiences, including case studies. The second considers multimodal interfaces and how to integrate them seamlessly and effectively in a multimodal environment. This issue is further explored in Chap. 17. The third chapter of Part describes newer, broader applications of BCI technology to improve human–computer interaction. The next two chapters show how phase detection and dry sensors could improve performance and usability.

In Chap. 11, van de Laar and colleagues discuss some issues that are emerging as BCI research draws on issues from the broader HCI community. They note that usability is a critical factor in adopting new technologies, which underscores the importance of evaluating user experience (UX). They review work showing that UX and BCIs both affect each other, including the methods used to evaluate UX such as observation, physiological measurement, interviews, and questionnaires. The authors use two different case studies as exercises in identifying and applying the correct UX evaluation methods. The chapter provides a strong argument that UX evaluation should be more common in BCI research.

As BCIs are put into service in real world, high-end applications, they will become one element in a multi-modal, multi-task environment. This brings with it new issues and problems that have not been prevalent in single task controlled environment BCI applications. In Chap. 12, we see what these possible problems may be and are presented with guidelines on how to manage this in a multi-modal environment. These issues are later explored in the fourth section of this book.

Another consequence of advanced BCI applications is the potential for enhanced user interfaces based on brain state. In this scenario, the current state of the user provides context to system in order to improve the user experience. These states may include alertness, concentration, emotion or stress. Chapter 13 introduces two application areas, medical and entertainment, based on recognition of emotion and concentration.

Steady-state-visual-evoked potential (SSVEP; [24]) are frequently used as control signals for BCIs. However, there is a practical limitation in the high frequency range (>30 Hz), because only a few frequencies can be used for BCI purposes.

Garcia-Molina and co-authors show in Chap. 14 how repetitive visual stimuli, with the same frequency but different phases, can be used as control signals.

The last chapter of this section addresses a recurrent problem in the area of BCI research, which is practical EEG recording. A limiting factor in the widespread application is the usage of abrasive gel and conductive paste to mount EEG electrodes, which is a technology that has not changed much in the last 20 years. Therefore, many research groups are now working on the practical usability of dry electrodes to completely avoid the usage of electrode gel. In Chap. 15, Edlinger and colleagues compare dry versus wet electrodes. Raw EEG data, power spectra, the time course of evoked potentials, ERD/ERS values and BCI accuracy are compared for three BCI setups based on P300, SMR and SSVEP BCIs.

1.2.4 Overview of Part

The previous sections each discussed different BCI components. This concluding section takes a step back by broadening the focus to complete BCI systems. Which software platforms are available to integrate different BCI components? What are the best ways to evaluate BCIs? What are the best ways to combine BCIs with other systems? Are any non-visual BCIs available? These important questions cannot be easily addressed without considering all the components of a BCI holistically.

The development of flexible, usable software that works for non-experts has often been underappreciated in BCI research, and is a critical element of a working BCI infrastructure [1, 2, 10]. In Chap. 16, Brunner and numerous co-authors describe the major software platforms that are used in BCI research. The lead developers of seven different publicly available platforms were asked to contribute a summary of their platform. The summaries describe technical issues such as supported devices and programming languages as well as general issues such as licensing and the intended user groups. The authors conclude that each platform has unique benefits, and therefore, tools that could help combine specific features of different programs (such as the TOBI Common Implementation Platform) should be further developed.

As BCIs gain attention, the pressure to report new records increases. In 2011 alone, three different journal papers, each from different institutions, claimed to have the fastest BCI [4, 5, 28]. Similarly, the influx of new groups includes some people who are not familiar with the methods used by established researchers to measure BCI performance and avoid errors. These two factors underscore the importance of developing, disseminating, and using guidelines. Chapter 17 reviews different methods to measure performance, account for errors, test significance and hypotheses, etc. Billinger and colleagues identify specific mistakes to avoid, such as estimating accuracy based on insufficient data, using the wrong statistical test in certain situations, or reporting the speed of a BCI without considering the delays between trials. We note that accuracy and information transfer rate are not at all the only ways to evaluate BCIs, and authors should report other factors too.

This book, like many emerging BCI publications [3, 14, 15, 21, 22, 25], has many references to hybrid BCIs. In Chap. 18, Müller-Putz and colleagues review the different types of hybrid BCIs. Hybrid BCIs combine different ways to send information, and so they are often categorized according to the types of signal combinations they use. While one signal must be a BCI, the other signal could also involve EEG, or heart rate, eye movement, a keyboard or joystick, etc. Different sections discuss the different types of BCIs, including technical details and examples of relevant papers. We conclude that BCIs could help people in different ways, and that most BCIs will be hybrid BCIs.

Most BCIs require vision. BCIs based on the brain's response to flashing or oscillating lights require lights, and even BCIs based on imagined movement usually require visual cues, such as observing a robot or cursor movement. But what if the user has trouble seeing, or wants to look somewhere else? Chapter 19 reviews non-visual and multisensory BCIs that could work for users with visual deficits. In addition, non-visual BCIs allow alternative communication pathways for healthy people who prefer to keep their vision focused elsewhere, such as drivers or gamers. Finally, emerging research shows the benefits of multisensory over unisensory cues in BCI systems. Wagner and colleagues review four categories of noninvasive BCI paradigms that have employed non-visual stimuli: P300 evoked potentials, steady-state evoked potentials, slow cortical potentials, and other mental tasks. After comparing visual and non-visual BCIs, different pros and cons for existing and future multisensory BCI are discussed. Next, they describe multimodal BCIs that combine different modalities. The authors expect that more multisensory BCI systems will emerge, and hence effective integration of different sensory cues is important in hybrid BCI design.

Chapter 20 returns to the general issue of evaluating BCIs, but from a different perspective. Randolph and colleagues first review major factors in BCI adoption. They then present the BioGauges method and toolkit, which has been developed and validated extensively over the years. Drawing on their earlier experience categorizing different facets of BCIs and other assistive technologies, they parametrically address which factors are important and how they are addressed through BioGauges. They review how these principles have been used to characterize control with different transducers—not just conventional EEG BCIs but also fNIRS BCI and communication systems based on skin conductance. The authors' overall goal is to help match the right BCI to each user, and BioGauges could make this process much faster and more effective.

1.3 Predictions and Recommendations

BCI research does have an air of mystery about it. Indeed, BCI research and development depends on a wide variety of factors that can make predictions and recommendations difficult. Nonetheless, we recently completed a roadmap that includes our expectations and recommendations for BCI research over the next

5 years. This roadmap, like this book, entailed extensive collaboration with other stakeholders in the BCI community and surrounding fields. Over more than 2 years, we hosted workshops, gave talks, scheduled meetings, send emails, and otherwise engaged people to learn their views about what is, and should be, next.

This roadmap was developed during the same time period as this book, and involves many of the same people. However, the book and roadmap were separate projects, addressing different topics and goals, without any effort to synchronize them. Thus, it is somewhat gratifying to note that the major issues that our chapter authors addressed generally aligned with the issues we considered important in the roadmap. This roadmap is publicly available from http://www.future-bnci.org/. Our predictions for the next 5 years are summarized across the top ten challenges that we identified within BCI research. The first two of these challenges, reliability and proficiency, are presented jointly because our expectation is that these issues will increasingly overlap in the near future.

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 5 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 5 years.

Support: Expectations are mixed. Various developments will reduce the need for expert help. In 5 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 5 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 5 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.

In addition to our 5 year view, we also developed recommendations for the next 5 years. These are directed mainly at decision-makers who will decide on funding BCI research and development, such as government officials or corporate decision-makers. However, they also can and should also influence individual developers and groups trying to decide where to focus their time and energy in the near future. Our recommendations are:

- Encourage new sensors that are comfortable and easy to set up, provide good signal quality, work in real-world 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.
- Research 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.

1.4 Summary

All BCIs require different components. This book discusses these components, as well as issues relating to complete BCI systems. In the last few years, BCIs have gained attention for new user groups, including healthy users. Thus, developing practical BCIs that work in the real-world is gaining importance. The next 5 years should see at least modest progress across different challenges for BCI research.

One of the most prevalent themes in BCI research is practicality. Perhaps 10 years ago, simply getting any BCI to work in a laboratory was an impressive feat. Today, the focus is much more on developing practical, reliable, usable systems that provide each user with the desired functionality in any environment with minimal inconvenience. While there was always some interest in making BCIs practical, this has become much more prevalent in recent years.

However, as BCI research and development gains attention, it also develops new challenges. Newcomers to BCI research may bring promising ideas and technologies, but may also bring different expectations and methods that might not be well suited to BCI research. The influx of new people also broadens the definition of "BCI" and may create new possibilities that are difficult to analyze and predict.

These factors underscore why the future is both promising and unpredictable. Some predictions seem reasonably safe. For example, we think that BCIs will be combined with new systems more often, leading to hybrid BCIs and intelligent systems that incorporate context and ambient intelligence. We are also optimistic about dry electrodes and improved usability. On the other hand, some emerging BCI systems, such as neuromodulation systems, could go in many different directions. Perhaps the safest prediction of all is that the next 5 years will be exciting and dynamic, with significant changes in BCIs and especially in how they are marketed, perceived, and used.

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