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Brain-Computer Interfaces in Their Ethical, Social and Cultural Contexts

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Contents

Chapter 1
Introduction

Gerd Grübler and Elisabeth Hildt

Seeing for the first time somebody wearing a strange cap and being connected via multiple cables to a computer and obviously giving instructions to a technical device without moving even a finger is probably impressive for almost everybody. One could easily become convinced that a 'mind-reading machine' is at work here and that the idea that the thoughts of human beings might be 'seen' from outside has now finally come true: Just by using – what else?! – a computer. That thinking is the core human faculty and thus the prime human way of doing something is in line with at least some of the most important European traditions in philosophy and religion. If the brain–computer interface (BCI) was a way to shortcut theory and practice, to take away the persistent dialectic between these two poles of human existence, they would without doubt be the most philosophical devices ever. However, learning more about BCIs makes things different. Understanding that current BCIs use only 'dull' signals without any semantic content leads to a disappointment – measured by the dramatic mind-reading impression one had before – but this is a necessary disappointment. While an unrealistic understanding of BCIs raises many of the most spectacular questions in ethics and metaphysics, the real existing BCIs render them inadequate and require rather sober and detailed work in applied ethics and philosophical anthropology.

While for the engineers the most urgent issue at the moment is to bring BCIs from the lab into everyday life and to make them robust enough to be set up by laypersons, physicians are probably most concerned whether BCI technology, given its proper functioning, really has the therapeutic and diagnostic potential commonly attributed to it. Societal questions, depending in their urgency from the

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results engineers and physicians might or might not achieve in the nearer future, arise concerning the imagined widespread use of BCI technology. Ethical questions have their focus on the immediate risk BCI use and/or research might bring for the involved people, although it is not the physical risk for the user that is in the center of interest for the majority of the (non-invasive) applications nowadays. General philosophical questions in the context of BCI revolve around agency, the personal bases of responsibility, and the changing of self-awareness in long-term intense BCI use. All these issues seem to be mutually dependent on each other and might contribute to the success or failure of BCI technology as a technological paradigm for man–machine interaction.

Thus, what is needed in order to achieve a realistic view of the current and future uses, opportunities, and risks of BCI technology is an interdisciplinary debate on the scientific, medical, anthropological, philosophical, ethical, and societal aspects of BCIs. To contribute to such an interdisciplinary discussion, we here present a book that based on a detailed description of the various current BCI applications in medicine, rehabilitation, and assistive technology focuses on the non-technical implications and impacts BCIs have and might have in the future. In this book, BCI experts give an introduction to their respective field of work, BCI users and stakeholders share their experiences, hopes, and criticisms, and philosophers and authors from the humanities reflect on current and prospective BCI use and development.

In Part I, three teams of experts give an overview of different ways of using BCIs. They offer an introduction to the most common fields of medical use for BCIs nowadays and explain the principles, achievements, and limits of this technology. In Chap. 2 Rüdiger Rupp and colleagues focus on assistive technology that can be used by people with severely restricted motor abilities. They introduce basic paradigms for BCIs and show how BCIs can be combined with other input modalities. Applications for communication, grasping and reaching, and assisted mobility are described and explained. In Chap. 3 Camille Chatelle and colleagues survey the current attempts to apply BCIs to the refinement of diagnosis in patients suffering from different sorts of disorders of consciousness. They point to astonishing findings as for instance the (rare) possibility to communicate with comatose patients, but also stress emphatically the shortcomings of current approaches. Then, in Chap. 4 Donatella Mattia and Marco Molinari give an introduction to using BCIs as tools for rehabilitation. They look at several paradigms how to trigger brain plasticity and to develop it in line with therapeutic aims. On the basis of their experiences with stroke patients they report some promising study results and discuss ethical implications resulting from the application of rehabilitation strategies without having exact knowledge of the brain processes behind recovery.

In Part II, several protagonists of the BCI community present their respective perspective. Here, the chapters are not written by researchers in the first place, but rather by practitioners, businesspeople and, of course, the end users of BCI technology. Evert-Jan Hoogerwerf and colleagues, in Chap. 5, give an overview of principles, guidelines, and strategies for matching people with disabilities and the best-fitting assistive technology in individual cases. They show how the quality and usability of such devices might be assessed and apply this expertise to currently available BCI solutions. From that they derive a competent estimation of already given potentials and further requirements to work in the future. Sonja Kleih and Andrea Kübler focus in Chap. 6 on psychological aspects that might play a role in BCI use. They call to mind how important communication and social interaction is for the experienced quality of life of the most severely impaired persons and characterize the role BCI technology might play for them. Furthermore, they consider the importance of motivation for the successful use of BCIs and report on ways to boost motivation and to distinguish between different sources of motivation in motor-impaired users. In Chap. 7, Christoph Guger and colleagues present the perspective of the businessman. They show how trends in BCI research might turn into market opportunities, especially if technologies surpass the 'traditional' assistive applications for patients or impaired users and conquer the general consumer market. The focus goes from BCI-related devices already available commercially to promising perspectives for the nearer and farther future and to some prognostics concerning the opportunities and risks for companies engaged in the BCI market. That BCIs might also play their role in the field of fine arts is shown by Adi Hoesle, one of the pioneers of Brain Painting, in Chap. 8. He reports on his passion for BCIs and the development of a new aesthetic experience. The admittedly rather limited means of Brain Painting (slow interaction and only a few options to choose colors and shapes to be displayed) open up not only a particular 'minimal' style of artistic expression but also raise fundamental questions concerning the theory and very concept of art and the status of the material pieces or products thereof. Hoesle also alludes to current developments that extend the principles of BCI to other fields of creative human expression. Even more personal and private are the insights that Sonja Balmer shares with us in Chap. 9. Being a motor-impaired artist and campaigner for the rights of disabled people she describes how BCI technology stepped into her life and how important the – albeit modified – restoration of her ability to paint via BCI is for her life and general encouragement to live. In Chap. 10 the voices of people are depicted who have taken part in BCI research studies. Their answers to several questions concerning their motivations, their hopes, their particular experiences with BCIs and BCI research, and also their disappointments and critical comments are presented. Part II of the book concludes in Chap. 11 with a very personal sketch of the last years of a patient and user of BCI technology. The wife and son of this patient provide us with this short report.

Part III presents various chapters on the philosophical, societal, and anthropological implications of BCIs. We start with a tour of some brain/neuronal–machine interfaces guided by Kevin Warwick in Chap. 12. He systematizes several approaches of combining neuronal biological tissue with technically construed hardware. By doing so he describes implications of BCIs for the human technological co-evolution and the melting of biology and technology. In Chap. 13 Guglielmo Tamburrini provides several philosophical reflections and by doing so gives an overview of current 'BCI ethics'. He starts with the epistemological status of BCIs and the implications of that status for the autonomy of the users. Then he focuses on responsibility and liability in BCI use. He goes on to reflect on the concepts of consciousness and agency in the context of diagnostic applications of BCI devices and ends with the way people talk about BCI technology and the possible hidden motivations behind this. Fiachra O'Brolchain and Bert Gordijn in Chap. 14 focus on the difficulties in attributing responsibility for the use of BCIs. On the basis of our traditional understanding of moral responsibility they survey the respective discussion on BCIs and support several claims about changes in or even the impossibility of responsibility attribution when BCIs become more sophisticated and widespread. The last two chapters combine philosophical reflection with the interpretation of empirical insights. Gerd Grübler and Elisabeth Hildt in Chap. 15 start with a short sketch of positions radically enthusiastic about the human technological self-evolution and show how BCIs can be interpreted as illustrations of one central transhumanist idea: The overcoming of the biological body by technological means. The question whether this is possible at all leads to the question whether there are substantial or essential human features given or rather an unlimited openness to (re)create oneself. This question, then, is discussed in the light of the concept of transparent practice and interpreted based on insights from interviews with BCI research subjects. In Chap. 16 Rutger Vlek and colleagues present their reflections on the feeling and the judgment of agency in BCI users. They start from cases in which people not doing something are nevertheless convinced they are agents and cases in which agents who have done something are convinced they are not agents. Introducing two different experiments, they show how the sense of agency in BCI use can be influenced and ask what the consequences of such effects, for good or bad, might be.

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Gerd Grübler (Dresden) — Spring 2014 — Elisabeth Hildt (Mainz)

Part I
Applications

Chapter 2
Brain–Computer Interfaces and Assistive Technology

Rüdiger Rupp, Sonja C. Kleih, Robert Leeb, José del R. Millan, Andrea Kübler, and Gernot R. Müller-Putz

2.1 Introduction

During the last century technology has become an integral part of our modern society. It is hard to imagine life without having access to the internet, being able to communicate with people through mobile phones, or share personal experiences with friends all over the world in electronic social networking services. Traveling large distances with motorized vehicles like cars, trains or planes appears to be somehow normal in a globalized world. Technology in general helps to overcome the natural limitations of mankind and extend the physical capabilities of each human being. The limits of each individual person cannot be defined in general, but strongly depend on the physical capabilities of an individual and his or her environment. In the case of individuals with motor, sensory, or cognitive disabilities technology can be helpful in order to perform functions that might otherwise be difficult or impossible. In this case technology is called assistive technology (AT). The definition of assistive technology most frequently cited in the relevant literature first appeared in the US 'Technology-Related Assistance of Individuals

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with Disabilities Act of 1988' as "any item, piece of equipment, or product system, whether acquired commercially off the shelf, modified, or customized, that is used to increase, maintain, or improve functional capabilities of individuals with disabilities". This is the generally accepted definition of AT internationally. Assistive technologies are meant to help people in their primary functional tasks. Wheelchairs, scooters, walkers, and canes are assistive technologies for mobility; related products include lifts on vehicles and portable ramps. More people use assistive technologies related to mobility (6.4 million in Germany) than any other general type of assistive technology (Scherer 2002). But while AT for mobility is the largest single group of AT products, there are many others. As of April 2013, ABLEDATA (http://www.abledata.com), the AT product database sponsored by the Institute on Disability and Rehabilitation Research, US Department of Education, lists almost 40,000 assistive devices (ADs). Among them are electronic or environmental aids for daily living as well as technologies for personal care and household management, augmentative communication devices, technologies to compensate for motor or sensory (hearing, eyesight) loss, and hardware, software, and peripherals that assist people with disabilities in accessing computers or other information technologies.

The latter is most important for individuals with severe motor impairments as a consequence of trauma or disease. Among them are individuals with Amyotrophic Lateral Sclerosis (ALS), brainstem stroke survivors, or people with high spinal cord injury. ALS is a neurodegenerative disease of unknown etiology which is characterized by rapidly progressive paralysis leading within a few years after symptom onset to a locked-in state with the complete loss of limb movements, the ability to speak, and – in the most severe cases – even the loss of voluntary eye movements. The incidence of ALS in the European Union is about 2.16 per 100,000 persons per year (Logroscino et al. 2010).

Stroke is one of the most prevalent neurological conditions worldwide and one of the leading causes of motor impairment in the population (Warlow et al. 2008). In Europe every year 1.1 million first strokes occur, of which around 4 % are a brainstem stroke (Truelsen et al. 1997). Severe brainstem stroke leads to nearly complete or total paralysis with preserved cognitive functions, the so-called locked-in syndrome.

In Europe an estimated 330,000 people are suffering from a spinal cord injury (SCI) with 11,000 new injuries per year (Ouzký 2002; van den Berg et al. 2010). Forty percent of them are tetraplegic due to injuries of the cervical spinal cord with paralyses of the lower as well as the upper extremities. The bilateral loss of the grasp function severely limits the affected individuals' ability to live independently (Anderson 2004; Snoek et al. 2004) and retain gainful employment post injury (NSCISC 2011). Beside traditional ADs for daily living like adapted eating tools or tools for operating a keyboard, neuroprostheses based on Functional Electrical Stimulation (FES) are offered to individuals with tetraplegia for restoration of a completely lost or improvement of a weak grasping function (Rupp and Gerner 2007).

A survey among individuals with severe motor impairments revealed that the prioritized needs of these persons with high spinal cord injury, neurodegenerative diseases, or cerebrovascular disorders are “mobility” and “activities of daily living” (Zickler et al. 2009). The needs of participants who used communication aids were partially different from those of the rest of the participants. They wanted to improve their independence in personal expression and social interaction. Considering the adoption of a new AT solution, participants rated “functionality” as the most important aspect followed by “possibility of independent use” and “ease of use”. The study revealed dissatisfaction with their current ADs for communication (16 %) and manipulation (30 %). This shows that there is the need for better or/and alternative AT solutions in the area of manipulation, communication, environmental control, and entertainment.

For use of most of the existing ADs a substantial number of residual functions have to be preserved. As a consequence persons with the most severe impairments are not able to use these devices sufficiently. Even end-users who are basically able to use a certain AD may not be able to use it over an extended period of time due to mental and physical fatigue. Therefore, it is crucial that users have a choice of options and that healthcare and rehabilitation professionals make them available, since each individual will find that some of the available options are more productive and work better than others.

Brain–Computer Interfaces (BCIs) may serve as an alternative human–machine interface for the control of ADs. BCIs are technical systems that provide a direct connection between the human brain and a computer (Wolpaw et al. 2002). Such systems are able to detect thought-modulated changes in electrophysiological brain activity and transform such changes into control signals. Most of the BCI systems rely on brain signals that are recorded non-invasively by placing electrodes on the scalp (electroencephalogram, EEG). A BCI system consists of four sequential components: (1) signal acquisition, (2) feature extraction, (3) feature translation, and (4) classification output, which interfaces to ADs. These components are controlled by an operating protocol that defines the onset and timing of operation, the details of signal processing, the nature of the device commands, and the oversight of performance (Shih et al. 2012). At present, EEG-based BCI systems can function in most environments with relatively inexpensive equipment and thus offer the possibility for practical BCIs in the field of AT. BCIs may provide an additional control channel and may serve as a valuable adjunct to traditional user interfaces.

This chapter will be devoted to providing an overview of the state of the art of non-invasive BCIs for the control of electronic devices for communication and computer access, electronic mobility aids like wheelchairs or mobile telepresence robots, and upper extremity neuroprostheses for the restoration of grasping and reaching.

2.2 BCIs for Communication

BCI research in the field of communication started with the idea of supporting severely disabled people. The loss of speech and therefore the possibility to communicate thoughts and needs tremendously affects a person's well-being and quality of life (Ganzini et al. 1999; Veldink et al. 2002). The first time a BCI was successfully used for communication was in 1988 (Farwell and Donchin 1988). With this spelling system words could be composed letter by letter, which were arranged in rows and columns (for a matrix example see Fig. 2.1).

One letter was chosen by implementing an oddball paradigm (Sutton et al. 1965). Rows and columns were highlighted randomly while the user was focusing on one specific letter (target letter) he or she wished to spell and tried to ignore all other letters that were highlighted in other rows or columns (non-target letters). Each time the target letter was highlighted, a P300 signal occurred. The P300 is a positive deflection in the EEG occurring 300 ms after stimulus onset and is a reliable, easy to detect event-related potential (Fig. 2.2). As one letter in the matrix is located on one exact position of one row and one column (for example the B in Fig. 2.1 is located at the cross section of the first row and the second column), each target letter can be identified by a classifier, which recognizes the largest amplitudes for rows and columns and selects the letter accordingly. Most BCI communication paradigms were later on based on this paradigm and successfully used for communication in unimpaired subjects and patients with severe motor impairments (Hoffmann et al. 2008; Nijboer et al. 2008; Guger et al. 2009; Kleih et al. 2010; Kaufmann et al. 2011). However, other brain signals were also used for the setup of a BCI. The first ever long-term independent use of a BCI was shown in a locked-in patient communicating by the regulation of slow cortical potentials (Birbaumer et al. 1999). Slow cortical potentials (SCP) represent shifts of the depolarization level of apical dendrites in cortical layers I and II and develop slowly after stimulus onset. The locked-in patient wrote the first communicated messages with such an SCP BCI system and used it for several years for independent communication at his home (Birbaumer et al. 1999). He wrote messages, for example to his caregivers, with the so-called 'Thought Translation Device' (Birbaumer et al. 1999) and also extensively used NESSI, an SCP-controlled browser for the world wide web (Bensch et al. 2007).

2.2.1 Visual P300 Paradigms

Nowadays, researchers mostly work with the P300 signal for communication purposes because its signal characteristics (relatively easy to elicit, short delay after stimulus onset) allow for faster spelling compared to SCP-based systems. Additionally, the P300 signal is very robust. ALS patients used a P300-based BCI with 36 choices (letters and numbers) for more than 40 weeks and no decrease in

Fig. 2.1 Example of a P300 Speller matrix. Letters of the alphabet are arranged in rows and columns as are numbers and additional punctuation marks

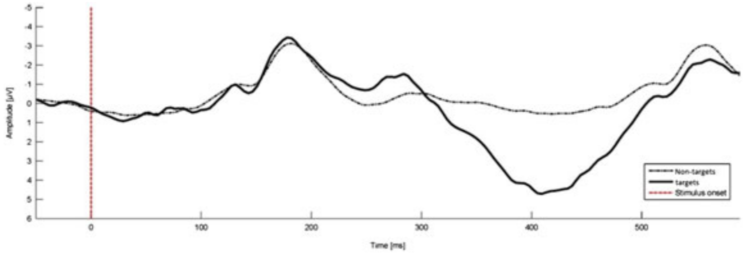

Fig. 2.2 Example of a P300. Activation (μVolt) is plotted against time (ms). Approximately 400 ms after the stimulus (*vertical line*) the amplitude of the P300 deflection is highest for the target stimuli (*bold curve*) while for non-target stimuli (*dotted curve*) no deflection can be observed

accuracy (constantly around 80 %) was found (Nijboer et al. 2008). Similarly, in an ongoing study, an ALS patient in the locked-in state has been using a P300-controlled BCI for 1 year for painting (see below) and neither a decrease in speed or accuracy nor an attenuation of the P300 amplitude has been observed (Holz et al. 2011). Numerous other clinical studies confirm the efficacy of the P300-BCI in paralyzed patients with four choice responses, such as "Yes/No/Pass/End" (Sellers and Donchin 2006) or "Up/Down/Left/Right", for cursor movement (Piccione et al. 2006; Silvoni et al. 2009).

In a recent study a new paradigm was introduced for the enhancement of the P300 control (Kaufmann et al. 2012). The authors superimposed a famous face on top of the matrix display, in this case the face of Albert Einstein. Every time the target letter was highlighted, not only was an increased P300 signal detected, but the recognition of the famous face also elicited the N170 (Bentin et al. 1996; Eimer 2000) and N400 (Eimer 2000) evoked potentials. Using all three evoked potentials improved the signal-to-noise ratio tremendously, thus allowing for a highly accurate classification and a more reliable selection of letters. This approach enabled for the first time two severely motor-impaired end-users, who were unsuccessful with the regular P300 speller, to spell with 100 % accuracy. Additionally, only one single sequence was needed, i.e. the target letter was highlighted only once in the row and once in the column before the letter was correctly selected (Kaufmann et al. 2012).

However, no completely locked-in patient has so far been successfully and reliably able to use a BCI system for communication. When a patient is in the complete locked-in state (CLIS), she or he completely loses control over any voluntary muscle activation including eye movements (Hayashi and Kato 1989; Murguialday et al. 2011). Therefore, the non-visual channels seem to be the only possible way to establish communication in individuals in CLIS, and tactile (Kaufmann et al. 2012) as well as several auditory BCI approaches have been investigated.

2.2.2 Auditory and Tactile Paradigms

Auditory BCIs allowing for a binary choice were recently introduced (Halder et al. 2010; Hill et al. 2012). In these systems a 'Yes' or 'No' decision could be detected by the system, therefore guaranteeing at least the most basic communication of approval or refusal, albeit tested in unimpaired volunteers only. The advantage of binary choice paradigms is that even users who are unable to focus on complex visual matrices are in principle able to use such a system. In those end-users it is better to present stimuli in a dichotic listening task, in which attention has to be focused on one of two streams of information (Hill et al. 2012; Pokorny et al. in press), rather than in a sequential order (Halder et al. 2010).

For more complex spelling applications, with which whole messages can be conveyed, the sequential presentation seems to be more advantageous (Furdea et al. 2009; Höhne et al. 2011; Schreuder et al. 2011). The user's intention can be derived from the brain response more directly compared to a binary choice paradigm, in which several subsequent choices would be necessary to narrow down the target and to finally identify the target letter. One recently investigated approach for complex auditory BCI systems included spatial information. Six speakers were equally distributed around a user in a circle (Schreuder et al. 2011). By focusing attention on one of the speakers a group of letters can be selected. Each of the letters in this group is subsequently allocated to one speaker position. Therefore, it only needs two steps to finally select the desired letter. This paradigm is the auditory complement of the Hex-o-Spell paradigm for the visual modality (Blankertz et al. 2006). Of 21 unimpaired subjects testing the Hex-o-Spell auditory paradigm, 16 were able to spell a full sentence with at least 26 characters. In an extended approach (Höhne et al. 2011), the spatial information was provided by headphones and therefore facilitated the setup. A user chose one of nine groups of letters by focusing on one of three tones differing in frequency, presented on the left, the right, or both ears. There were nine groups of letters, similar to the grouping on mobile phones. After the detection of the selected letter group, again the user had to focus on one of the presented tones and thereby could select a single letter. In ten unimpaired subjects an accuracy of 77 % was achieved when spelling a 36-character sentence. However, again, this paradigm has not yet been tested with severely motor-impaired patients and thus it remains open whether this approach is feasible and effective in a clinical setting (Zickler et al. 2011).

The first tactile two-class BCI interface based on attention-modulated steady-state somatosensory evoked potentials (SSSEPs) was reported earlier (Müller-Putz et al. 2006). The index fingers of both hands were simultaneously mechanically stimulated in the "resonance"-like frequency range of the somatosensory nervous system. Four unimpaired subjects were trained to modulate their SSSEPs by focusing attention on one of their index fingers. Classification accuracies of up to 80 % were achieved using only three bipolar EEG-channels covering the primary somatosensory cortex.

In summary, there are several promising paradigms in BCI research that hold the potential to enhance the communication skills of severely motor-impaired end-users. For a first proof of principle it is enough to test these paradigms in unimpaired subjects. However, if sufficient performance is obtained in unimpaired subjects this may not directly apply to applications with motor-impaired end-users. In a single case study the best possible strategy was investigated to enable communication in an end-user diagnosed with locked-in syndrome (Kaufmann et al. 2013). In this person a clearly distinguishable P300 response elicited by a visual oddball paradigm was found, but communication with the visual speller matrix could not be established. However, the tactile P300 response was most prominent and most successful for classification. Following a user-centered approach (Zickler et al. 2011), tactile input will be used in this end-user for the setup of a P300-based communication device.

2.2.3 Alternative Implementations of BCI-Controlled Communication

So far this subchapter focused on communication in its purest sense as one major goal in BCI research and one major contribution to include severely motor-impaired people in social interaction. However, there are also extended applications of BCI-based inclusion which are (1) access to the internet and (2) a different form of communication, which is painting.

It was successfully shown that ALS patients could browse the internet using an application that was based on the P300 Speller matrix (Mugler et al. 2010). In this application, two screens were needed, one for the internet page display and one for a regular spelling matrix. By coding each link on the webpage with one letter or sign of the spelling matrix, a user could mimic a click on a link by focusing on the target sign. Using this method, all three ALS patients ordered a book on an online vending store without help from their family or caregivers. Furthermore, it has been shown that BCI-controlled e-mailing and internet surfing could be realized by combining a

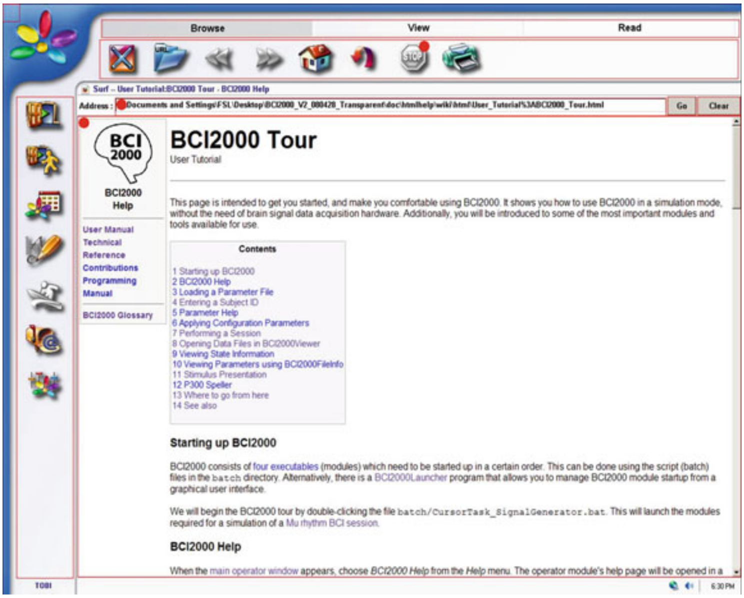

Fig. 2.3 Connection of the commercially available software QualiWorld (QualiLife SA, Paradiso, Switzerland) and the P300 BCI. Instead of letters, *red dots* are being flashed, indicating the link on the screen to be chosen

BCI with commercially available assistive technology (Fig. 2.3; Holz et al. 2011; Riccio et al. 2011; Zickler et al. 2011).

Another P300-based application is Brain Painting (Munssinger et al. 2010). The P300 matrix was adopted so that instead of letters, painting commands could be selected from the flashing matrix (Fig. 2.4).

For example, shapes such as rectangles or circles could be chosen and when selecting a color, the 'object' was transferred onto a 'canvas' on a separate screen. By zooming into the canvas, blurring objects, and playing with color, astonishing paintings were created (Fig. 2.5) by end-users in the locked-in state. Most recently, an exhibition was launched in Rostock, Germany, in which an ALS patient used Brain Painting on site.[1] In conclusion, with this fascinating application an entertaining and highly satisfactory way of inclusion has been established by the use of BCI technology. One locked-in patient, named HHEM, is using Brain Painting daily, as she used to be a painter before being diagnosed with ALS (Holz et al. 2013).

In summary, in the preceding paragraphs we presented promising BCI paradigms and applications that have been successfully used as communication tools by end-users with severe motor impairments. All of them are meant to support

[1] http://www.rostock-heute.de/brain-painting-kunsthalle-rostock-adie-hoesle/41228. Accessed 24 April 2013.

Fig. 2.4 The P300 Brain Painting matrix with commands for colors, size, zooming, blurring, etc

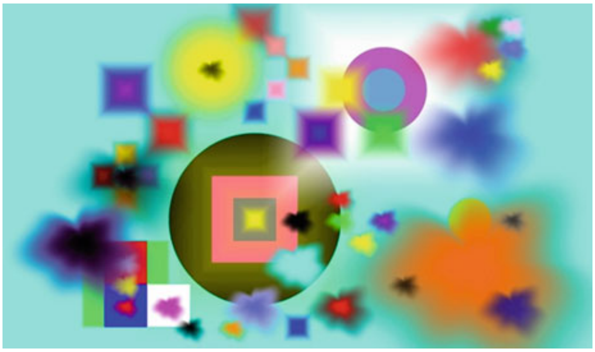

Fig. 2.5 The Brain Painting picture “The Moths’ Revenge” by the artist and ALS patient HHEM

end-users to express their needs and wishes in their own words, to interact and communicate with their environment independently, or to allow them creative expression. Several end-users stated how important it is for them to contribute to the development of communication systems for end-users in need. Although at its current state they would not consider BCI as an option for communication and interaction in daily life, patients are highly satisfied and even happy about contributing to BCI research which could help future potential end-users. One end-user’s quote may suffice to illustrate this attitude: “The participation in this research truly is the one and only thing that I can now do that I could not have done without being diagnosed with ALS”.

2.3 Hybrid BCIs

A novel development in BCI research is the introduction of the hybrid BCI concept (Müller-Putz et al. 2011). A hybrid BCI (hBCI) consists of a combination of several BCIs or a BCI with other input devices (Allison et al. 2012). These input devices may be based on the registration of other biosignals than brain signals e.g. electromyographic activities. Using this approach a single command signal can be generated either by fusion of different input signals or by simply selecting one of them. In the latter case the input signals can be dynamically routed based on their reliability, i.e. continuously monitoring the quality, and the input channel with the most stable signal will then be selected (Kreilinger et al. 2011). In the case of signal fusion each of the input signals contributes with a dedicated weighting factor to the overall command signal (Leeb et al. 2011). These factors are in general not static, but can be dynamically adjusted according to their reliability, which is quantified by appropriate quality measures. The hBCI is fully compliant with the user-centered design concept (ISO 2010). The key message of this approach is that the technology has to be adapted to the individual users' abilities and needs and not vice versa. By combining BCIs with established control devices more end-users may gain access to assistive technologies in general or the use of existing assistive devices may be simplified in certain applications.

2.3.1 BCIs as an Additional Input Channel

A concrete example of an hBCI is the control of a computer by the combination of an EEG-based brain switch and a mouth-controlled joystick namely the IntegraMouse® (LIFEtool Solutions GmbH, Linz, Austria). The IntegraMouse measures the direction of force applied to a stick put in the mouth in two dimensions and moves the cursor on a screen in this direction accordingly. It is intended to be used by individuals with high SCI, who still can control their head movements and are able to produce a change in air pressure in the sense of a suck-and-puff control for simulating a mouse-click. However, this user group has restrictions concerning the breathing volume due to the paralysis of muscles contributing to lung inflation or – even worse – may be ventilator-dependent. Therefore, it is hard or even impossible for end-users to generate relevant air pressure changes voluntarily and thereby produce a mouse-click. It has been shown that a one-channel BCI can reliably detect short imaginations of movements, which can be used for setting up a simple brain switch (Müller-Putz et al. 2010) substituting the mouse-click functionality of the IntegraMouse®. Unimpaired subjects were able to use this hBCI to control the mouse cursor on a screen with minimal movements of the head and selecting files or programs with the use of the brain switch (Clauzel et al. 2012).

2.3.2 BCIs as an Alternative Input Channel

Another way of using an hBCI is to provide an alternative input channel in the case of degrading reliability of input channels. This can happen either due to mental fatigue or stress (BCI) or due to muscular fatigue or spasticity (traditional user interface). A key prerequisite for using the BCI in such a setup is the implementation of measures that allow for continuous quantification of the reliability of each input channel and automatically switch between them. It was shown in a first implementation of the hBCI that unimpaired users could move a car in a game-like feedback application to collect coins and avoid obstacles either via a manual joystick or BCI control (Kreilinger et al. 2011). The outputs of both input devices were constantly monitored with four different long-term quality measures to evaluate the current state of the signals. As soon as the quality dropped below a certain threshold, a monitoring system would switch to the other control mode and vice versa. Additionally, short-term quality measures were applied to check for strong artifacts that could render voluntary control impossible. These measures were used to prohibit actions carried out during times when highly uncertain signals were recorded. The switching possibility allowed more functionality for the users. Moving the car was still possible even in a condition in which one control source did not work at all (Kreilinger et al. 2011).

2.3.3 Fusion of Multiple Input Channels

Apart from simply switching between multiple input signals, continuous fusion of at least two signal sources is also a promising method of setting up an hBCI. The basic idea behind the fusion approach is to improve the reliability and accuracy of the hBCI output(s) by dynamic weighting of the input signals based on their influence on the overall classification result. By using this approach an overall signal quality better than the quality of each of the single input signals could ideally be achieved.

A first practical implementation is based on the fusion of brain (EEG) and muscular (EMG) signals into one control signal (Leeb et al. 2011). The results obtained in unimpaired participants show that a good level of hBCI control could be achieved independently from the level of muscular fatigue. The multimodal fusion approach of muscular and brain activity yielded better and more stable performance compared to the single conditions. In a second experiment muscular fatigue was simulated by reducing the amplitude of the EMG-signals to 10 % and thereby decreasing the signal-to-noise ratio. Even in this case a good control, i.e. moderate and graceful degradation of the performance compared to the non-fatigued case, and a smooth handover could be achieved. This means that in a real-world scenario an end-user would rely exclusively on muscular control in the beginning and with increasing physical and muscular fatigue the BCI progressively takes over. Vice versa, if the EEG contains a lot of noise or if the end-user becomes mentally fatigued the weight of the muscular channels is increased. Therefore, such systems allow the users a constantly reliable hBCI control although they are becoming more exhausted or fatigued during the day.

2.4 BCIs for Grasping and Reaching

One type of EEG-based BCI exploits the modulation of sensorimotor rhythms (SMRs). These rhythms are oscillations in the EEG occurring in the alpha (8–12 Hz) and beta (18–26 Hz) bands and can be recorded over the sensorimotor areas on the scalp between the ears. Their amplitude typically decreases during actual movement and similarly during mental rehearsal of movements (motor imagery; MI) (Pfurtscheller and Lopes da Silva 1999; Neuper et al. 2005). Several studies have shown that people can learn to modulate the SMR amplitude by practicing MIs of simple movements, such as hand/foot movements, to control output devices (Pineda et al. 2003; Cincotti et al. 2008). This process occurs in a closed loop, meaning that the system recognizes the SMR amplitude changes evoked by MI and these changes are instantaneously fed back to the user. This neuro-feedback procedure and mutual man–machine adaptation enables BCI users to control their SMR activity and thereby the complete system.

With MI-BCIs the detection of an intended movement based on brain signals is possible. Thus, they are an exciting option for control of neuroprostheses based on Functional Electrical Stimulation (FES) for restoring permanent lost hand and arm functions after cervical SCI.

2.4.1 Grasp Neuroprostheses

Today, the only possibility of restoring permanently restricted or lost functions to a certain extent in the case of missing surgical options (Hentz and Leclercq 2002) is the application of FES. Over the last 20 years FES systems with different levels of complexity have been developed and some of them introduced into the clinical environment (Popovic et al. 2002). These systems deliver short current impulses eliciting physiological action potentials on the efferent nerves, which cause contractions of the innervated yet paralyzed muscles of the hand and the forearm (van den Honert and Mortimer 1979). On this basis FES artificially compensates for the loss of voluntary muscle control. In individuals with a chronic SCI a profound disuse atrophy of the paralyzed muscles occurs, which leads to a severely decreased fatigue resistance and capability for force generation. This atrophy can be reversed by a low-frequency FES training even many years after the SCI. The time needed for achieving a meaningful fatigue resistance and force is dependent on the individual status of the muscles and ranges from weeks to months (Gordon and Mao 1994).

When using the FES in a compensatory setup the easiest way of improving a weak or lost grasp function is the application of multiple surface electrodes. Generally, the major advantage of non-invasive systems is that they can be offered to patients for temporary application also at a very early stage of primary

Fig. 2.6 Three states of the sequence of the lateral grasp pattern. Subfigures (**a–c**) show the hand fully open, fingers closed with an extended thumb, and the full lateral pinch

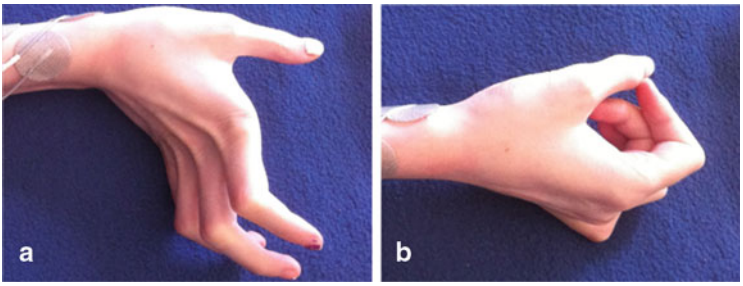

Fig. 2.7 Two states of the palmar grasp pattern. Subfigure (**a**) shows the hand fully open and (**b**) the hand fully closed with the thumb touching the tip of the index finger

rehabilitation, during which the electrode setup has to be adapted to the neurological status due to spontaneous recovery.

With only seven surface electrodes placed on the forearm two grasp patterns, namely lateral grasp and palmar grasp, can be restored (Rupp et al. 2012). The lateral grasp pattern provides the ability of picking up flat objects between the flexed fingers and the flexing thumb (Fig. 2.6) and with the palmar grasp pattern, where the thumb is positioned in opposition to the index finger (Fig. 2.7), larger objects can be handled. With the combination of surface electrodes and a finger synchronizing orthosis the difficulties with daily reproduction of movements and huge variations of grasp patterns depending on wrist rotation angle can be overcome (Leeb et al. 2010). Nevertheless, the disadvantages of the limited excitability of deeper muscle groups and pain sensations persist. Additionally, patients describe the placement of the electrodes as complicated (Kilgore et al. 2001). Since surface electrodes tend to drop off over time an adjunct fixation mechanism in the form of a sleeve or an orthosis is needed, which users often rate as uncomfortable or not cosmetically acceptable.

Since these are relevant limitations when using the systems in everyday life, implantable neuroprostheses for the permanent restoration of motor functions have been developed. Implantable devices include the BION (Loeb and Davoodi 2005), a small single-channel microstimulator that is injectable through a cannula, a stimulus router system (Gan and Prochazka 2010) – an implantable electrode that picks up the current from surface electrodes – a multichannel implantable stimulator (Smith et al. 1987), and a modular networked and wirelessly controlled system for stimulation and sensing (Wheeler and Peckham 2009). Implantable systems inherently bear the risk of infections and risks associated to the surgery. Complex revision surgeries are necessary in the event of a failure of any implanted component. Though it has been shown that these events occur rather rarely (Kilgore et al. 2003), it has to be clearly communicated to patients who decide to receive an implant.

One of the implantable grasp neuroprostheses – the Freehand system – achieved commercialization in 1997, and has been successfully used by over 300 C5/C6 individuals with SCI throughout the world and is therefore the most widespread implantable neuroprosthesis for the restoration of the grasp function (Keith and Hoyen 2002). Though the first systems have been operating for 15 years, its commercialization stopped in 2001 not for clinical but for financial reasons. Freehand users control hand grasp through operation of an external joint angle sensor controlled by movement of the opposing non-paralyzed shoulder, which through an implanted stimulator powered and controlled by radio frequency delivers electrical impulses to the hand muscles (Rupp and Gerner 2007). The results of a multi-center trial including 51 Freehand users quantitatively demonstrated its high level of functional efficacy (Peckham et al. 2001) and economic benefits (Creasey et al. 2000).

Despite all the technical progress made, it has to be clearly stated that the degree of functional restoration by the currently available neuroprostheses either based on surface or implantable electrodes is rather limited. Even with the most sophisticated systems the restoration of only one or two grasp patterns is possible, which does not include the independent activation of single fingers or joints (Wheeler and Peckham 2009). Additionally, the movements and forces generated by FES are less graduated when compared to the physiological condition. This is in particular the case when low forces for fine control are needed.

2.4.2 Hybrid Neuroprosthesis for Grasping and Reaching

Most of the current neuroprostheses for the upper extremity have only been used in individuals with SCI with preserved shoulder function and elbow flexion. Only a few experimental studies showed the feasibility of generating meaningful elbow movements with FES in very high spinal cord lesioned subjects (Crago et al. 1998). These systems have not been tested in real-world conditions during daily living, since a rapid muscle fatigue occurs due to the non-physiological, synchronous activation of paralyzed muscles by electrical stimulation. A major problem in FES-based restoration of movements is the occurrence of a combined lesion of the spinal fiber tracts and motoneurons in subjects with cervical SCI (Mulcahey et al. 1999; Dietz and Curt 2006). Stimulated denervated, flaccid muscles do not produce enough force to contribute effectively to any functional restoration (Kern et al. 2010). To overcome these limitations a so-called hybrid neuroprosthesis consisting of a combination of FES and an orthosis with actively driven or at least (de-)lockable joints is proposed. In general, an orthosis is a mechanical device that fits to a limb and corrects a pathological joint function. An actively driven orthosis supports the joints' movements with active drives such as an electrical motor or a pneumatic actuator. The disadvantages of these exoskeletons are their mechanical complexity, limited possibility for use in daily activities, and their need for a sufficient power supply (Schill et al. 2011). Therefore, these systems are mainly intended to be applied in users in which sufficient movements cannot be generated by FES. If sufficient joint movements can be generated by FES a more efficient solution is the application of an orthosis with a (de-)lockable joint. In its released state this joint allows for free movements and keeps a fixed joint position in the locked state. This helps to avoid fatigue of the stimulated muscles needed to maintain a stable joint position. Both types of FES-hybrid orthoses may lead to an expansion of the group of potential users of an upper extremity neuroprosthesis in the future.

At this point it has to be emphasized that the neurological status and functional capabilities of individuals with SCI even with the same level of injury vary to a large degree. As a consequence, an upper extremity neuroprosthesis necessarily has to consist of several modules that can be personalized according to the capabilities, needs, and priorities of an end-user. Though this fact is well known in the AT community, only a few technical solutions incorporate it (Rohm et al. 2011).

2.4.3 BCIs for Control of Neuroprostheses

Through the last decade it has become obvious that the user interfaces of all current FES devices are not optimal in the sense of natural control, relying on either the movement or the underlying muscle activation from a non-paralyzed body part to control the coordinated electrical stimulation of muscles in the paralyzed limb (Kilgore et al. 2008; Moss et al. 2011). In the case of individuals with a high, complete SCI and the associated severe disabilities not enough residual functions are preserved for control. This has been a major limitation in the development of a reaching neuroprosthesis for individuals with a loss not only of hand and finger but also of elbow and shoulder function.

Several BCI approaches mainly based on steady-state visual-evoked potentials (SSVEPs) have been introduced as a substitute for traditional control interfaces for the control of an abdominal FES system (Gollee et al. 2010), a wrist and hand orthosis (Ortner et al. 2011), or a hand and elbow prosthesis (Horki et al. 2010). Another exciting application is the use of a BCI to detect voluntary movement intentions in the presence of arm tremor for control of a compensatory FES (Rocon et al. 2010). Beyond these applications, BCIs have enormous implications providing natural control of a grasping and reaching neuroprosthesis control in particular in individuals with a high SCI by relying on volitional signals recorded from the brain directly involved in upper extremity movements.

In 2003 pioneering work showed for the first time that a MI-BCI control of a neuroprosthesis based on surface electrodes is feasible (Pfurtscheller et al. 2003a). In this single case study the restoration of a lateral grasp was achieved in a tetraplegic subject, who suffers from a chronic SCI with completely missing hand and finger function. The end-user was able to move through a predefined sequence of grasp phases by imaging foot movements detected by a brain-switch with 100 % accuracy. He reached this performance level already prior to the experiment after several years of training with the MI-BCI (Pfurtscheller et al. 2003b) and has maintained it for almost a decade by regular continuation of the training (Enzinger et al. 2008).

A second feasibility experiment was performed in which short-term BCI training was applied in another tetraplegic individual. This subject had been using a Freehand system for several years. After 3 days of training the end-user was able to control the grasp sequence of the implanted neuroprosthesis with a moderate, but sufficient performance (Müller-Putz et al. 2005).

In these first attempts the BCI was used more as a substitute for the traditional neuroprosthesis control interface than as an extension. With the introduction of FES-hybrid orthoses (Fig. 2.8c) it has become more and more important to increase the number of independent control signals. With the recent implementation of the hybrid BCI framework it became feasible to use a combination of input signals rather than BCI alone. In a first single case study a combination of an MI-BCI and an analog shoulder position sensor is proposed (Rohm et al. in press). With upward/downward movements of the shoulder the user can control the degree of elbow flexion/extension or of hand opening/closing. The routing of the analog signal from the shoulder position sensor to the control of the elbow or the hand and the access to a pause state is determined by a digital signal provided by the MI-BCI (Fig. 2.8a). With a short imagination of a hand movement the user switches from hand to elbow control or vice versa. A longer activation leads to a pause state with stimulation turned off or a reactivation of the system from the pause state (Fig. 2.8b). With this setup a highly paralyzed end-user, who had no preserved voluntary elbow, hand, and finger movements, was able to perform several activities of daily life, among them eating a pretzel stick, signing a document, and eating an ice cone (Fig. 2.9), which he was not able to perform without the neuroprosthesis.

Despite the tremendous progress that has been made in recent years there are still a lot of open issues that have to be addressed for a successful application of BCI-controlled neuroprostheses in tetraplegics. One of the major limitations of the human work is that the results were obtained either in unimpaired subjects or in selected users with SCI who already had a high BCI performance in the first screening session. This raises the question to which extent the published results can be generalized to a wider user population. To address this question the BCI performance of 15 end-users with complete SCI – eight paraplegic and seven tetraplegic – was assessed (Pfurtscheller et al. 2009). It was found that five of the paraplegic individuals had an initial accuracy above 70 % but only one tetraplegic

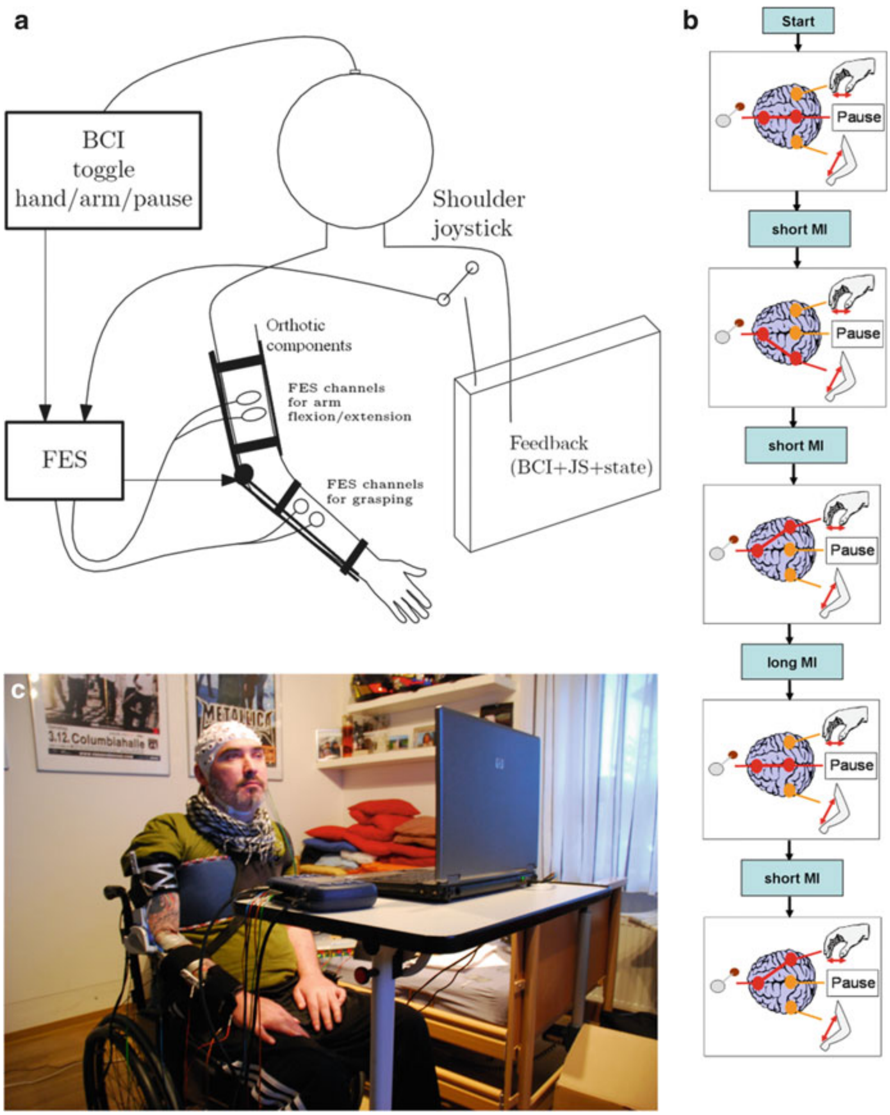

Fig. 2.8 Schematic overview of the setup of the hybrid-BCI-controlled hybrid arm neuroprosthesis (**a**, *top*), example flowchart of the hybrid control scheme integrating the shoulder joystick and the MI-BCI (**b**, *right*), and a photograph of an end-user with the complete system (**c**, *bottom*)

achieved this performance level. Though the reason for this is still unclear, it was found that movement-related β-band modulations, which are necessary for a good BCI performance, are significantly different in SCI compared to unimpaired individuals (Gourab and Schmit 2010). Though only a small number of subjects with

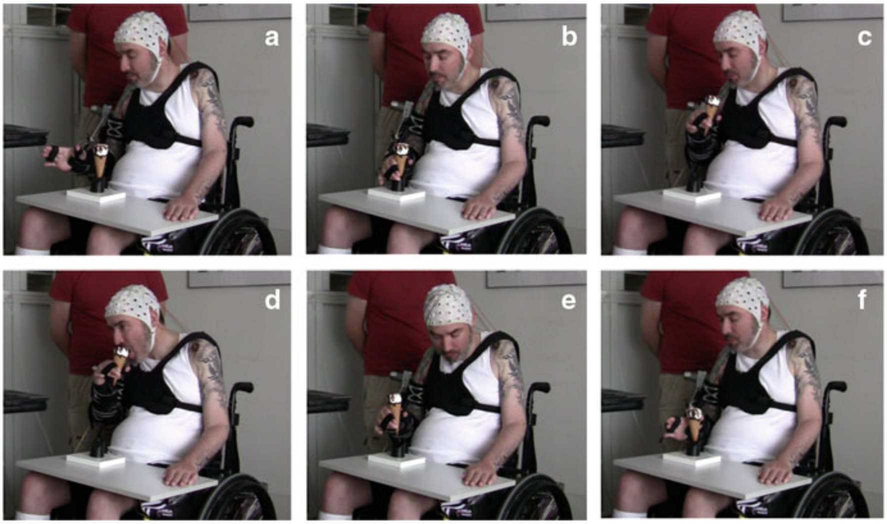

Fig. 2.9 Sequence of pictures showing the eating of an ice cone. The user starts in the hand control mode, lifts his left shoulder to open the right hand for grasping the ice cone (**a**). After successfully grasping the ice cone (**b**), the user emits a BCI command to switch from hand control to elbow control and lifts his shoulder to flex his elbow (**c**). Now, the user licks the ice (**d**). Finally, the user lowers his left shoulder to extend the elbow (**e**), he puts the cone in its original place and switches back to hand mode to release the cone (**f**)

SCI were involved in the study, the results indicate a correlation between the decreased amplitude during event-related synchronization (ERS) immediately following the movement attempt and the severity of the impairment of the lower extremities in which the movement was attempted.

In general, the performance of a non-invasive BCI as a neuroprosthesis control interface is rather low compared to traditional control interfaces based on either the movement or the underlying muscle activation from non-paralyzed body parts (Hart et al. 1998; Rupp et al. 2008). This applies not only to the limited number of possible commands per minute, but also their nature, which is mainly digital (brain-switch). Furthermore, the EEG is a non-stationary signal and therefore BCIs require calibration and tuning. The latency and low number of degrees of freedom of non-invasive BCIs are major drawbacks for real-time, complex neuroprosthesis control (Lauer et al. 2000). This may be overcome with implantable BCI systems. However, these sometimes highly invasive systems have not yet reached a maturity beyond the experimental level (Hochberg et al. 2012; Collinger et al. 2013).

The ultimate goal of a BCI-controlled neuroprosthesis would be to establish a technical bypass around the lesion of the spinal cord and to provide end-users with a natural control, enabling them to accomplish movements in an unconscious and intuitive way. The current state of technology is far away from this goal, because imageries of movements are used that cause the highest effects on SMR signals. This might – in an extreme case – be an imagination of feet movements, which is then used for control of an upper extremity neuroprosthesis. A prerequisite for a natural BCI control of a neuroprosthesis is the independence of an imagined and FES-generated movement of the same limb. A first study with unimpaired subjects shows that MI of hand movements can be used to control the FES of the same hand for a grasping and writing task (Tavella et al. 2010). Nevertheless, a real breakthrough in neuroprosthesis control would be the decoding of body movements from EEG. First attempts into this direction have been started recently, which might pave the way for non-invasive BCI systems with a more intuitive control scheme (Bradberry et al. 2010; Ofner and Muller-Putz 2012). For further development of this revolutionary method of real-time neuroprosthesis control a deeper understanding of the underlying brain physiology has to be attained.

2.5 BCIs for Mobility

Being mobile is apart from communication and manipulation an essential need of motor-impaired end-users for participation in social life. Wheelchairs are the most common assistive device to allow for in-house mobility and also outside the home environment. Persons with severe motor disabilities are dependent on electrical wheelchairs controlled by hand- or chin-operated manual joysticks. If not enough residual movements are possible, eye-gaze or suck-and-puff control units may serve as a wheelchair user interface. Suck-and-puff control is mainly based on four types of commands. If air is blown into/sucked from the device with high pressure/vacuum, the controller interprets this as a forward/backward drive signal. If a low pressure or vacuum is applied, the wheelchair drives right or left. With this rather simple control scheme users are able to perform most navigation tasks with their wheelchair.

Though the thresholds for low/high pressure are individually calibrated, the end-user must be able to reliably generate two different levels of air pressure/vacuum over a sustained period of time to achieve a good level of control. Since these prerequisites are not present in all end-users, BCIs may represent an alternative control option. As already outlined in the preceding subchapters, at the moment all types of non-invasive BCIs provide only a limited command rate and are insufficient for dexterous control of complex applications. Thus, before the successful application of control interfaces with low command rates – including BCIs – in mobility devices, intelligent control schemes have to be implemented. Ideally, the user only has to issue basic navigation commands such as left, right, and forward, which are interpreted by the wheelchair controller integrating contextual information obtained from environmental sensors. Based on these interpretations the wheelchair would perform intelligent maneuvers including obstacle avoidance and guided turnings. In conclusion, in such a control scheme the responsibilities are shared between the user, who gives high-level commands, and the system, which executes low-level interactions with more or fewer degrees of autonomy. With this so-called shared control principle, researchers have demonstrated the feasibility of

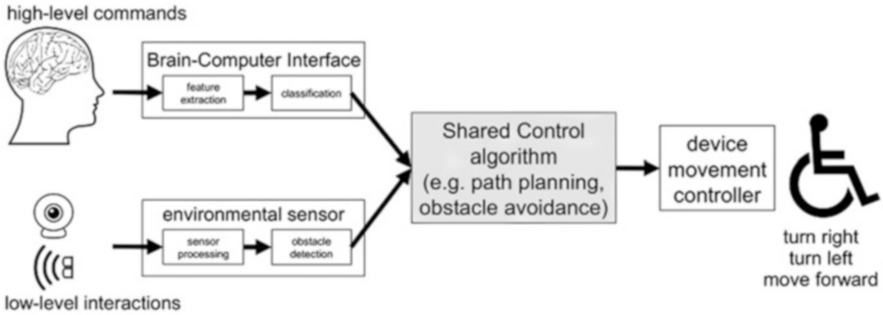

Fig. 2.10 Overview of the shared control structure: The user issues high-level commands via a BCI mostly on a lower pace. The system is quickly and precisely acquiring the environmental information with its sensors. The shared control system merges both information sources to achieve path planning and obstacle avoidance

mentally controlling complex mobility devices by non-invasive BCIs, despite its slow information transfer rate (Flemisch et al. 2003; Vanhooydonck et al. 2003; Carlson and Demiris 2008).

2.5.1 Principles of Shared Control

Generally, the basic idea of shared control is the continuous estimation of the operator's mental intent and providing technical assistance for completion of the intended tasks (Millán et al. 2004; Galán et al. 2008; Tonin et al. 2010). In order to improve the estimation of the user's intent, the user interface outputs are combined with information about the environment, i.e. obstacles perceived by the robot sensors, and the robot itself, i.e. position and velocities (Fig. 2.10). A promising concept for the human–machine interaction in vehicle control is the H-metaphor concept (Damböck et al. 2011). This shared control concept has been specifically established to solve the problem of the human-out-of-the-loop in highly sophisticated mobility systems like autonomous cars and airplanes. The H-metaphor proposes a bidirectional interface, which consist of a mix of discrete and analog communication and a multimodal interface allowing both human and machine to be in the physical loop simultaneously. It suggests that operating a vehicle should be like navigating through an unknown and changing environment sitting on a horse, with notions of "loosening the reins", allowing the system more autonomy or vice versa (Flemisch et al. 2003). Shared control is helping on a direct interaction with the environment but is conveying a different principle than autonomous control. In autonomous control more abstract, high-level commands, e.g. drive to the kitchen or the living room, are issued and executed completely autonomously by the mobility device without any possibility for intervention by the user (Carlson and Millán 2013). A completely autonomous control concept prevents the user from spontaneously interacting with other people. 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 commands. Otherwise, people find it difficult to form mental models of the mobility device, which results in an unreliable control.

Shared control is a fundamental component of BCI-controlled mobility aids, as it will shape the closed-loop dynamics between the user and the brain-actuated device in a way that tasks can be performed as easily and effectively as possible. The idea is to integrate the user's mental commands with the contextual information captured by the intelligent mobility device, so as to reduce the user's workload in reaching the target destination or to correct for 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 such as driving zigzag, and can help to generate meaningful motion sequences.

2.5.2 BCIs for Wheelchair Control

Although asynchronous, spontaneous BCIs seem to be the most natural control option for wheelchairs, there are a few applications using synchronous BCIs (Iturrate et al. 2009; Rebsamen et al. 2010). Like in most communication applications these BCIs are based on the detection of the P300 potential evoked by concentrating on a flashing symbol in a matrix. For wheelchair control the system flashes a choice of predefined target destinations several times in a random order and finally the stimulus that elicits the largest P300 is selected as the target. Afterwards the intelligent wheelchair drives to the selected target autonomously. Once there it stops and the subject can select another destination. The fact that the selection of a target takes approximately 10 s and that the user intent is only determined at predefined time points puts the usability of cue-based BCIs for control of mobility devices into question.

The European projects MAIA (Mental Augmentation through determination of Intended Action) and TOBI (Tools for Brain-Computer Interaction) largely contributed to the implementation of the shared control approach in brain-controlled robots and wheelchairs. In BCI-controlled mobility devices developed in the framework of these projects the users' mental intent was estimated asynchronously and the control system provided appropriate assistance for wheelchair navigation. With this approach the driving performance of the BCI-controlled device greatly improved in terms of continuous human–machine interaction and enhanced practicability (Vanacker et al. 2007; Galán et al. 2008; Millán et al. 2009; Tonin et al. 2010). In the most recent approach of shared control the user asynchronously sends – with the help of a motor-imagery-based BCI – high-level commands for turning left or right to reach the desired destination. Short-term low-level interaction for obstacle avoidance is done by the mobility device autonomously

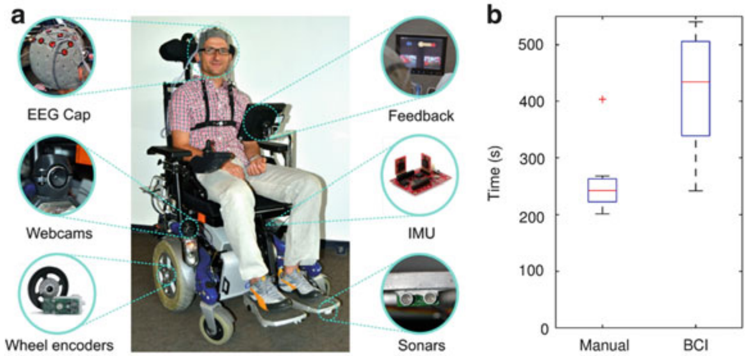

Fig. 2.11 (**a**) Picture of a healthy subject sitting in the BCI-controlled wheelchair. The main components on the brain-controlled robotic wheelchair are indicated with close-ups on the sides. The obstacles identified via the webcams are highlighted in red on the feedback screen and will be avoided by the shared control system. (**b**) Averaged time in seconds required to complete the task, either in manual or BCI condition (Modified from Carlson and Millán 2013)

(Fig. 2.11a). In the applied shared control paradigm the wheelchair proactively slows down and turns for avoidance of obstacles as it approaches them. For the provision of this functionality the wheelchair is equipped with proximity sensors and two webcams for obstacle detection. Using the computer vision algorithm described in Carlson and Millán (2013), a local occupancy grid with 10 cm resolution was computed (Borenstein and Koren 1991), which was later used by the shared control module for local path control. Generally, the vision zone is divided into three regions: Obstacles detected to the left or right trigger rotation of the wheelchair, whereas obstacles in front slow it down. Additionally, a docking mode is implemented in which any obstacle is considered to be a potential target if it is located directly in front of the wheelchair. Consequently, the user is able to dock to any "obstacle", be it a person, table, or even a wall. One prerequisite for the quick transfer of the technological developments to end-users is that additional equipment should not cost more than the wheelchair itself. Thus, the decision to use cheap webcams instead of an expensive laser rangefinder was taken.

Four healthy subjects participated successfully in an experiment in which the webcam-equipped wheelchair is used to enter an open-plan environment through a doorway. The user was then to dock to two different desks whilst navigating around natural obstacles, and finally reach the corridor through a second doorway. It took the subjects on average 160.0 s longer to complete the task with the BCI compared to manual joystick control (Fig. 2.11b). In terms of path efficiency there was no significant difference between the distance traveled in the manual (43.1 ± 8.9 m) and the BCI condition (44.9 ± 4.1 m) (Carlson and Millán 2013). The fact that more time is needed with the BCI control is caused by a slightly higher number of turning commands. In particular, inexperienced BCI users had a bigger difference than experienced ones. This is likely associated with the fact that performing an MI task while navigating and being seated on a moving wheelchair is much more demanding than simply moving a cursor on a screen. Additionally, precisely controlling the timing of the commands under real-world conditions, where negative events such as a crash may also occur (although a supervisor was always in control of a fail-safe emergency stop button), is a challenging task (Leeb et al. 2013). Nevertheless, the users were able to successfully steer the wheelchair they were sitting in by BCI commands, even in stressful situations.

In the future start/stop or pausing functionality will be added. Using the hybrid BCI implementation such rare start/stop commands could also be delivered through other channels such as residual muscular activity. For this purpose any signal which the user is able to control reliably at a slow pace is suitable. Finally, recent research looks at supporting different feedback modalities and using cognitive states, real-time determination of signal reliability, and online task performance to adapt the degree of autonomous control provided by the shared control system.

2.5.3 BCIs for Control of Telepresence Robots

In end-users with severe motor impairments or autonomous dysfunctions mobilization in a wheelchair may not be possible. To still allow these end-users to navigate in a domestic environment, to join their relatives and friends located somewhere else, and to participate in their activities a telepresence robot might be very helpful. An example of such a mobility robot is Robotino™ (Festo, Esslingen, Germany), a small circular mobile platform (diameter 36 cm, height 65 cm) which is equipped with nine infrared sensors that can detect obstacles at up to 30 cm distance and a webcam that can additionally be used for obstacle detection. Furthermore, a conventional notebook with a webcam is added on top of the robot for telepresence purposes (Fig. 2.12a), so that the participant can interact with the remote environment via Skype™ (Skype Communications, Rives de Clausen, Luxemburg).

Exploration of an unknown environment with a robot controlled by a BCI would be a complex and frustrating task, in particular due to the limited temporal precision and low command rate of the BCI. Furthermore, the user has to share attention between the feedback of the BCI classifier, the telepresence screen, the current position, and the route to the desired destination. Here, the shared control principle comes into play. Its actual implementation is based on the dynamic system concept coming from the fields of robotics and control theory (Schöner et al. 1995). Two dynamic systems have been created which control two independent motion parameters: the angular and translation velocities of the robot. The systems can be perturbed by adding attractors or repellers in order to generate the desired behaviors. The dynamic system implements a navigation modality, in which the default device behavior is to move forward at a constant speed. If repellers or attractors are added to the system, the motion of the device changes in order to avoid the obstacles or reach the targets. At the same time, the velocity is determined according to the proximity of the repellers surrounding the robot.

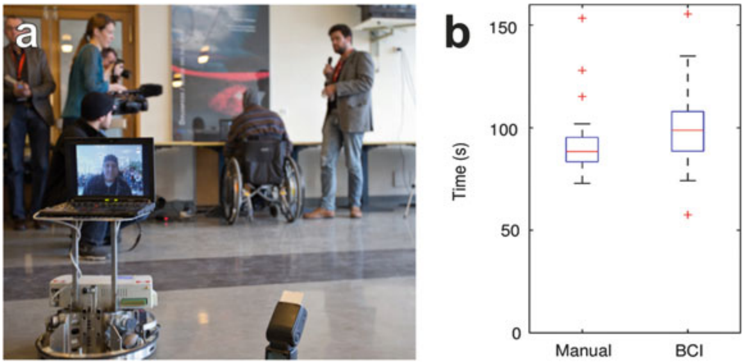

Fig. 2.12 (**a**) A tetraplegic end-user maneuvering the brain-controlled telepresence robot by motor imagery in front of participants and press at the "TOBI Workshop IV", Sion, Switzerland, 2013; (**b**) Averaged time in seconds required to complete the task for each path, either in manual or BCI condition

Applying this principle allows subjects to drive the mobile telepresence platform remotely by a motor-imagery-based BCI (Tonin et al. 2011). In this example, end-users remotely control the robot turning to the left or to the right to reach a selection of four predefined targets within a natural office environment. The space contains natural obstacles such as desks, chairs, furniture, and people in the middle of the paths. Importantly, participants have never explored the environment prior to the experiment. The robot's turnings to the left and right are controlled via a two-class BCI (Galán et al. 2008). Whenever the BCI output exceeds the threshold for left or right a command is delivered to the robot. In addition, the participant can intentionally decide not to deliver any mental commands to maintain the default behavior of the robot, which continues to move forward and avoids obstacles with the help of its on-board sensors (Leeb et al. 2013).

Nine severely motor-disabled end-users, who had never visited the lab environment in person, were able to use such a telepresence robot to successfully navigate around the lab whilst they were located in their own homes or in clinics at distances of up to 550 km away. The same paths were followed with BCI and manual control, i.e. button presses. Furthermore, shared control was either applied or not. Remarkably, the end-users with motor impairments (Tonin et al. 2011) performed similarly to the healthy users (Tonin et al. 2010), who were already familiar with the environment. Shared control also helped all subjects including novel BCI subjects or users with disabilities to complete a rather complex task in a similar amount of time and with similar numbers of commands to those required by manual commands without shared control (Fig. 2.12b). Thus, these results show that shared control reduces subjects' cognitive workload as it (a) assists them in coping with low-level navigation issues such as obstacle avoidance and allows the subjects to focus the attention on the final destination and thereby (b) helps BCI users to maintain attention for longer periods of time, since the number of BCI commands can be reduced and their precise timing is not so critical.

2.6 Conclusion

Taken together, BCI research has made tremendous progress in recent years and end-users benefit from BCI-controlled Assistive Technologies in the application domains of communication, mobility aids, and neuroprosthesis control. However, BCIs are not yet ready for independent home use. To establish BCIs as AT in the end-user's home, three gaps need to be bridged: (1) the usability, (2) the reliability, and (3) the translational gap. In general, the setup and handling of current BCI systems is relatively complicated compared to traditional AT and needs the (tele-) presence of technical experts. Thus, BCIs have to be improved to a stage at which end-users together with their caregivers are able to apply the systems independently at home. A key component for achieving this goal is the availability of easier to handle, gel-less electrodes providing sufficient signal quality. Only long-term studies with end-users will allow us to demonstrate the reliability of BCIs and further improve the systems. With the extensive implementation of intelligent shared control mechanisms, uncertainties and non-stationarities, which are inherent to non-invasive MI-BCI systems, may be partly tackled. Nevertheless, a MI-BCI should not be considered as an add-on to existing user interfaces for real-time neuroprosthesis control, if the initial BCI performance is low and not stable over sessions. The relatively new concept of the hybrid BCI holds promise that BCIs seamlessly integrate into traditional user interfaces and might expand the group of potential users. First studies incorporating the hybrid BCI approach show that a general setup of the system in different end-user groups does not exist. In fact, the possibility of a personalized configuration – something very common to the AT field – will be essential for the success of BCIs as control interface for ADs.

Most important, more translational studies involving end-users at their homes are needed to address the problems and issues arising from applications outside research labs. Adopting the user-centered approach in BCI research and development enables us – in an iterative process between developers and users – to further improve BCI and to address the specific needs and requirements of end-users.

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Chapter 3
Brain-Computer Interfaces and Diagnosis

Camille Chatelle, Steven Laureys, and Quentin Noirhomme

3.1 The Challenge of Diagnosis in Patients with Disorders of Consciousness

Following severe brain damage, patients may fall into a coma (i.e. absence of eye opening, reflex responses). After some days or weeks, they may awaken (i.e., open their eyes) but still fail to show voluntary behaviors. This syndrome is known as "unresponsive wakefulness syndrome" (UWS; Laureys et al. 2010), formerly coined "vegetative state" (VS). Some patients will remain unresponsive for decades; other patients may evolve to a minimally conscious state, i.e., showing more than reflex behaviors such as visual pursuit (MCS minus; Bruno et al. 2012) or command following (MCS plus) but lacking functional communication (Giacino et al. 2002). Others may awaken and be fully aware but paralyzed and mute, i.e., locked-in syndrome (LIS; Plum and Posner 1966). Nowadays, the clinical diagnosis of patients with disorders of consciousness (DOC) such as unresponsive wakefulness syndrome (UWS) and minimally conscious state (MCS), and therefore their access to rehabilitation, is mainly based on behavioral observations. Keystones in diagnosis are the acquisition of voluntary responses such as command following and functional communication, which indicate emergence from the UWS and the MCS, respectively. Command following and functional communication also distinguish LIS from UWS patients. However, the difficulty of distinguishing reflex from voluntary responses makes the assessment very challenging for clinicians, particularly in a population often suffering from motor disabilities associated with brain damage.

Some electrophysiological and neuroimaging studies have been proposed to probe residual brain function in DOC. They aimed at providing diagnosis and

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prognosis markers. Some, in line with BCI studies, aim at detecting command-specific changes in electroencephalography (EEG) or functional magnetic resonance imaging (fMRI) signals providing motor-independent evidence of conscious thoughts.

In the context of patients with DOC, the first goal of a BCI is to establish, beyond reasonable doubt, that a patient is able to follow a command. To do so, the patient would need to be able to understand the task requirements, which ideally should be as simple as “squeeze my hand”, and execute the task multiple times. Then, the software and hardware could be extendable to test communication with “responders”. The patient would therefore need to be able to attend to stimuli/questions while retaining task information in working memory. Current BCIs require much greater capacities from the patient than behavioral testing but they are a unique opportunity to establish an early diagnosis of LIS in patients who cannot behaviorally express their consciousness.

When looking at the results obtained in studies in patients with DOC, we need to take into account the number of patients showing command following with the system, but also how many of them were able to follow a command at the bedside and could not be detected by the system. Indeed, this ratio would give us important information about the false negatives in the studied population with a given paradigm. We will therefore always give this information for every study reviewed below.

3.2 BCIs as a Diagnostic Tool in Patients with DOC

The first case study using BCI as a diagnostic tool of consciousness was a patient diagnosed as being in an UWS, who was instructed to “imagine playing tennis” and “walking through her house” during an fMRI session (Owen et al. 2006). The paradigm consisted of a 30-s period of mental imagery followed by a resting period of 30 s. Each imagery task was repeated ten times. This patient displayed similar brain activations compared to control subjects for both tasks. A few months after the study, the patient behaviorally evolved into MCS. In a follow-up study (Monti et al. 2010) including 54 patients (23 UWS and 31 MCS), five (four UWS) were able to willfully modulate their brain activity. One of them was even able to answer simple questions, e.g. “Is your father’s name Alexander?”, using one task for “yes” and the other for “no”. However, out of 18 patients showing command following at the bedside, only one could be identified with the system (false negative: 94 %). Bardin et al. (2011) investigated the use of a different imagery task instructing patients to imagine themselves swimming or playing tennis with their right hand, using a protocol very close to the one used by Owen et al. (2006) and Monti et al. (2010). Out of six patients, three of them were able to follow commands with the system. However, if five patients were able to follow commands at the bedside, two of them could not be identified with the system (40 %). In the same idea, Monti et al. reported preserved working memory abilities in an MCS patient exceeding expectations based on the standard behavioral assessment, using an active task in fMRI (counting target-neutral words in an auditory sequence of non-target words) (Monti et al. 2009). This patient was able to follow a command and communicate intentionally at the bedside. Nevertheless, this study only included one patient and the results have not been replicated yet, preventing any interpretation in terms of the false negative rate.

Despite the many advantages of fMRI, this technique is limited in terms of availability, affordability, and ease of use in this population. On the other hand, EEG can potentially lead to the development of relatively cheap and compact systems that can be readily deployed at the bedside. Schnakers et al. proposed using an auditory P300 for EEG-driven commands following detection (Schnakers et al. 2008). The advantage of the P300 is that it can be elicited by meaningful stimuli requiring only a limited workload from the patient. However, some of the most successful P300-based BCI systems are based on visual P300 whereas patients with DOC often suffer from gaze fixation impairments, and hence cannot react to visual stimulations. Consequently, auditory P300 is more likely to be usable by a greater number of patients (Chatelle et al. 2012). Schnakers et al. instructed patients to count the number of times a name (subject's own name or unfamiliar name) was presented within an auditory sequence of random names (Schnakers et al. 2008). Results showed that, out of 14, five MCS patients showed significantly better P300 responses when actively counting the occurrence of their own name as compared to when only passively listening. Interestingly, four other patients showed a response only when they were asked to count an unfamiliar name as compared to passive listening. Since both sessions were recorded at the same time, these results could highlight an important fluctuation of vigilance in this population. On the other hand, the eight UWS patients did not show any response to the active task. Moreover, when administered in a complete LIS patient behaviorally diagnosed as being comatose, they also observed a significant difference between the passive and the active task (Schnakers et al. 2009). Using this paradigm, two (22 %) out of nine patients showing command following at the bedside that could not be detected with the system.

Building on the auditory P300, Lulé et al. tested a four-choice auditory P300-based BCI on 13 MCS, three UWS, and two LIS patients (Lule et al. 2013). After a training phase, each patient had to answer ten questions by concentrating on repetitions of "yes" or "no" presented in a stream of words. One LIS patient had a significant correct response rate of 60 % while the other LIS patient had a response rate of 20 % and could not use the BCI for communication. No MCS patient could communicate through the BCI. Out of six patients showing command following at the bedside, five (83 %) could not be detected with the BCI. It is important to highlight that this paradigm was designed as a communication protocol, and it would therefore be interesting to adapt it to first study command following in a population with DOC.

Another well studied BCI is based on motor imagery. Imagination of movement is well known to be associated with a power decrease in the sensorimotor or mu-rhythm (8–15 Hz; SMR; Pfurtscheller et al. 1997; Neuper et al. 2005), called event-related desynchronization, focused in the motor region implicated in the target movement (Pfurtscheller and Lopes da Silva 1999). For these BCIs, the stimulation can be effectively delivered auditorily (Chatelle et al. 2012). Goldfine and colleagues (Goldfine et al. 2011) recorded EEG from three patients showing command following at the bedside (MCS, MCS/exit-MCS and LIS), while they were involved in motor imagery and spatial navigation tasks. A session alternated eight 15-s periods of mental imagery with 15-s periods of rest. All patients demonstrated the capacity to generate mental imagery on the same tasks, via independent fMRI studies. With univariate comparisons (individual frequencies), Goldfine and colleagues were able to show evidence of significant differences between the frequency spectra accompanying the two imagery tasks in one MCS patient (however inconsistently) and one LIS patient (33 % not detected with the system). Multivariate comparisons (patterns across the frequency range) using linear discriminant analysis did not lead to any evidence of brain-related activation in any patient (100 % undetected).

In another study from Cruse et al., motor imagery task was investigated in 16 UWS and 23 MCS patients (Cruse et al. 2012), showing that eight of them (three UWS, five MCS) were able to voluntarily control their brain activity in response to a command ("imagine squeezing your right hand" vs "imagine moving all your toes"). Out of 15 patients showing command following, 13 could not be identified by the system (87 %). However, these results have to be taken with caution as the methodology emphasizes the need for powerful statistical tests for that kind of BCI application (Cruse et al. 2013; Goldfine et al. 2013).

3.3 Future Perspectives

The high rate of false negatives achieved using current BCIs highlight the need to develop more sensitive tools for diagnosing DOC patients (Table 3.1). Indeed, a system which is not sensitive enough to detect patients diagnosed as conscious at the bedside could not be reliably used in a population with unclear diagnosis. Currently, research on BCI in patients with DOC will have to overcome a number of challenges. First, there is the barrier associated with the lesions leading to awareness fluctuation, fatigue, and limited attention span commonly observed in these patients, especially in MCS patients (Giacino et al. 2002). Hence, task/ stimulus complexity and duration is an important factor to consider when evaluating BCI applications. Moreover, multiple repetition of the BCI session must be considered to ensure a reliable diagnosis. In terms of communication, evaluation should be assessed with simple questions as severely brain-damaged patients may have difficulty giving accurate answers even to trivial yes/no questions (Nakase-Richardson et al. 2009). Furthermore, brain injury is often associated with sensory deficits (such as cortical blindness or deafness). When research on BCI in healthy participants seems to highlight better performance with a visual BCI as compared to auditory or tactile BCIs (Pham et al. 2005; Kübler et al. 2009; Halder et al. 2010),

Table 3.1 Brain–computer interfaces in patients with disorders of consciousness and false negative cases (patients showing command following at the bedside but not detected by the system)

References	Technique used, Brain response	Task	Total number of patients included	False negative ratio (%)
Owen et al. (2006) and Monti et al. (2010)	fMRI-motor imagery	Command following and communication	55	17/18 (94 %)
Bardin et al. (2011)	fMRI	Command following and communication	6	2/5 (40 %)
Monti et al. (2009)	fMRI, P300	Command following	1	0/1 (0 %)
Schnakers et al. (2008, 2009)	EEG, P300	Command following	23	2/8 (25 %)
Lulé et al. (2013)	EEG, P300	Communication	18	5/6 (83 %)
Goldfine et al. (2011)	EEG, motor imagery	Command following	3	1/3 (33 %) and 3/3 (100 %) depending on the analyses used
Cruse et al. (2011, 2012)	EEG, motor imagery	Command following	39	13/15 (87 %)

The percentage is calculated as the ratio between the number of patients showing command following at the bedside who did not show command following with the system and the total number of patients showing command following at the bedside.

the key challenge here will be to develop sensitive systems offering stimuli, instructions, and/or questions through multiple channels.

Third, feedback and motivation – known factors influencing BCI results – must be considered with care as we cannot distinguish a patient not paying attention to the task (lacking motivation), an unsuccessful patient, and an unconscious patient. Fourth, suboptimal data quality due to movement and ocular and respiration artifacts in these challenging populations may also be confounding factors that need to be overcome using appropriate statistical analyses. In addition, the suitability of different BCI designs for individual patients is significantly variable and will need to be comparatively assessed in each case. While some patients have been shown to be able to generate reliable P300s in response to task-relevant stimuli, others have demonstrated the ability to consistently perform mental imagery in response to commands.

One last main challenge that also needs to be pointed out is that in EEG, the classification accuracy achieved with a BCI naturally depends on the quality and inter-trial consistency of the data used to train the classifier. This is problematic for most patients with DOC, particularly those in MCS, who are prone to frequent and prolonged bouts of fatigue and attention fluctuation. This would effectively render them unable to pay attention for sufficiently long periods. For many patients, this limitation will adversely affect the statistical power of the classifiable patterns latent in their EEG data (e.g. dependency). It is therefore important to design protocols accordingly (avoid using blocks of one stimulation and long-lasting sessions, assess the patient at different time periods (Cruse et al. 2013; Goldfine et al. 2013)).

Amongst the different designs developed in healthy controls and tested in DOC, motor imagery BCIs are less hindered by problems of stimulation modality. There is relatively little stimulation that needs to be presented and this can be effectively delivered auditorily. Results on their use in some DOC patients have produced promising results (Monti et al. 2010; Goldfine et al. 2011). This knowledge, along with the fact that motor imagery (e.g. playing tennis vs. spatial navigation imagery) in fMRI has already allowed some patients to communicate when unable to do so at the bedside (Monti et al. 2010), bodes well for similar BCI variants. However, as motor imagery relies on the user's ability to learn mappings between intention and movement imagery, they require adequate training before reliable performance can be achieved, which poses a significant challenge in a population of DOC patients, as illustrated by the high rate of false negatives achieved in previous studies on imagery tasks. In this context, P300-based BCI designs could be of interest since they rely on "automatic" responses of the brain to salient stimuli and hence require relatively little explicit user training. As highlighted earlier, previous findings by Schnakers et al. (2008) and Monti et al. (2009) have shown that some patients with DOC can generate consistent changes in EEG and fMRI when asked to selectively respond to task-relevant stimuli. Moreover, the P300 paradigm has shown to be the least sensitive to false negatives as compared to the other designs studied recently. Potentially, if successful with a patient, a P300-based BCI for spelling words and sentences using a predictive language support program could provide a true, multi-class system with relatively high efficiency. Moreover, a study on the P300 in healthy subjects has reported 89 % of healthy controls being able to use it with an accuracy of 80–100 % (Guger et al. 2009), compared to only 20 % of users with a motor-imagery-based BCI (Guger et al. 2003). Since we know the most successful P300-based BCI is visually based, it would also be possible to adapt a visually-based BCI for patients with eye control disabilities using one by one stimulus presentation, as successfully developed, although not tested on DOC patients, by Hoffmann et al. (2008). On the other hand, future studies should take into account the topographic and latency variabilities observed in the P300-based BCI in healthy subjects to interpret patients' data (Bianchi et al. 2010; Kaufmann et al. 2011).

Other kinds of BCIs were only studied in healthy controls and LIS patients, but can be of interest for patients with DOC. Steady-state visually evoked potentials (SSVEPs; Regan 1989; Vialatte et al. 2010) are the oscillatory electrical responses of neurons in the visual cortex to stimuli that are repeatedly presented (or flashed) at frequencies above 6 Hz. SSVEPs are easy to detect, as their frequency content is completely determined by the visual stimuli used to elicit them. The advantage of this response is that it has high signal-to-noise ratios and is nearly completely free of eye movement (Perlstein et al. 2003) and electromyographic artifacts (Regan 1966; Gray et al. 2003). If this response has been shown to allow healthy subjects and motor-disabled patients to successfully use the system for communication (Parini et al. 2009), it will have to be tested in DOC using alternative approaches based on covert attention to solve the problem of eye motor control disabilities (Lesenfants et al. 2011).

Birbaumer and colleagues (Elbert et al. 1980; Birbaumer et al. 1999, 2000) have worked on the development of slow cortical potentials (SCPs)-based BCIs, slow voltage changes generated in the cortex, occurring over periods of 0.5–10.0 s. Usually, negative SCPs are associated with motor movement and other functions involving increased cortical activation, while positive SCPs are more associated with reduced cortical activation (Birbaumer 1997). Further, this system has been tested in people with late-stage amyotrophic lateral sclerosis (ALS) and has proved capable of providing basic communication capacities (Kübler et al. 1999). However, the main problem is again that the most successful system uses visually-based feedback (Birbaumer et al. 2000; Pham et al. 2005) and a relatively long period of training is needed (Birbaumer 2006). On the other hand, SCPs have the advantage of being the most stable over long periods (Chatelle et al. 2012).

3.4 Conclusion

In this chapter, we highlighted several studies performed on patients with DOC that consider the use of diagnostic tools. These results could have a significant impact on rehabilitation strategies, quality of life, and prognosis. However, for all of the BCI designs discussed here, results from patients with DOC will need to be interpreted with great caution. Indeed, results from these studies showed that the likelihood that a covertly aware patient might go undetected (i.e. the false negative rate) is likely to vary significantly across different paradigms. Hence, none of these tests applied individually to look for command following can currently be used to interpret negative results without combining findings from multiple testing methods to mitigate the level of uncertainty. Future research will need to overcome several challenges limiting current BCI applications in DOC patients, in order to create a more sensitive tool for diagnosis. Studies on BCIs in healthy participants could be used as a basis for the development of new paradigms, but there is a need to conduct extensive testing with patients likely to benefit from various BCI systems in their daily lives (Kübler et al. 2006), since we know it is often the case that results from controls do not generalize well to patient groups (Hill et al. 2006).

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Chapter 4
Brain-Computer Interfaces and Therapy

Donatella Mattia and Marco Molinari

4.1 Introduction

Brain–computer interfaces (BCIs) have historically primarily been developed to provide alternative communication devices to people disabled by neuromuscular disorders such as amyotrophic lateral sclerosis, cerebral palsy, stroke, or spinal cord injury. BCIs acquire brain signals, analyze them, and translate them into commands that are relayed to output devices that carry out desired actions (Shih et al. 2012). Only recently has the idea been advanced that BCI technology can be used not to extract brain activity to control the external environment but in the opposite direction toward the brain to control brain mechanisms to improve functions and sustain recovery (Grosse-Wentrup et al. 2011; Rossini et al. 2012). This change in BCI research and application raises ethical issues quite different from those previously addressed (Tamburrini 2009; Clausen 2011; Shih et al. 2012; Schneider et al. 2013). Previous interest in ethical BCI arguments focused on BCI technology as a means to provide an alternative channel of communication to disabled people and eventually to healthy people in specific contexts. Much less attention has been given to therapeutic application. Here we would like to focus on ethical, social, and cultural aspects that might stem from the application of BCI technology to treat brain lesions specifically favoring functional recovery.

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4.2 BCI, Neurofeedback and EEG-Based Treatment Protocols

Electromagnetic brain signals have been extensively studied and a large body of evidence indicates the capacity of EEG analyses to detect brain activity related to specific functions and its physiological or pathological changes. Even more challenging and interesting as a potential therapeutic tool is the possibility of volitional modulation of brain activity. In this latter field data are scarce but promising findings have been reported on the capacity by volitional modulation of slow cortical potentials of reducing seizure frequency (Rockstroh et al. 1993) and to improve ADHD symptoms (Strehl et al. 2006). Recently different groups have addressed the possibility of improving stroke rehabilitation through BCI or neural-brain-computer interface (NBCI) derived approaches (Grosse-Wentrup et al. 2011; Bundy et al. 2012; Pichiorri et al. 2012). In these approaches it is not clear whether we are facing a BCI application or innovative neurofeedback protocols. On the other hand, as recently pointed out (Allison 2011), much confusion still exists in defining BCI. Literally one would refer to BCI when brain activity is used to control an external device even if the device is used to provide therapy, for instance using BCI for controlling attention during gait robotic training (Broetz et al. 2010). On the other hand neurofeedback would imply providing a subject with information of ongoing brain activity in order to voluntarily modulate it (de Zambotti et al. 2012). A third condition, somehow in between, is that in which the subject is not directly aware of the characteristic of the ongoing brain activity but the performance of an external device is used to guide the modulation of the recorded brain (Mattia et al. 2013). In all three conditions the basic idea is to drive brain activity toward a recovery/improvement of the damaged function. To achieve this a somehow automatic close link is instated so as to favor the rearrangement of brain synapses and circuits considered the substrate of functional recovery (Nudo 2007). Despite differences in definition, as regards ethical issues the three approaches are largely similar. In the following we will address different clinical conditions focusing on non-technical aspects related to BCI and related technology-based therapies.

4.3 BCI and Rehabilitation of Motor Functions

Among the possible applications of BCI technology, the neurorehabilitation of motor function in stroke survivors is constantly gaining interest among researchers and is gathering a considerable amount of resources in the field. In recent years the application of BCI in stroke rehabilitation has been investigated by different groups, either with preliminary studies on healthy subjects (Nagaoka et al. 2010; Gomez-Rodrig 2011) or with case reports (Daly et al. 2009; Broetz et al. 2010) and small clinical trials (Buch et al. 2008; Prasad et al. 2010).

The theoretical framework to support such interventions regards BCI systems (either alone or combined with neuroprosthetic devices) capable of enhancing activity-dependent neuroplasticity (Nudo 2007) guiding the spontaneous plastic changes occurring in the brain after stroke towards a more normal brain activity that in the end would mean a better recovery outcome.

Two different strategies have been identified: the first strategy foresees the use of BCIs to train patients to produce more normal brain activity; the hypothesis behind this approach is that more normal brain activity reflects more normal brain function, and more normal brain function results in an improvement of motor control. The second strategy is to use BCIs to operate devices which are capable of assisting movement: The sensory input resulting from this assisted movement induces plastic changes in the central nervous system leading to better motor function (Daly and Wolpaw 2008). The latter approach was explored in the first trial involving stroke patients in a BCI paradigm for motor rehabilitative purposes (Buch et al. 2008). In this study, patients with no residual finger function underwent a motor imagery MEG-based BCI training in order to operate a mechanical orthosis that passively flexed or extended their fingers. Similar approaches have been used in other studies, albeit mainly based on EEG signals (Broetz et al. 2010; Ang et al. 2010; Dimyan and Cohen 2011; Caria et al. 2011). Of particular interest are the differences in the methods used to select the features of the brain activity to be strengthened by the rehab protocol. In the first MEG study (Buch et al. 2008) the features chosen were those that best discriminated the motor imagery from the rest condition regardless of their location on the scalp (either collected from the lesioned hemisphere or the intact one). In the other cited studies control features selection was guided by the idea that for motor recovery application, the source of the signal adopted for BCI training must be as close as possible to normal activity. Thus, features were selected comparing the EEG activity generated from motor imagery (MI) of the affected hand to that generated from MI of the unaffected one (Daly et al. 2009), or the control signal was collected from the ipsilesional hemisphere only (contralateral to the imagined movement of the affected hand) (Broetz et al. 2010; Ang et al. 2010; Caria et al. 2011). Why is the method chosen to select control features relevant? Sensorimotor rhythm-based BCI training has long-lasting effects on brain plasticity (Ros et al. 2010; Pichiorri et al. 2011) and it is conceivable that different sensorimotor rhythms are sustained by different circuits. If this is the case differences in the brain rhythm used in the BCI application would imply differences in the therapeutic effects, meaning, for instance, that a given rhythm might favor plasticity in circuits that inhibit, for example, increasing spasticity, or that support recovery. This relation between characteristics of mental activity and differences in cortical plasticity phenomena has been demonstrated in healthy subjects (Pichiorri et al. 2011). Relations between mental activity and "bad plasticity" have been reported in subjects using MI for controlling central pain (Gustin et al. 2008). The possibility of sustaining "bad" plasticity during BCI training has already been advanced but it has generally been discarded as unlikely at least in the classical BCI settings (Schneider et al. 2013). This statement has to be reconsidered when addressing conditions quite different from those present in the "therapy" BCI setting. In this BCI application, brain rhythm is not used to communicate but rather the "therapy" and modification of the related brain circuits is the principal target of the intervention.

4.4 BCI for Rehabilitation of Cognitive and Behavioral Deficits

Besides motor function, cognitive functions such as executive planning, attention, and memory can also be enhanced through modulation of brain rhythms (Serruya and Kahana 2008). Applications have included sustained attention (Egner and Gruzelier 2001, 2004), working memory (Vernon et al. 2003), music (Egner and Gruzelier 2003), dance performance (Raymond et al. 2005a), and mood enhancement (Raymond et al. 2005b). Up to now, BCI neurofeedback applications for cognitive/behavioral rehabilitation have been almost exclusively limited to epilepsy and attention deficit/hyperactivity disorder (ADHD). Epilepsy application suggested that learning to control brain patterns by neurofeedback training might help to reduce the frequency of seizures (Kotchoubey et al. 2001; Strehl et al. 2005). Regarding ADHD, neurofeedback training in addition to behavioral therapeutic approaches has been suggested to improve cognitive and behavioral performances (Strehl et al. 2007).

Besides epilepsy and ADHD, attempts to improve non-motor functions through brain rhythm control also included the treatment of cognitive symptoms following traumatic brain injury (TBI). In particular, data indicate that, at least for attention abilities, EEG-guided biofeedback approaches, either alone or in association with cognitive strategy training, are helpful in sustaining recovery (Thornton and Carmody 2009).

Obviously the same caveat about the possibility of sustaining bad plasticity indicated in the previous section also applies to BCI application to cognitive impairments. Furthermore, BCI application to cognitive and even more to behavioral functions triggers particular ethical aspects. One obvious topic regards the definition of normality and the need to treat within the realm of behavior and cognition. This aspect has been addressed many times and a thoughtful discussion would be beyond the scope of the present topic (Tennison and Moreno 2012; Kadosh et al. 2012; Rachul and Zarzeczny 2012). More specific to BCI therapeutic applications is the idea of a self-sustaining apparatus that in more or less independent closed loops modifies someone's behavior. This setting is quite new and specific to the BCI-neurofeedback approach and potentially harmful. At present data are not sufficient to draw a complete scenario but it is worth considering the quite profound ethical issues related with these applications.

4.5 BCI-Assisted Mental Practice and Rehabilitation

Notwithstanding the numerous novel approaches proposed to boost motor recovery after brain lesions, rehabilitative interventions aimed at motor recovery are still mainly based on active movement training and passive mobilization (Sharma and Cohen 2012). Among the new interventions proposed, motor imagery (MI) represents an intriguing new "backdoor" approach to access the motor system and rehabilitation at all stages of stroke recovery (Liu et al. 2004; Guttman et al. 2012). MI can be defined as a dynamic state during which the representation of a specific motor action is internally rehearsed without any overt motor output, and it is governed by the principles of central and peripheral motor control (Jeannerod and Decety 1995). This is likely the reason why mental practice using MI training results in motor performance improvements (Short et al. 2005). In addition, MI training can independently improve motor performance and produce similar cortical plastic changes (Mulder 2007), thus providing a useful alternative when physical training is not possible. MI training combined with conventional physiotherapy has been reported in one clinical trial with subacute to chronic stroke patients and it demonstrated a greater improvement of hand function with additional mental practice (Hardy et al. 2010). On the other hand, a more recent randomized controlled trial on a cohort of stroke patients showed no efficacy of motor imagery on hand motor recovery with respect to other mental task practice and/or usual treatment (Ietswaart et al. 2011). Clinical trials involving MI have to face specific difficulties mainly related to problems of measuring performance and compliance. When dealing with a pure mental task, despite the instruction provided, it is particularly hard to control for the cognitive strategy employed. For instance, when aiming at activating the motor networks by MI it is crucial to perform the mental task from the first-person perspective (so-called kinesthetic MI), and not from the third-person perspective or with visual imagery that would specifically activate visual networks (Neuper et al. 2006). Furthermore, as stated above, the challenge neurorehabilitators are faced with is clear: Modulating the sensorimotor experience to induce specific forms of plasticity to boost relearning processes. BCI technology is the right approach for controlling for the target circuit of a given rehab intervention when no motor outputs can be used. Thus, within the context of MI training, BCI technology may allow individual MI ability to be objectified and monitored, both in terms of performance (relation between subject's MI performance and subject's level of accuracy in controlling basic BCI applications) and compliance (identification of a correct MI task which is needed to achieve BCI control).

Within the EC-founded research project TOBI (http://www.tobi-project.org) the use of BCI technology has been proposed to overcome the intrinsic limitations of MI training for motor recovery. In particular the BCI approach has been implemented to enhance hand function recovery in stroke patients. In Fig. 4.1 the setup developed for the TOBI BCI prototype to support the MI-based hand treatment of stroke survivors is depicted. Preliminary results of this approach have

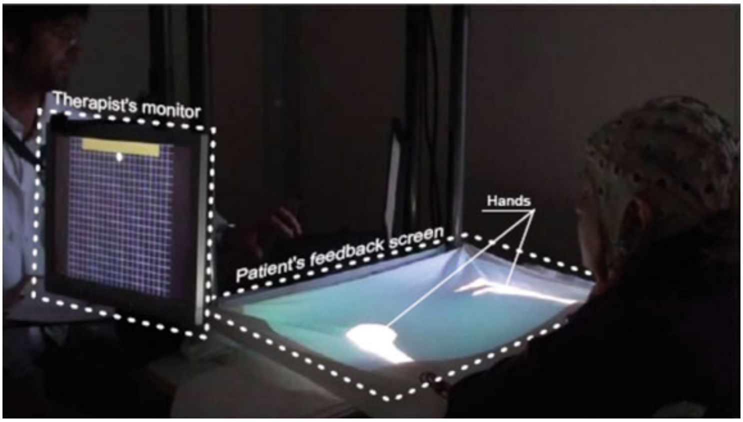

Fig. 4.1 TOBI BCI prototype to support MI-Scalp EEG potentials are collected from 31 positions and data acquisition, online EEG processing, and feedback to the therapist are performed using BCI2000 software. During the session, the patient is seated while hands are covered by a screen. Dedicated software provides a visual representation of the patient's hands, matching the shape, color, and size of the real hand. The "virtual" hand is then projected over the screen matching the position of the real hands positioned under the screen. The therapist has to continuously monitor the patient's mental "activity" by means of the continuous BCI feedback (currently a moving cursor) displayed on a dedicated screen and rewards the patient or corrects his performance. The patient is asked to perform motor imagery of the affected hand and this generates a visual "illusion" of hand movement each time (trial) the patient successfully controls the grasping or the opening of the "fake" hand

recently been published (Mattia et al. 2013; Pichiorri et al. 2012). In extreme synthesis, in the cited approach a mix of BCI and neurofeedback models is employed. The tool is based on a classical BCI system with an external device, producing the movement of a fake hand, that is controlled by brain activity. Notably, in this approach the brain–machine loop is not automatic but is mediated by therapist intervention, allowing adaptation to the patient's capacity and performance monitoring. On the other hand the final objective is not the movement of the fake hand but, as in a neurofeedback protocol, the training of a specific brain rhythm by adding up the effects of MI and visual feedback of the imaged movement. Preliminary results show this approach to be more effective than MI alone in promoting recovery (Mattia et al. 2013).

As stated above, BCI training for rehabilitative application is not limited to the acquisition of a good control of the system; it is also directed toward identification of the brain activity more reliable for sustaining function recovery. In the cited TOBI study this aim has been considered by immersing the patient in a setting which helps him to keep his attention focused on the required task and on the final objective of the training by providing a feedback congruent with the task he is performing.

In this way it is hypothesized that the visual or somatosensory input resulting from the neurofeedback induces plastic changes in the circuits of the central nervous system that are critical for the task. In the absence of more strict characterization of the "correct" brain activity to sustain recovery, the proposed approach is an attempt to guide the BCI training following current knowledge linking mental activity and motor recovery.

4.6 Ethical Issues (Caveats) Emerging from the Therapeutic Use of BCI

In the previous sections we reported on a different use of BCI technology. We now focus on two main ethical issues stemming from this approach – namely thepossibility of iatrogenic effects because of potentiating maladaptive circuits and difficulties in addressing cognitive/behavioral performances in an uncontrolled loop.

4.6.1 Iatrogenic Effects

The proposed BCI-based MI training for motor recovery after stroke is based on repetitive use of stereotyped brain signals within the context of BCI training-induced plasticity. This concept implies that we can guide neuronal rewiring by mental activity. At present very little is known about relations between mental activity and functional recovery. One first obvious statement is that a brain that suffered from a stroke is by no means the same as a healthy brain. The brain activity associated with a given function might therefore be quite different from the physiological one after a stroke. Using BCI approaches to sustain recovery would imply knowing beforehand which will be the right "brain activity" to train to obtain an optimally recovered function. At present we are still missing this piece of information and many variables, such as lesion localization, compensatory strategies, and patient compliance, may influence the characteristics of the optimal brain activity for a given rehabilitation context. The multifactorial framework of influences makes it difficult to predict the brain activity to train in the absence of experience-driven data. Thus it is conceivable that a given "brain activity", although correct in a healthy brain, might not be the right one to sustain recovery. Following this line of thought it could be argued that through BCI it could be possible to sustain a brain activity that inhibits rather than supports recovery. To avoid this possible negative effect, brain algorithms capable of developing patient-tailored BCI training that can adapt or modify itself as long as recovery in ongoing are the right line to pursue for a greater use of BCI-based approaches in neurorehabilitation. To achieve this goal, large libraries of task-related brain rhythms from neurological patients at different stages of recovery are needed. In the absence of such hard data, approaches like that of the TOBI project presented here are needed to guide the choice of the brain rhythm to train, and careful control strategies have to be implemented to reduce the risk of BCI therapy deriving negative effects.

4.6.2 Cognitive/Behavioral Treatments

As often with therapeutic approaches aiming at controlling behavior, special attention to ethical issues is mandatory. This aspect is even more important when supposed “brain reading” techniques such as BCI are involved (Farah 2002). Particularly in the context of neurorehabilitation it should be stressed once more that the “brain reading” approach has to face a damaged brain and that in such a condition the definition of “normality” is even more foggy than usual. While it might seem straightforward to guide the recovery of some cognitive functions like attention or speech, the application of these “objective” approaches to areas like emotion, affection, and aggression is obviously less direct. Although at present no such studies have been attempted, the encouraging results in treating attention and ADHD behavioral disorders with brain activity training would in a short time support proposals of addressing with BCI-derived technologies also disabilities in emotion, affection, or aggression control for instance in traumatic brain injury patients. This ethical aspect is not unique to BCI but is common to other approaches influencing behavior like drugs or surgery or more recently deep or transcranial brain stimulation (Heinrichs 2012). Nevertheless, the idea that an individual can modify his affectivity or aggressiveness by training neural activity and that this can be achieved by the use of a machine that reads someone’s thoughts and redirects them might have quite an impact on the general public and in the general perception of this therapy. As recently stated by Allison (2011), the future of BCI research – and we would particularly stress its use in a therapeutic environment – will depend greatly on the correct perception of benefit and risk of its use. To achieve this goal, a shared terminology together with high sensibility to ethical issues are key elements to supporting the exploitation of BCI outside the classical communication and control fields of application.

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Part II
Stakeholders and Perspectives

Chapter 5
Brain-Computer Interfaces as an Emerging Assistive Technology (AT): The AT Professionals' Perspective

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5.1 Assistive Technology: A Professional Field of Intervention

BCI technology is a "new entry" in the world of technology-based assistive solutions for people with disabilities. But what does this world look like, who are its custodians, and what is important to them?

5.1.1 Assistive Technology Professionals

The aim of every Assistive Technology (AT) professional is to support people with disabilities by identifying appropriate technology-based solutions that will enhance their independence and participation. As a matter of fact, there are a wide range of high- and low-tech solutions that offer empowerment for people with functional limitations, but for many reasons, some of which will be discussed in this chapter, matching people with the right technological solution for them is not an easy task. Professional expertise is therefore essential and ever since assistive devices became more widely available, professionals with differing backgrounds, such as occupational therapists, physiotherapists, speech and language therapists, psychologists, special needs teachers, educators, rehabilitation engineers, information and communication technology (ICT) experts, and others, have started to specialize in Assistive Technology. Ideally all these professionals have had some basic preparation in AT on which to build in order to become an AT professional. In other

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words, AT professionals will typically have a disciplinary background in some domain of the health, education, or technology sectors and become AT experts through further formal and non-formal learning and work experience. According to the Guidelines for Lifelong Learning in Assistive Technology developed under the *Keeping Pace with Assistive Technology* project (Gresswell and Hoogerwerf 2007), levels of professional development in AT are determined by different factors, all related to performance requirements, such as the particular concerns of the professional, the depth of the knowledge demanded for the utilization of available solutions, deployment strategies and their implementation, and responsibilities in the process of selection and recommendation of solutions to people with disabilities. The latter process involves user-centered needs assessments, i.e. identifying solutions and implementation paths in collaboration with the user. This process might be actuated in a social, educational, or medical setting, but ideally it would take place in a context in which all these different domains are drawn upon.

Making sure that the user is at the center of this process is an important prerequisite for various reasons, including ethical ones. Ethical behavior in AT provision involves recognizing the importance of values such as self-determination, equal opportunities, and justice as the basis of the AT assessment and implementation process (Vanhove 2011).

Many AT professionals work in multidisciplinary teams, either in a context that provides general rehabilitation in which AT provision is one of the many considerations (Steel et al. 2011) or in specialized AT centers (Hoogerwerf et al. 2002), as it is their firm belief that successful outcomes are the result of the integration of different viewpoints.

Although AT professionals are important stakeholders and gatekeepers for the development of BCI applications for people with disabilities, their knowledge and understanding of BCI is often limited and vague. It is expected that studies involving users outside BCI research laboratories will increase this knowledge, especially when the added value of BCI applications compared to other AT solutions can be demonstrated.

5.1.2 Assistive Technology and Related Fields

The Association for the Advancement of Assistive Technology in Europe (AAATE) defines AT as an umbrella term that refers to "… any product or technology based service that enables people of all ages with activity limitations in their daily lives, work, education and leisure" (AAATE 2009). This definition is very broad and includes both mainstream technologies and special devices designed specifically for people with disabilities. It further includes services, often remotely delivered, that enable people in their environment, such as telecare services, translation services, or GPS and navigation systems and services. As a matter of fact, it could be said that many assistive technologies are enabling technologies because they allow access to opportunities that are normally only available to people without disabilities.

It is important to highlight that assistive technologies are not just "compensating" for impairments by allowing access to opportunities that might be considered normal for people without disabilities. Just like any other technology it has the potential to empower people beyond its strictly intended function, thus creating other opportunities, sometimes even unexpected. The act of installing a lift does not just allow a person to leave the house. It might also remove a significant barrier to employment, education, or social life.

Nevertheless, enablement would be more successful if opportunities were inherently accessible. As people are not only disabled *in* their environment but also *by* their environment, an important area of concern for AT professionals is the accessibility of mainstream products, systems, and services. Products, systems, and services that are designed according to *Universal Design* (UD) principles are intended to be more accessible for people with disabilities than those that are not designed according to those principles. In recent years, UD principles have started to be successfully applied on a wider scale. UD is the process of designing environments, services, and products to be usable, as far as possible, by people with a wide range of disabilities without the need for special adaptation (Centre for Excellence in Universal Design 2013). UD leads to more opportunities for the inclusion of people with disabilities in society and makes the border between AT devices and mainstream technologies less clearly defined (Pullin 2011). When environments are designed not only to be accessible, but also to support people in their daily lives, we speak of *Ambient Assisted Living*.

The rapid development of ICT has not left the field of disability untouched. New opportunities, some of them previously unimagined, have become widely available and have led to a wealth of applications in the field of assistive technology.

However the way digital content is presented has also created new difficulties. E-accessibility is an important area of interest and research. Complementary to assistive technology it aims at solving problems of accessibility to digital content, so predominantly in relation to the mainstream digital environment.

BCI applications targeting people with disabilities have not, therefore, presented themselves in a vacuum, but in an environment where other solutions are available and where the thinking on AT is not only governed by what is technically possible, but also by what is desirable and by environmental, economic, political, and educational considerations.

5.1.3 Identifying Appropriate Solutions

The process of selecting and using a technology is a familiar one to most people. Studies of user acceptance of new technologies have highlighted the importance of expected benefits and perceived ease of use (Davis 1989). However, a wide variety of factors are involved in technology take-up. The most important, of course, concern the needs or wishes of an individual. Why is the technology needed? In what kinds of activities does the person want to participate or enhance his/her independence? Is the technology needed to allow or facilitate communication, learning, mobility, social networking, etc.? The border between needs and wishes is not always clear, but in a citizenship model of disability, as opposed to the medical model where the person is merely considered a non-proactive patient, the wishes of a person are equally important. For example access to games or social networks might not be relevant needs from a strictly medical point of view but from a social or rights-based perspective they certainly are.

Then there are factors related to the health of the person, which ever since the adoption of the International Classification of Functioning, Disability and Health (ICF) by the World Health Organization (World Health Organization 2001) have been referred to as “body functions” and “body structures”. Each person is unique and functional restrictions of various kinds can impact on their potential to use mainstream devices, especially when these are not designed according to universal design principles.

Other factors concern the environment in which the technology is to be used and the conditions in that environment, e.g. indoor or outdoor, quiet or noisy, standalone or connected to mainstream technologies. There are a wider range of such variables that impact on the choice of one solution over another or on the creation of a solution with the highest possible level of usability under different conditions.

An AT professional trying to support a client with disabilities in identifying an appropriate solution will have to take these all variables into consideration before recommending a choice of one solution over another. This also goes for BCI-based applications, which in certain cases have to prove that they are a better choice than other technologies.

In the case of BCI technology for people with disabilities we are still speaking about new and innovative technologies that are somewhere between the research & development stage and the demonstration stage. Deployment will follow when AT experts outside the immediate BCI research community, “early adopters” (Rogers 1962), start to design and develop highly personalized solutions for their clients.

At this stage in the knowledge translation process (Sudsawad 2007), collaboration between end users, AT experts (professional users), and BCI system developers is fundamental. All AT provision that includes BCI components will need to be implemented according to User-Centered Design principles (UCD; ISO 2010), as no standard solutions are available yet (Holtz et al. 2013).

5.1.4 Meeting the User’s Needs: The Evaluation of Outcomes

A key question that AT experts face is the following: When can technology deployment be considered successful?

Knowing what constitutes a measure of AT success and factors related to a user's acceptance of a technology can help professionals involved in designing BCI-based applications to set clear objectives for their technology and, most importantly, learn a common language for communicating with AT professionals and users.

The term *outcome* identifies the effects of any intervention. In the specific case of AT interventions, outcomes refer to (Fuhrer et al. 2003):

> [...] the changes that are produced by AT in the lives of users and their environments. Those changes may range from improvements in delimited aspects of users' motor, sensory, and cognitive functioning to enhancement of their social participation, vocational productivity, and sense of control over their own lives. The cascade of outcomes may extend to individuals' environments as well and include, for example, a reduction in caregivers' assistance and decreased costs to insurers and social welfare agencies.

What is clear from this definition is that assessing the outcomes of an AT intervention means measuring the impact of any device not only in relation to the specific functions which are supposed to be replaced or compensated by the AT, but also, and equally importantly, on aspects related to psychosocial and environmental dimensions. Indeed, measuring AT-related outcomes is a complex process which goes far beyond the evaluation of the usability of an AT device. Once AT professionals and the user have together identified a possible AT solution that seems to match the user's needs, the technology (or set of technologies) involved have to be tried and tested, and often modified over an extended period of time, within the context of the user's everyday life. How long this will take cannot be predetermined as it should continue until the technology becomes an integral part of the user's life.

During this phase in the AT provision process, the role of the AT professionals is to collaborate with the user in order to find answers to the following questions:

(a) What is considered as successful use of AT by the particular user?
(b) What factors (individual characteristics of the user, family environment, training opportunities) influence outcomes and to what extent?
(c) Is the aid becoming an integral part of the person's life?

In order to answer these questions and avoid the non-use or abandonment of AT devices, AT professionals have started to develop instruments based on evidence for measuring the effects of AT solutions on factors related to the user's experience which seem to affect the user's acceptability of an AT device (Federici et al. 2012). In particular, the user's attitudes and user satisfaction are important factors that should be taken into account in any outcomes evaluation process. In this section, we briefly review two commonly used evidence-based instruments which can be used by BCI researchers and AT professionals together to explore the opinions of the end users over specific potential use motives and barriers, and to investigate their general satisfaction and level of intention to use any new AT device in order to develop solutions which will fit the ever-changing user needs.

First, Matching Person and Technology (MPT; Scherer 1998) is a model which offers a wide range of tools both for clinical and research purposes. MPT is the most widely validated client-centered approach to AT provision. Central to the model is the idea that both the use and the non-use of any AT solution is mainly influenced by three interrelated factors: (i) the *milieu*/environment(s) in which the user interacts with the technology; (ii) personal factors unique to any user, like preferences, predisposition to use the AT solution, and his/her needs; and (iii) the characteristics of the technology. In particular, the *Assistive Technology Device Predisposition Assessment* (ATD PA) scale of the MPT set of tools represents a thorough instrument for measuring the user's attitudes towards specific AT solutions, taking into account all the factors that could affect the user's attitudes towards the technology. The ATD PA asks users about their subjective satisfaction in several functional areas (nine items), asks them to prioritize the aspects of their lives they consider most important to improve (12 items), and profiles their psychosocial characteristics (33 items). The last worksheet of the ATD PA asks the users to rate 12 aspects which can affect the use of a particular type of AT solution and could be used by researchers to collect specific information about users' attitudes towards a particular AT device.

User satisfaction with an AT solution represents another important dimension which should be measured during the outcomes assessment process. A definition of user satisfaction with any AT solution is provided by Demers and colleagues (2002) and refers to a person's critical evaluation of several aspects of a device and may be influenced by expectations, perceptions, attitudes, and personal values. These authors developed a widely employed instrument for measuring user satisfaction with an AT device named *Quebec User Evaluation of Satisfaction with Assistive Technology* (QUEST 2.0; Demers et al. 2002). The questionnaire consists of 12 items divided in two scales. In the first scale, eight items focus on dimensions related to the device (comfort, dimensions, simplicity of use, effectiveness, durability, adjustments, safety, and weight); while in the second scale, four items focus on the quality of service (professional service, follow-up services, repairs/servicing, and service delivery). The study conducted by Zickler and colleagues (2011) provides an example of how QUEST 2.0 can be employed for the usability evaluation of BCI-based AT.

5.2 BCI Technology: The AT Professional's Perspective

This section, written by AT professionals, draws upon the experience of our AT team in working on a major European BCI research project and on its experience of testing the non-invasive BCI applications for communication, control, and leisure developed in the project with a variety of end users in different conditions.

5.2.1 Just Another New Assistive Technology?

The AT ICT sector has developed greatly in the last 30 years and, in many ways, can now be considered to have reached maturity. The contexts in which AT ICT technology can be employed are well defined and there is general agreement on their classification. Among the most important fields of application are access to ICT devices with interfaces adapted to the various needs of users, access to digital content (e-accessibility), augmentative and alternative communication (AAC), environmental control, and smart homes/domotics.

As far as AT devices are concerned, a mature market now offers a wide range of solutions at differing prices covering many of the operational needs of users.

Over the years, alongside the development of technological solutions, protocols and methods of use have also been developed, as well as modes of assessment involving multidisciplinary teams and methodologies for the assessment of outcomes. In this scenario, when a new technological solution is made available, whether by the market or as a result of a process of research and development, it is evaluated by AT professionals, ideally at a specialist AT center. Given the level of sophistication that has been reached in the sector, most new solutions take the form of modest improvements to existing products. In other cases, however, a product may extend AT functionality to a whole new class of ICT solutions: This is true, for example, of the special input modality recently proposed for smartphones and tablets. In all these cases, evaluation by AT experts involves a variety of activities, including a technical and functional assessment of the new product, in comparison with the existing solutions covering similar end user needs, as well as field trials, possibly in collaboration with expert final users in real-life situations.

The appearance of a completely new class of solutions happens comparatively rarely nowadays, and their development makes sense if they promise potential improvements on existing solutions, are able to meet the needs of users who have not been able to benefit from existing solutions, or can offer novel modes of use. An important sector in which there is still room for new developments, and where breakthroughs are needed, is that of human–machine interfaces, understood in the broadest sense of the term, relating not just to technology but also to methods of use and the modes of interaction available to users. One of the most significant cases of recent years has been that of gaze-controlled technology, which has made it possible to interact with technology using a part of the body, the eye, whose primary function is that of receiving information as opposed to controlling technological devices. It is worth noting that, while gaze-controlled technology has been used successfully for some considerable time, the range of users was largely limited to people with relatively little involuntary ocular or physical movement. A significant change occurred comparatively recently when systems and software were developed that were able to accommodate involuntary physical and ocular movement (e.g. due to nystagmus). These changes have meant that many disabled people can now control technology using their eye movement who were unable to before, including some people with significant involuntary physical movement due to, for example, athetoid cerebral palsy, or people with involuntary eye movement following a stroke.

Nonetheless, the interaction provided by gaze-controlled systems is still linked to a relatively well-controlled eye movement and so there remains the problem of how to interact with technological solutions without any kind of controlled muscular activity or any physical movement at all. For this reason, and also because of the particularities linked to the possibility of interpreting at least some aspects related to the mental states of the users, BCI is now considered to be an extremely interesting field of research by many AT experts, potentially filling or reducing the gap still left by gaze control and other assistive technology control devices. For example, Donegan et al. (2011) emphasize the need for BCI to be investigated as a viable alternative to gaze control, particularly for those who are in a completely locked-in state where gaze control might not be an option but where, for example, the user might use a BCI to make selections from a range of auditory prompts.

5.2.2 Discovering the BCI Together with End Users

When the team became involved in the project on BCI, it brought with it know-how accumulated through 30 years of experience in the field of AT. Within the project the team has been involved, among other things, in the definition of experimental protocols and in the testing of solutions with end users.

The following objectives have been pursued:

- Considering BCI applications no differently to any other AT solution
- Highlighting the similarities and specificities of BCI technologies and existing AT
- Involving AT experts and skilled AT users in a user-centered design process based on the evaluation of the new technology in real-life environments
- Evaluating not only the functioning of the prototypes, but also broader aspects related to human–machine interaction such as user acceptability

These objectives have guided the definition of the project's test procedures and protocols.

Regarding the selection of the potential end users of these new technologies, the team has decided to move away, at this stage of development of the prototypes, from those groups that are typically considered potential BCI beneficiaries, for example people with locked-in syndrome and ALS patients for whom the BCI could provide the only possible means of communication. Although it is a long-term aim to provide these groups with functional solutions, it was felt that for many reasons of an *ethical*, *political*, and *practical* nature it would be better to engage experienced AT users with severe motor disabilities but at least one other communication channel (body signal) in more stable physical conditions (Hoogerwerf et al. 2010).

The *ethical reasons* here concern the management of expectations and frustration, including the emotional stress that could arise from the product not being immediately available even in the case of positive results, as well as other considerations such as lack of choice and lack of balance in the relationship of power between the researcher and the user.

The *political reasons* concern the difficulty of creating the conditions for an early and full involvement of these groups in all phases and aspects of the project. Such involvement is necessary in order to make the design process as user-driven as possible and requires users who are fully aware and able to choose, consent, agree, or disagree.

The *practical reasons* involved concern the need to reduce disturbance arising from those non-BCI-related factors that often characterize hospitals or other institutional care settings (noise, the presence of non-relevant people, prevalence of a medical approach, shortage of time, life support equipment, etc.).

5.2.3 New Interfaces for New Forms of Interaction

One of the aspects that most differentiates BCI from other AT technologies is the nature of the interaction between the system and the user, which takes on completely new characteristics that can only partly be related to the experience of other AT solutions.

From the point of view of AT experts, BCI may not represent a unique class of solutions, but they will have to turn to various types of BCI as points of reference rather than to their previous experience of AT solutions. For example the interaction with BCI applications based on a paradigm of evoked potentials, for example by a flashing cursor highlighting icons represented on the screen, is completely different from the interaction with a BCI application based on the motor imagery paradigm, where a signal is retrieved by the person imagining for example the movement of a hand. Also the training to develop the necessary control skills requires a different approach.

In other words, users (and this also goes for most AT professionals) are not used to the new forms of interaction possible with BCI. During testing, traditional interfaces for access to ICT, which distinguish sharply between output channels and input channels, proved to be ill suited to the forms of interaction possible with BCI. And this situation can therefore easily give rise to problems of usability.

In addition to problems related to usability, another problem to address is that of acceptability. This is a very important issue for interfaces which are so new, and it is also a more invasive issue than others. For these reasons it is evident that interface and interaction paradigms are something that cannot be forced on users and must be designed with their input.

5.2.4 *Objective: At the User's Home*

The ultimate objective of the experimentation was to test the prototypes in real situations and in the context of the daily lives of the users. The project provided for the testing of application prototypes at different stages of their development. This allowed the team to plan its testing activities over time and in different settings. Preliminary prototypes were tested at an AT center in order to benefit from a more protected environment in which tools were readily available for the solution of any potential technical problems that might arise.

In order to maximize user contribution, it was also decided to carry out these tests with the help of more experienced AT users, also because users of this kind would be more aware of the limitations of preliminary prototypes (this is an important factor with a view to avoiding disappointment in the event of negative results due to technical problems). In later stages, when the prototypes were more developed and reliable with greater functionality and human–machine interfaces (HMI) developed within the UCD process (ISO 2010), testing was extended to less experienced technology users and those with more severe disabilities and in their home environments.

5.2.5 *Results and Conclusions*

The very fact of having BCI applications for everyday activities with prototypes being tested in the context of everyday life is a big step forward and finally makes it possible to compare BCI with alternative AT solutions in similar contexts.

As with many other technologies, the success of AT solutions is often related not so much, and not only, to the main functions, but to a multiplicity of details regarding both hardware and software. The most important are those relating to the human–machine interface for the end user and for the operator and the procedures for use and assembly, dismantling, and activation.

The criteria proposed by Batavia and Hammer for AT device evaluation, reflecting a very pragmatic approach and probably therefore still useable, can serve as a framework of reference for AT experts to make a comparison between different assistive technologies (Batavia and Hammer 1990). However, the comparison between advanced BCI prototypes and products currently available on the AT market is only possible for some aspects. There is not much sense, in this stage of development of BCI applications, to evaluate factors such as affordability, consumer and supplier reparability, durability, ease of maintenance, flexibility, and securability.

Regarding other criteria such as compatibility, dependability, ease of assembly, effectiveness, learnability, operability, physical comfort and security, personal acceptability, and portability, it has nevertheless been possible to evaluate the advanced prototypes developed in the project.

As the prototypes have been able to successfully perform the functions for which they were designed and developed, the BCI can definitely be considered a new AT. The possibility to use them without any muscle movement has also been ascertained; an element that substantially differentiates the BCI-driven AT applications from all other AT solutions.

From the point of view of compatibility, the tested prototypes were based on standard ICT hardware and software solutions, while the hybrid BCI approach developed in the project successfully allowed the BCI to be interfaced with other AT solutions, both hardware (for example special input devices) and software (for example on-screen keyboard or integrated software environments).

The non-invasive BCIs tested confirmed to be input interfaces with low bit rates. Like other AT with similar characteristics, such as those based on a scan approach, they require, in order to improve the productivity performance, dedicated software modules like word prediction software and interfaces optimized for better access to frequently used functions. The prototypes were complex machines, composed of numerous hardware and software modules, and accordingly were quite complex to assemble. However future products developed for the AT market might be based on simpler, more integrated architectures, with a complexity similar to the ones of other AT solutions, such as eye trackers.

Caps and the electrodes are still critical elements in BCI technology. The development of caps which are comfortable and aesthetically pleasing and of electrodes which are comfortable and dry has to be pursued with determination. The setup procedures that operators and assistants have to perform in order to allow the end user access to BCI solutions is still a complicating factor. It is very important that these setup and configuration operations are simplified, and troubleshooting should be included in the setup software. The world of neural signals is often completely unknown to end users and their carers. Therefore, where possible the extraction of suitable features from the signals, the identification of classifiers, the management of training sessions, and the management of problems should be dealt with directly by the operating systems.

The end goal is that well-functioning BCI solutions respond to the needs of specific groups of end users, probably including those with complex disabilities, and are reliable, well supported, and competitively priced compared to other solutions. If there is market potential, industry will invest and solutions will become widely available. This will also lower the costs. It is envisaged that AT professionals will play a key role in further fine-tuning the systems and in fully realizing their potential. Nevertheless they won't be able to do this alone. More basic research is still necessary to better explore and cope with BCI's intrinsic limitations.

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Chapter 6
Psychological Perspectives: Quality of Life and Motivation

Sonja C. Kleih and Andrea Kübler

6.1 Quality of Life in End-Users of BCI Technology

The main target population for BCI technology is people in the locked-in state (e.g. Kübler et al. 2001) as their communication possibilities are severely restricted (Doble et al. 2003). If the locked-in state occurs as a consequence of progressive disease like Amyotrophic Lateral Sclerosis (ALS; Kiernan et al. 2011; Mitchell and Borasio 2007), prejudice exists (Bach 2003) that the people affected by such disease must suffer from poor quality of life and depression or even experience the wish to die as they can only express themselves to a very limited extent (Smith and Delargy 2005), are exceedingly dependent on caregivers (Doble et al. 2003) and life expectancy is usually short (Mitchell and Borasio 2007). Certainly cases exist for whom life becomes a tremendous or even unbearable burden with disease progression. Meyer and colleagues (2008) describe eight cases of people diagnosed with ALS who at various stages of disease progression chose the termination of artificial ventilation and decided for assisted death. Acute depressive symptoms were precluded before the end of life decision had to be formulated explicitly by the person. The patients then were informed about other possible treatments that could alleviate symptoms and the possibility of withdrawal from their prior decision at any time. In those cases where a person adhered to his or her end of life decision, artificial ventilation was terminated after pharmacological intervention leading to strong sedation for symptom control or to an anesthesia-like state (Meyer et al. 2008). While in the former the goal was to pharmacologically decrease possible agitation and feelings of fear resulting from dyspnea while being conscious, in the latter diminishing the consciousness level to a non-awakening state was the main goal.

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Even though it might seem comprehensible for healthy people that those diagnosed with ALS and being artificially ventilated could at some point express the wish to die (Meyer et al. 2008), one should be cautious to draw general conclusions on the basis of such reports. Single cases' decisions do not permit generalizations concerning the wish to die or the existence of depression in people diagnosed with ALS or the locked-in state. Indeed, a long-term study on activity, participation and life satisfaction of people in the locked-in state (LIS) by Doble and colleagues (2003) revealed that after 11 years, 13 of the original 24 people with LIS had survived and only one of them expressed the wish to die while the others either had considered euthanasia and rejected it (n = 5) or never even had considered it (n = 7). Similar findings were reported in a sample of 54 people in the locked-in state of whom also only one reported to have frequent suicidal thoughts while 33 reported to have never thought about suicide (Bruno et al. 2008). Likewise, in a sample of 89 people diagnosed with ALS in all stages of the disease the average score for the wish to hasten death (4.43) was far below the critical clinically relevant threshold (>10; total score 20, Schedule of Attitudes towards hastened Death) (Lulé et al. submitted).

The same positive results were found for the prevalence of depression among people diagnosed with ALS. Even though depressive symptoms occurred in 12–80 % of cases depending on the study (n = 28 included in the review), the rate for a depression disorder was 5.5 % provided a structured interview was applied (Averill et al. 2007). This result suggests a depression rate that is almost equivalent to that of the general population (Averill et al. 2007). Several other studies in which the DSM-IV criteria for depression diagnosis were used also suggest a relatively low and reliable percentage of depression in people diagnosed with ALS of between 9 and 11 % (Ganzini et al. 1999; Hammer et al. 2008; Kurt et al. 2007; Rabkin et al. 2005). Furthermore, when comparing subjectively reported Quality of Life (QoL) in people with ALS and healthy controls, no significant group differences were detected (Lulé et al. 2008). With disease progression even higher QoL ratings were found in comparison to persons in earlier ALS stages, indicating that health state does not predict QoL (Lulé et al. 2008; Matuz et al. 2010). Doble and colleagues reported on 13 individuals in the locked-in state who were satisfied with their lives, were actively involved in family decisions and their presence was valued by the family (Doble et al. 2003). In another study 37 of 53 people with LIS reported enjoying recreational activities such as hobbies, television, crafts, etc. and 36 reported to be satisfied with their role in the family (León-Carrión et al. 2002).

To conclude, the majority of people in the locked-in state seem to adapt successfully to their situation without major negative psychological effects, notwithstanding that there is also a minority of cases who do not experience their life worth living. This imposes the question on the origin of such discrepancy in coping; a topic addressed, for example, by Matuz and colleagues (2010). In a sample of 27 participants diagnosed with ALS, the authors found subjective QoL to be high and depressive symptoms to be less frequent when (1) participants subjectively perceived social support (2) used specific coping strategies and (3) had confidence in their coping potential. The authors found high confidence in one's coping potential to be an alleviating factor specifically on depressive symptoms (Matuz et al. 2010). They pointed out that this internal confidence may reflect a strong internal locus of control in which hopelessness is rarely experienced (Matuz et al. 2010). The importance of a high internal locus of control was also supported by other studies (Doble et al. 2003; Lulé et al. 2008), and is independent of physical well-being. Thus, a high internal locus of control can also be experienced by people in the locked-in state – provided communication is possible (Doble et al. 2003; Lulé et al. 2008)!

Communication is mandatory for social interaction and nowadays access to the internet is the prerequisite for full participation in social life (e-inclusion; Zickler et al. 2011; Kleih et al. 2011a). As locked-in people are almost completely paralyzed with tetraplegia and anarthria, assistive technology (AT) is needed for communication which is either based on eye movement or even independent from voluntary muscular control, e.g. eye trackers or brain-computer interfaces (BCIs; Kübler and Müller 2007). It has been shown in abundance that muscle-independent communication via BCI is possible, even for people in the locked-in state (Birbaumer et al. 1999; Kübler et al. 1999; Piccione et al. 2006; Sellers and Donchin 2006; Hoffmann et al. 2008; Nijboer et al. 2008a; Kaufmann et al. 2013). Different input signals can be used for BCI control (see Kübler et al. 2001 for an early review and Wolpaw and Wolpaw 2012 for a recent) and, to date, those which are based on event-related potentials elicited in an oddball paradigm (P300-BCI) provide the most reliable and effective control (Kleih et al. 2011a; Fazel-Rezai et al. 2012 for reviews). While numerous studies exist on improving classification of the acquired signal and, albeit fewer, on the presentation of stimuli or feedback, the persons in need of BCI are only rarely in the focus of research and little is known about how psychological factors influence BCI performance. Thus, to date, the only psychological variable potentially influencing BCI performance which has been systematically investigated and manipulated and thereafter proven to be efficacious is motivation (Kleih 2013; Kleih et al. 2010a, b, 2013).

6.2 Motivation Influences BCI-Based Communication

The positive effect of highly subjectively reported motivation on BCI performance in healthy participants was not only found when motivation was monitored (Käthner et al. 2013; Nijboer et al. 2008a, b; Kleih et al. 2011b, c), but has also been supported by results of systematic manipulation of motivation (Kleih 2013; Kleih et al. 2010a, b, 2013).

For people in potential need of a BCI (further referred to as end-users; Zickler et al. 2011) we would readily assume high motivation to participate in respective studies. According to anecdotal end-user reports, their motivation seems to be twofold: One part may arise from the interest of being able to control a BCI system even though end-users are informed before each study that they will not be offered to keep the system at their home. The other part of motivation may arise from the personal belief of valuably contributing to BCI research and thus fostering AT-based communication (see chapter 2; Grübler et al. 2013). The only study including end-users that monitored motivation before BCI training was conducted by Nijboer and colleagues (2010). They assessed motivation with the Questionnaire for Current Motivation (Rheinberg et al. 2001) adapted to BCI (Nijboer et al. 2008a). In the QCM-BCI motivation is assessed with four subscales: mastery confidence, interest, challenge and incompetence fear. Mastery confidence indicates a person's belief of being competent to successfully handle a task while interest indicates how appealing a topic seems to be for a participant. Challenge assesses the task's performance aspect subjectively judged by the participant while incompetence fear measures how likely a person judges him- or herself to be unable to master a task. Nijboer and colleagues (2010) found in two of six end-users the motivational components challenge and mastery confidence to be positively related to BCI performance while incompetence fear negatively influenced BCI performance in one end-user when using the P300 BCI. These results already indicated a potential relation between motivation and the ability to use a BCI.

To elucidate the influence of motivation on BCI performance it is mandatory to perform experimental studies. Thus, most recently, Kleih and colleagues (2010b) manipulated motivation in a sample of ALS end-users who participated in one session with a P300-BCI. Participants were offered a gift certificate (monetary reward) from an online store if they managed to spell more letters correctly in the second of two spelling blocks compared to the first one. We hypothesized that motivation could be increased by offering a reward for high BCI performance and that accuracy and spelling speed would be higher when being motivated by reward as compared to not being motivated.

Overall spelling performance of the ALS patients was exceptionally high with 98 % on average. We found that ALS patients' motivation cannot be increased by monetary reward as patients did not report to have felt more motivated by the gift certificate. But the strength of motivational components was linked to performance after the gift certificate was offered, albeit only in offline analysis (when analyzing the data without the patient still being connected to the system). We found a significant negative correlation between the spelling speed and mastery confidence. The more participants were confident about mastering the task, the faster they could spell with the P300 BCI system. Thus, although our reward manipulation failed, we found a reward-independent effect of motivation on BCI performance.

We conclude that the patients in our study participated because they were excited about trying BCI-based communication but not because they received a reward. Therefore, the results of this study can be interpreted in the light of the Cognitive Evaluation Theory (CET, Deci and Ryan 1985). In the CET, intrinsic motivation is defined as leading to actions that are taken because they are enjoyed; therefore the task itself is the major motivator. Extrinsic motivation, on the contrary, is defined as action taking because of reward (money or praise) anticipation after finalizing a task. Therefore, the task itself is a means of receiving the reward. The CET postulated that intrinsic motivation arises as a consequence of the

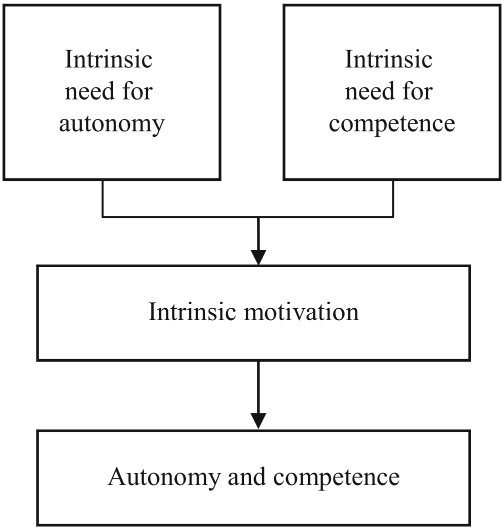

Fig. 6.1 The cognitive evaluation theory (Modified from Deci and Ryan 1985)

fulfillment of the need for autonomy and need for competence (Deci and Ryan 1985, see Fig. 6.1).

Using a BCI, participants could fulfill both of the needs postulated in the CET: The need for autonomy by participation as they independently decided to participate and experienced spelling words independent of the caregivers' support. Their need for competence could be fulfilled by achievement of high accuracies. Therefore, also the internal locus of control was very likely high, which could explain why further extrinsic reward could not increase participants' motivation. According to their reports, participants interpreted the gift certificate more as a confirmation that their participation in the study was appreciated instead of a real motivator and reported to have tried their very best as a consequence of the instruction in the beginning of the experiment (reward-independent motivation). We cautiously conclude that potential BCI end-users may be highly intrinsically motivated to use the BCI and if successful, perceive the locus of control internally. This feeling of autonomy together with the fulfillment of the need for competence might have further positive effects on end-users' quality of life, although the latter relation awaits confirmation.

In conclusion, motivation as a psychological variable of BCI end-users is related to BCI performance, albeit moderately. More research is required to specify motivational components and their possible influence on BCI operation, i.e. further experiments that manipulate motivation preferably in larger samples. The progress in hardware and software development has considerably improved BCIs and their applications. BCI-based communication is on the way to supporting end-users in need, thereby increasing quality of life. Especially for locked-in patients, reliable BCI-based communication could contribute to inclusion. To foster this process, further research is required, specifically focusing on the BCI users themselves who are still the largely unknown "variable" of brain-computer interaction. The psychological, biological, and social facets of the users and their environment therefore deserve more attention and investigation in the coming years.

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Chapter 7
Emerging BCI Opportunities from a Market Perspective

Christoph Guger, Brendan Z. Allison, and Günter Edlinger

7.1 Introduction

Brain-computer interface (BCI) systems are devices that directly measure brain activity to translate a user's thoughts into messages or commands. Users perform simple mental tasks, such as imagining hand movement or focusing on certain items on a monitor, and control applications such as spellers, Internet browsers, smart homes, or robots. BCI technology is advancing rapidly, as are closely related systems that passively monitor brain activity or facilitate recovery from conditions such as stroke. In this chapter, we review emerging trends and developments and discuss emerging market opportunities.

BCIs typically require a laptop, an amplifier designed to work with electroencephalography (EEG) data, an electrode cap, and software. However, emerging technologies are making it even easier to realize a BCI. For example, some new BCI systems require only a headband or modified headset to position the electrodes needed for relatively simple applications, and many groups now provide open-source BCI software (Chi et al. 2012; Brunner et al. 2013). Dry electrodes can provide signals just as good as those from gel-based electrodes in some BCIs, and can be ready to use in under a minute without the delay and inconvenience of electrode gel (Guger et al. 2012). BCIs are also getting cheaper, more effective in noisy environments, and better integrated with other technologies. These and other trends should encourage even broader adoption and new market opportunities (Allison 2010; Nijboer et al. 2011).

BCIs have four components (Wolpaw et al. 2002; Allison 2011). First, a *signal acquisition* mechanism must detect activity from the user's brain. Second, a *signal*

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processing system must use this information to determine what the user wants to do. Third, this information must be translated into *device commands*, which might move a wheelchair or select items to spell. Fourth, an *operating protocol* must govern how these devices interact with each other and with the user. Progress is being made on all of these components, drawing on concepts and lessons from neuroscience, psychology, human-computer interaction, medicine, communication, and many different engineering disciplines. New market opportunities are emerging due to progress in all four of these components. Although no fundamentally new signal acquisition systems have been developed – most BCIs still rely on the EEG recorded from electrodes on the head – active and dry electrodes have made EEG recording much more practical and convenient (Guger et al. 2012; Edlinger and Guger 2013). Active and dry electrodes also entail improved signal processing, with chips on each electrode that amplify the signal when it is recorded and thus reduce noise. Many new BCI applications are emerging or improving, such as BCIs to control orthoses, virtual environments, smart homes, mobile robots, and games such as World of Warcraft (Ortner et al. 2011; Kapeller et al. 2012; Scherer et al. 2012; Lotte et al. 2013). These applications are especially important for opening new market opportunities, since they provide new opportunities for end users to use BCIs for the applications they need or want. New and/or improved operating protocols such as intendiX and public domain software have made BCIs more accessible to users without a technical background (Brunner et al. 2013). We present some of these advancements in more detail below.

7.2 Emerging Directions

7.2.1 Research Trends

One way to explore these emerging trends is through the Annual BCI Research Awards. Each year, g.tec hosts a competition for the best BCI project that year. The award is selected by a jury of top BCI scientists, and encourages strong competition. About 60 projects are submitted each year, and the jury selects ten nominees (for details see Guger et al. 2013). The BCI Award is also meant to show trends, such as themes that become more or less popular across different years. In 2011, four projects used invasive technology (ECoG – electrocorticogram/spikes) and six projects measured brain activity non-invasively. Two nominated projects used evoked potentials and three projects motor imagery (MI). The division into application areas shows that control applications are most prominent (three), followed by robot control, communication, and speech reconstruction (two each), and finally by stroke rehabilitation (one). The winning team addressed a very important point to make BCI systems more robust in future utilizing gamma activity of the EEG spectrum. To more broadly explore the different facets of BCI research, we conducted another analysis with all 64 projects submitted to the 2011 BCI

Table 7.1 Properties of all of the projects submitted to the BCI Awards in 2010 and 2011

Property	2011 % (N = 64)	2010 % (N = 57)	Property	2011 % (N = 64)	2010 % (N = 57)	Property	2011 % (N = 64)	2010 % (N = 57)
Real-time BCI	95.3	65.2	**Stroke/ Neural plasticity**	12.5	7.0	**Sensation**	1.6	–
Off-line algorithms	3.1	17.5	**Spelling**	12.5	19.3	**Learning**	3.1	–
P300	25	29.8	**Wheelchair/Robot**	6.2	7.0	**Electrodes**	1.6	–
SSVEP	12.5	8.9	**Internet/VR**	3.1	8.8	**Other signals**	1.6	–
Motor imagery	29.7	40.4	**Control**	34.4	17.5	**Spikes**	12.5	–
ASSR	1.6	–	**Platform/ Technology**	9.4	12.3	**Authentication**	1.6	–
EEG	70.3	75.4	**Monitoring**	1.6	–	**NIRS**	4.7	1.8
fMRI	3.1	3.5	**Speech**	4.7	–	**Mechanical ventilation**	1.6	–
ECoG	4.7	3.5	**Coma**	3.1	–			

Award, and compared the results to all 57 projects submitted to the 2010 BCI Award. Table 7.1 summarizes the results. Among other trends, the 2011 BCI Award drew more submissions that described real-time BCIs, and also introduced many new properties.

Interestingly, only two projects worked on off-line algorithms, which used to be much more prevalent. This change shows that BCIs have become practical real-world devices. Most of the BCIs use motor imagery and P300s, and just a few use steady-state visual evoked potentials (SSVEP) or auditory steady-state response (ASSR). More than 70 % of the submissions use the EEG because of its simplicity and high time resolution, compared to just a few functional magnetic resonance imaging (fMRI), ECoG and near-infrared (NIR) projects. The most common applications among the 64 submissions are control, stroke/neural plasticity, and spelling. But there are also many new applications like monitoring, speech, coma patients, authentication, mechanical ventilation, learning and sensation that did not exist in 2010.

7.2.2 Examples from the Market

Until a few years ago, the primary market for BCI systems was research groups. Very few patients, or their carers, purchased BCIs for home use, mainly because expert assistance was needed to identify, assemble, install, configure, use, and maintain the BCI system. Therefore, the number of BCI systems sold per year was too small to foster broad adoption, and did not encourage expensive or speculative improvements. Recently, BCI systems have been designed for simple games and entertainment purposes. BCIs for conventional purposes – providing communication and control to severely disabled users – have also become more practical. BCI technology is gaining attention for new directions such as stroke rehabilitation, functional brain mapping, coma assessment, and other applications that could greatly expand the markets interested in BCIs. In this section, we review these and other emerging directions.

7.2.2.1 Spelling

The first commercial BCI system for home use, intendiX, has been purchased and used by people without technical backgrounds, who use it to provide needed communication for patients. IntendiX is designed to be installed and operated by caregivers or the patient's family at home. The software has been tested and revised with non-expert users to ensure that intendiX can provide useful communication without help from people with special technical skills. The system consists of active EEG electrodes to avoid skin abrasion, a portable biosignal amplifier, and a laptop or netbook running the software under Windows. The electrodes are integrated into the cap so the intendiX electrodes can be mounted quickly and easily. IntendiX relies on an EEG component called the P300 and related components, and studies have shown that nearly all healthy adults can control a BCI using these components (Guger et al. 2009, 2012). The intendiX software can display the raw EEG so users can inspect data quality, but also automatically informs the user if the data quality on a specific channel is inadequate. The first time the system is used with a particular person, a brief training period is necessary to teach the intendiX software how to best classify the data. Typically, a user must spell five characters (specified by the system), which takes under 5 min. The EEG data are used to calculate the user specific weight vector, which is stored for later usage. After that, users can freely spell without any further training of the user or the system. While the initial training period typically entails 15 flashes per row and column, users can then reduce the number of flashes and thereby spell more quickly. The user can specify the number of flashes needed to select each item, or use a statistical approach that automatically detects and selects the optimal number of flashes. The latter approach has the advantage that no characters are selected if the user is not looking at the matrix or does not want to use the speller (Fig. 7.1).

IntendiX recently added an alternative matrix in which the icons change to celebrities' faces when flashing, instead of turning into color-reversed versions of the same icon. This "FACE-speller" mode seems to elicit stronger changes in the EEG than the regular flash mode, and thus improves accuracy (Kaufmann et al. 2011; Jin et al. 2012). Tests with over two dozen volunteers who used intendiX in field settings have shown a clear performance improvement using the FACE-speller mode.

7.2.2.2 Screen-Overlay Control

In 2012, another new intendiX application called "SOCI" – Screen-Overlay Control Interface – (Kapeller et al. 2012) was released. SOCI is designed to allow people to control a wide variety of applications with a BCI, and has been validated with more advanced and mainstream games such as World of Warcraft and Angry Birds. The system allows users to overlay the PC screen with a mask that contains icons used to control the program running on the screen. Unlike the default intendiX system, SOCI uses the steady-state visual evoked potential (SSVEP) approach, which also allows effective control for most users (Allison et al. 2010). The different icons on the monitor each flicker at certain frequencies. When the user pays attention to one of the icons, its flickering frequency can be detected in the EEG, which is picked up by a few sensors on the back of the user's head. Then, the system executes a command that is assigned to that icon, such as typing a letter on the keyboard. Using its advanced sensors and recently upgraded signal processing algorithms, SOCI can detect these different brain signals with an accuracy of up to 100 %. The goal of SOCI is to provide a tool that can control many different PC applications without requiring any muscle activity. For example, users could play many different games, opening new markets for different types of gamers. Many games are demanding given the speed and accuracy of a typical BCI, but many users have nonetheless

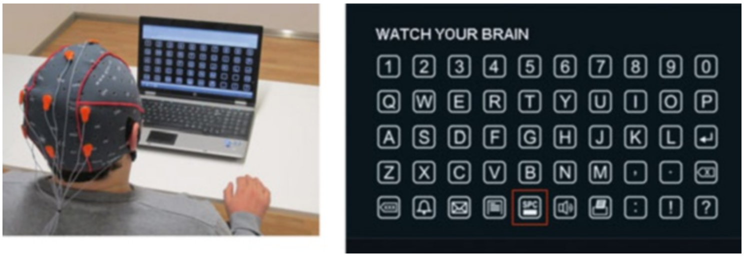

Fig. 7.1 The *left panel* shows the user wearing active dry electrodes in front of a laptop. The *right panel* shows the default intendiX layout, with five rows and ten columns of letters and other characters. In addition to spelling, the user can send different special commands, such as: (i) copy the spelled text into an editor; (ii) copy the text into an email; (iii) send the text via text-to-speech facilities to the loudspeakers; (vi) print the text; or (v) send the text via UDP to another computer. Each of these functions is associated with a specific icon. Users can easily change the content and layout of the board

reported enjoying such games. Online gaming also provides a way to connect disabled or healthy people to rich online communities with millions of people.

7.2.2.3 Painting

Another specialized intendiX module, intendiX Painting, lets users paint without moving. This module uses flashing characters with the P300 approach to select icons, like the default intendiX system, but the icons show different commands to paint instead of spell (see Fig. 7.2). For example, users can choose different colors, shapes, sizes, and positions on a virtual canvas. Hence, intendiX Painting could bring BCI technology not only to patients but also to a new market: artists. Moreover, some users who might otherwise have little interest in BCIs for other functions might enjoy painting with their brains. The painting system draws on research from Andrea Kübler and Adi Hösle and colleagues, who have shown that some severely disabled people "greatly enjoyed" the BrainPainting approach (Münßinger et al. 2010; see also Chaps. 8 and 9 of this book).

7.2.2.4 Connecting Minds

Many futurists believe that people in the distant future will use advanced technology to work together more directly, something like a "hive mind". People could use technology to help them not just work together but also think together, accomplishing goals more quickly and effectively. That future may not be so distant. Recently, the intendiX speller was used for a demonstration called "Hyperscanning" that represents an important step toward direct cooperation through thought alone. Today, several different groups have EEG-based P300 spellers that can identify targets reliably with about three flashes per letter (Fazel-

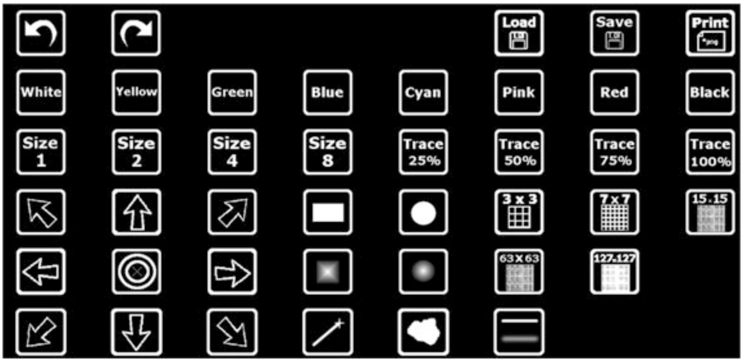

Fig. 7.2 IntendiX Painting; screenshot of the main screen

Rezai et al. 2012; Guger et al. 2012; Jin et al. 2012). But, despite very extensive efforts from groups around the world, faster communication has not been possible without neurosurgery, since brainwave activity from one flash is usually too noisy for accurate classification. Recently, eight people worked together to spell "Merry Christmas" through intendiX with only one flash per letter. intendiX spelled all 14 characters without a single mistake. Hence, by combining the brainwave signals across eight people, intendiX managed to substantially improve communication speed and accuracy. This approach could be used for cooperative control for many different applications. People might work together to play games or draw paintings by combining the intendiX SOCI or Painting modules, or could work together for other tasks like making music, voting or otherwise making decisions, or solving problems. Someday, users might put their heads together for the most direct "meeting of the minds" ever.

7.2.2.5 Avatar Control

Avatar control has been developed through the research project VERE (Virtual Embodiment and Robotic Re-Embodiment; http://www.vereproject.eu). The VERE project is concerned with embodiment of people in surrogate bodies so that they have the illusion that the surrogate body is their own body – and that they can move and control it as if it were their own. There are of embodiment considered: (i) robotic embodiment and (ii) virtual embodiment. In the first case the person is embodied in a remote physical robotic device, and which they control through a brain-computer interface. For example, a patient confined to a wheelchair or bed, and who is unable to physically move, may nevertheless re-enter the world actively and physically through such remote embodiment. In the second case the VERE project uses the intendiX ACTOR protocol to access the BCI output from within the eXtreme Virtual Reality (XVR) environment (VRMedia, Italy) to control the virtual avatars and to control the robotic avatars. The BCI is part of the intention recognition and inference component of the embodiment station. The intention recognition and inference unit takes inputs from fMRI, EEG, and other physiological sensors in order to create a control signal together with access to a knowledge base, taking into account body movements and facial movements. This output is used to control the virtual representation of the avatar in XVR and to control the robotic avatar. The user gets feedback showing the scene and the BCI control via the HMD or a display. The BCI overlay, for example, allows users to embed the BCI stimuli and feedback within video streams recorded by the robot and the virtual environment of the user's avatar. The user is situated inside the embodiment station, which also provides different stimuli such as visual, auditory, and tactile. The setup can also be used for invasive recordings with the electrocorticogram (ECoG). The avatar control is promising from a market perspective because it could be used in rehabilitation systems, such as for motor imagery with stroke patients.

7.2.2.6 Stroke Rehabilitation

One of the most common types of brain-computer interface (BCI) systems relies on motor imagery (MI). The user is asked to imagine moving either the right or left hand. This produces specific patterns of brain activity in the EEG signal, which an artificial classifier can interpret to detect which hand the user intended to move. This approach has been used for a wide variety of communication and control purposes, such as spelling, navigation through a virtual environment, or controlling a cursor, wheelchair, orthosis, or prosthesis (Ortner et al. 2011, 2012; Scherer et al. 2012; Edlinger and Guger 2013; Lotte et al. 2013). However, in the last few years, a novel and promising application for MI-based BCIs has gained great attention. Several recent articles have shown that MI-based BCIs can induce neural plasticity and thus serve as important tools to enhance motor rehabilitation for stroke patients. In other words, the overall goal of the BCI system is not communication, but improved stroke recovery (see Chap. 4 of this book). If BCI technology can facilitate stroke rehabilitation, then the market could broaden dramatically.

7.2.2.7 Functional Mapping

BCIs could also become useful to coma patients (see Chap. 3 in this book). Some research to assess cognitive activity in coma patients relies on fMRI, which can be very powerful. But fMRI is expensive, very bulky, and requires much more time than EEG-based assessments. fMRI systems can be especially problematic for patients for other reasons. For example, fMRI scans are ineffective in patients with uncontrollable movements and impossible for patients who have metal implants or who rely on medical equipment containing metal. Therefore, the market for fMRI-based coma assessment is limited because many patients cannot be scanned at all, and others would prefer a simpler solution. EEG can however be useful for assessing cognitive state and allowing communication.

7.2.2.8 Invasive Options

The material presented above describes non-invasive systems that measure the brain's electrical activity from the surface of the scalp. While most BCIs rely on the EEG, some newer work has drawn attention to BCIs based on ECoG. ECoG-based systems have numerous advantages over EEG systems, including (i) higher spatial resolution, (ii) higher frequency range, (iii) fewer artifacts, and (iv) no need to prepare users for each session of BCI use, which usually requires scraping the skin and applying electrode gel. Recent research has demonstrated, over and over, that ECoG can outperform comparable EEG methods because of these advantages. For example, for over 20 years, researchers have published work with EEG-based P300 BCIs, which allow users to spell or select other items from a matrix. Despite dozens of major papers describing improvements to every component of the P300 BCI, these systems are still fairly slow. However, in the very first P300 BCI using ECoG, the authors broke the speed record for BCIs, with the first BCI to break the 100 bit per minute barrier (Brunner et al. 2011). A critical reason for the speed improvement is the improved signal quality. Subjects could accurately spell based on only one target flash, whereas EEG-based P300 BCIs typically must average together the P300s resulting from three or more flashes before the signal is clear enough for accurate classification. Other work showed the ECoG methods can not only improve BCIs but also help us address fundamental questions in neuroscience. A few efforts have sought to map the "eloquent cortex" with ECoG (Brunner et al. 2009). That is, scientists have studied language areas of the brain while people say different words or phonemes. Results revealed far more information than EEG-based methods, and have inspired new ECoG BCIs that are impossible with EEG BCIs. Other work explored the brain activity associated with movement. This has been extensively studied with the EEG, leading to the well-known dominant paradigm that real and imagined movement affects activity in the 8–12 Hz range. ECoG research showed that this is only part of the picture (Brunner et al. 2009). Movement also affects a higher frequency band, around 70–200 Hz, that cannot be detected with scalp EEG. This higher frequency band is more focal and could lead to more precise and accurate BCIs than EEG methods could ever deliver.

Newer ECoG systems are also very promising for epilepsy surgery. Brain surgery is a therapeutic option for many patients with intractable seizure disorders and brain tumors. There are two major challenges when selecting the tissue to remove. On the one hand, the epileptogenic tissue or tumor has to be removed. On the other hand, essential brain regions like primary motor and sensory cortex, as well as brain areas supporting language and memory functions, have to be spared to avoid neurological deficits. The decision to perform surgery and what brain region to resect is based on several considerations including the clinical examination, history, MRI, non-invasive video-EEG monitoring, neuropsychological testing, metabolic imaging studies (PET, SPECT), functional MRI and magnetoencephalography (MEG). However, these tests sometimes do not provide enough

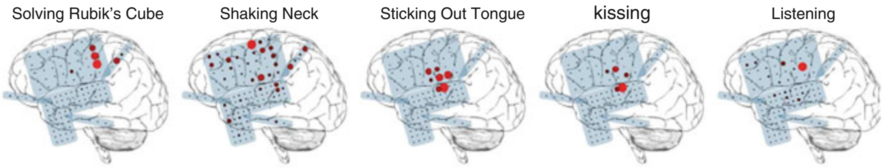

Fig. 7.3 Five different tasks, and the brain areas active during each of them

information. In these cases, ECoG electrodes may be implanted for an additional diagnostic procedure with invasive monitoring. The surgical procedure is then tailored such as to resect the affected areas while simultaneously sparing areas subserving important functions.

CortIQ was developed to identify functional brain regions in real-time with invasive sensors. Using that data, the system constructs and continuously updates a Mental Activity Profile (MAP). This MAP is unique for each patient, reflecting which brain areas are active during specific functions. Medical experts can get more relevant information than previously possible, presented in a straightforward fashion with clear and helpful images, with less work than currently required. CortIQ takes advantage of existing ECoG grids and consists of the following additional components: A biosignal amplifier (high quality biosignal amplifier with 24 bits and 256 channels), a real-time processing system (high performance real-time control unit to manage all devices in real-time, to analyze the signals and to visualize and store data), and a mapping system (high performance source localization and mapping system based on SIGFRIED mapping technology). CortIQ allows doctors to position the electrode grids they used (which can be selected from a library) over a schematic brain map. Patients perform different mental tasks (e.g. using the Ritaccio paradigm), and high gamma activity is indicated in the form of red circles over relevant electrodes. A large red circle shows that the corresponding electrode is placed over a brain area which is highly involved in that task (see Fig. 7.3).

Electrical cortical stimulation (ECS) is used to verify the correct electrodes that reflect brain activity during a specific task or action. Multiple grids and strips are often used to cover large cortical areas and results of the ECS are shown in Fig. 7.4, indicating the important brain functions identified.

7.3 Outlook

BCIs and related technologies are gaining ground with existing and new users. Classically, BCI research aimed to provide assistive technology (AT) for severely disabled users. Dry sensors, cheaper and more portable hardware, interfaces that are more immersive and easier to use, improved integration with other hardware and software, and other factors are making BCIs into effective real-world assistive

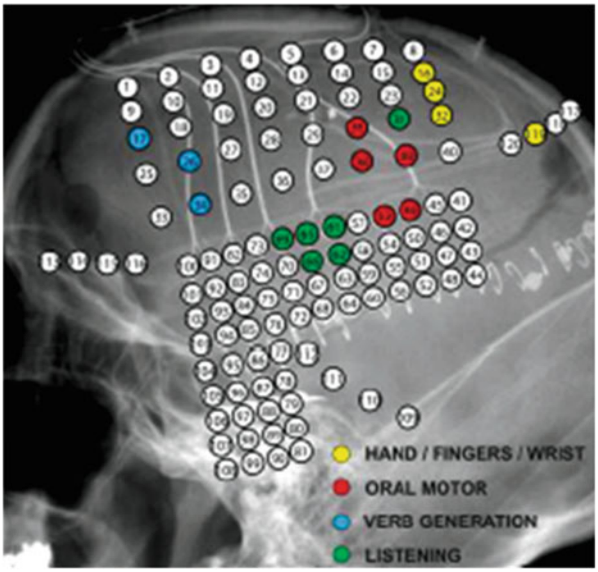

Fig. 7.4 Electrical cortical stimulation (ECS) results for hand/finger/wrist movement, oral motor, verb generation and listening (Image courtesy of Gerwin Schalk, Wadsworth Center, USA)

technology AT solutions for a wider variety of users. These factors have also made BCIs more appealing as game input devices, even among some healthy users, and are making BCIs more practical as research tools. Other progress suggests that BCI technology could benefit much broader user groups, particularly for health and rehabilitation. The broadening range of such applications is a major reason why BCIs are gaining traction – people can do more things with a BCI. Of course, cost is another major factor in determining the market appeal of BCIs (see Fig. 7.5). Many other factors are also important, including reliability, portability, speed, accuracy, invasiveness, usability, design, service, training time, integration, and public perception (Allison 2010).

Changes in reimbursement could also increase the market appeal of BCIs. Right now, there are few reimbursement options for people who wish to purchase a BCI as a medical or assistive technology. Many patients and their families cannot afford a BCI system, which may cost over €10,000. However, if BCIs prove to be helpful tools for a broader variety of patients and rehabilitation situations, health authorities and insurance companies may pay for some or all costs of a BCI system. Rehabilitation options may vary substantially between different countries, regions, and insurance providers. Currently it is also possible to rent BCI systems to perform testing, with a view to purchasing the system if the patient uses it successfully.

As BCIs gain ground across different markets, opportunities will emerge for companies and people that can provide a variety of BCI-related services. Different users will need help to assemble, configure, adapt, maintain, and repair BCI systems. Doctors, nurses, caretakers, assistive technology experts, therapists, mental health professionals, and other health care providers will need training. These and other service needs will require specialists to operate technical support lines,

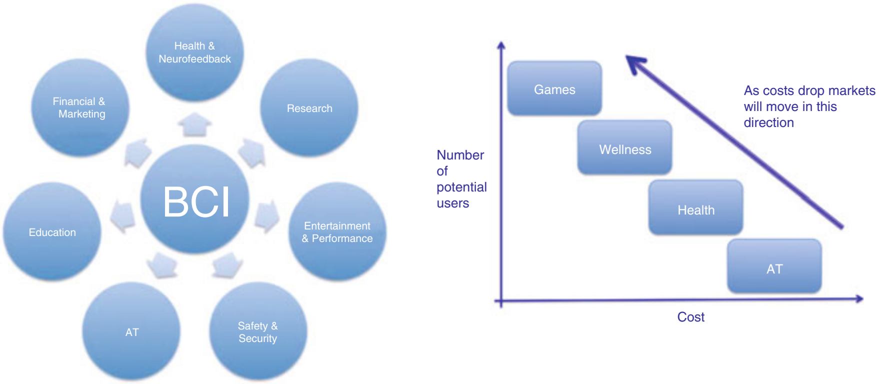

Fig. 7.5 The *left panel* presents different markets for BCIs and related technologies. The *right panel* shows how cost may influence appeal to different markets. From the Future BNCI roadmap at www.future-bnci.org

field e-mails, provide on-site support (sometimes working directly with patients), lead seminars and classes, market products to varied groups, interface BCIs with smart homes and other technologies, proffer various consulting services, and write manuals, reports, proposals, web pages, and book chapters.

Companies that have focused on extending invasive BCIs to patients have not been commercially successful. The two most prominent companies, Neural Signals and Cyberkinetics, both had significant problems with regulatory approval, and Cyberkinetics ceased operations in 2009. Regulatory issues will remain a major expense, especially for BCI systems intended as medical devices. This is one reason that noninvasive BCI companies focused on consumer devices have been more successful.

However, there are some promising opportunities for invasive BCIs, communication and control, functional assessment for neurosurgery, and different rehabilitation applications. If invasive BCIs can provide prosthetic control with a high degree of freedom a much larger market will exist than with locked-in patients.

Overall, BCIs are likely to gain adoption in many new markets, particularly in the medium and long term.

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Chapter 8
Between Neuro-potentials and Aesthetic Perception. Pingo Ergo Sum

Adi Hoesle

8.1 Raffaelle Locked In

A cup with a straw was on the table in the oversized light-flooded room and several cigarette boxes were randomly lying there. The artist was sitting beside the table on a mobile office chair with rests of worn-out black leather, slightly leaning his head backwards and to the side. The body was so infirmly and strangely twisted, cowering on the chair as if it was about to fall to ground. A young assistant placed a cigarette between the middle and the index finger of the hand of his left, drooped arm. With an iron will and like a Foucault pendulum he now swung his left arm, in an angle of about 30° against the body, as long back and forth till he caught, at the highest amplitude of the arm, the cigarette in his mouth and avidly sucked in the smoke. He repeated these acrobatic movements several times till the cigarette was consumed up to the filter. Then he dropped it from the flabby hand to the floor laced with color splatters. Now the assistant, reaching with both arms through the armpits from behind the chair, skillfully grasped the artist's right, flexed arm in a kind of Rautek grip, lifted the saggy body up so that it was no longer at risk of falling down, and then brought the cup with the straw to the artist's mouth.

In this situation the artist's mental presence and alertness seemed to rise, to spread all over the room, to apprehend all and everything. The resulting electrified atmosphere and mood could almost be felt physically. But the usual lively ado and creative fabricating in an artist's workshop had given way to an unbearable silence. The assistants moved slowly, carefully and thoughtfully as if time would soon stop. The pictures, the assistants, the interior, and the room itself appeared in their surreal interconnectedness like the inner of a cocoon irresistibly going to dissolve into pastel-colored blurs. At that very moment, at the moment of cessation and immobility, the completely flagged, skinny body ventilated via a tracheostoma merged with

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the medical machines and gadgets and, from the aesthetic point of view, turned into a sculpture of timeless beauty within his ‘cathedral’.

The encounter with the amyotrophic lateral sclerosis (ALS) diseased painter who couldn’t hold a pen with his weak hands any more refers to the question an artist asks the prince in Gottfried Ephraim Lessing’s play Emilia Galotti: “Or do you hold, Prince, that Raffaelle would not have been the greatest of all artists even had he unfortunately been born without hands?” (part I, scene 1). Though for Lessing this question had a rather rhetorical function it nevertheless brings an interesting issue on the social and cultural canvass in the beginning ‘cyborgzoikum’, the era of brain-computer interfaces (BCIs), robots, and avatars: Can we still speak of a painter and his/her creation? Can we see this creation? How can we perceive it? And is it a picture at all? Can we debate about it? Or is it an elusive, immaterial, virtual work? Where does it come into being? In the artist’s head? Is the process in the brain the actual creative act?

8.2 The History of Brain Painting

Painting without hands, drawing without muscular force, sculpting without hammer and bit, only by the power of thoughts, willful imagination, and concentration: All this was realized with comprehensive research from the universities’ side (University of Tübingen and University of Würzburg 2004–2012) but was motivated by artistic ideas. The starting point for the artistic involvement, currently culminating in the project ‘Pingo ergo sum’ (http://www.pingo-ergo-sum.com), was the question about the place where a piece of art comes into being. Where is the borderline between the artistic idea and the piece of art as such – concerning both the artist and the beholder? Can the creative, cerebral, or mental processes be measured before they are realized in a transformative process of confection?

What meanwhile has been experienced in several exhibitions and performances as well as during workshops and training sessions of the Brain Painting project and what is permanently developing further began in 2003 with the Ars Electronica festival. There I did electroencephalography (EEG) brain activity measuring in visitors who were beholding pieces of art (Fig. 8.1).

Interesting were the statements coming from the participants in these experiments, who were at the same time the recipients of a performance. Nearly concordantly all the participants were convinced that the thoughts they had when beholding pieces of art can be recognized and decoded from the EEG graphs, as if they existed in the EEG apparatus in a digitalized shape. This led them to observe art in a more intense and concentrated manner. Thus, this connection of machine and brain (art played the role of a stimulus) changed and enhanced the quality of reception in the sense of ‘event-correlated evoked aesthetic’. This work, continued in other exhibitions, lead to EEG sculptures (SIGGRAPH Los Angeles 2004, Fig. 8.2) displaying the mental flow of art viewing. This was a first step towards

Fig. 8.1 EEG recording in visitors beholding pieces of art (Photo, Staatsgalerie Stuttgart, 2004)

Fig. 8.2 EEG sculpture wood, EEG-Sculpture of Jörg Immendorff brain activities, 2006

finding creativity where it becomes measurable for the first time: As electrical flows in the brain evoked by external stimuli.

The next step, from the measurement of stimuli when viewing art to the translation of stimuli into form and color, is based on software making effects out of stimuli. To match the electrical signals coming from the brain with the 'right' effects a BCI and the innovative painting software Brain Painting (designed by Dirk Franz) is needed. Basically, the BCI is calibrated to causally connect certain patterns of brain activity with certain thoughts. In artistic practice this happens for instance by choosing alternative tools on the matrix (Fig. 8.3 shows the first shape of the matrix): Among other things, colors, geometrical forms, and the place where they will appear. You can also make them disappear again or 'explode'. Since only the thoughts determine the result, the selection of materials, manual activities, painting, drawing, hammering, sawing, cutting, taking pictures, making movies, etc. is not part of the overall message. Only the thoughts are directly

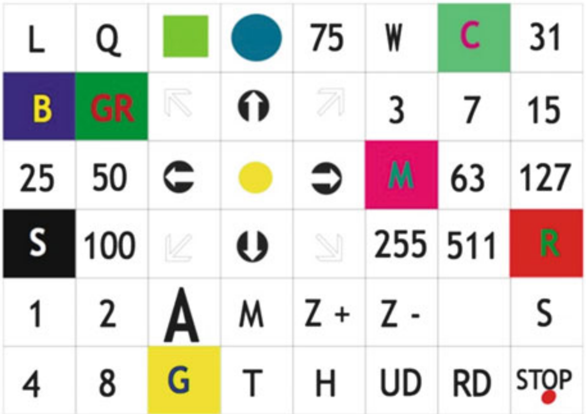


Fig. 8.3 First Brain Painting matrix

translated by the software. It's an impressive, non-verbal process when only the will makes things happen. De facto, it needs a high level of concentration so that the BCI recognizes the intended and distinguishes it from the non-intended and has it realized by the computer.

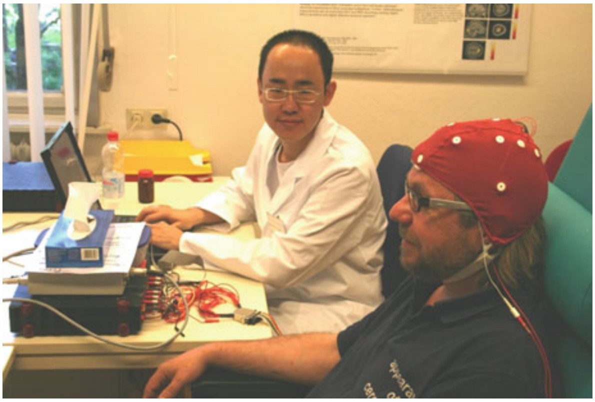
"Whatever a person thinks becomes the deed, without him doing anything with his hands" (Böttcher 2012, 6). This citation alludes to the intensely debated creative act. In the field of arts and cultural history this triggers the question of how ideas are merged into art and when this process is completed and a piece of art is finished. With Brain Painting this question becomes transparent for the first time and can be taken up again and developed further. Can we map the creative act without materializing it? Does art have to materialize itself at all? Or can the creation stay in a virtual state, 'realize' into virtual reality?

8.3 Pingo Ergo Sum

The artistic field research is accompanied by scientists. Between 2005 and 2012 the Brain Painting software was tested in practice, integrated in art projects, scientifically evaluated, and permanently optimized. What started out of an interest in immediate applicability has become an interdisciplinary project. After that many years of artistic research in this project, the necessity to actively express one's own thoughts extends Descartes' dictum *cogito ergo sum* – I think therefore I am – to *pingo ergo sum* – I paint therefore I am (Polte 2012).

In 2005 an EEG lab of the University of Würzburg was the sober location for the first Brain Painting session (Fig. 8.4): Putting on the EEG cap, gel to the hair, connecting the electrodes to the amplifier, calibration, classification, localizing the P300 wave. Now I was 'in line' with the machine, I turned into a cybernetic organism.

Fig. 8.4 The author in the BCI lab



The flashing stimuli coming from the paint matrix pervaded my brain via the nervus opticus and provoked event-related potentials (ERPs). It was an exciting moment and a sublime feeling when I saw how my imagination of colors and well-defined or diffuse figures were decoded and appeared on the screen that transformed into a digital canvass. Peu à peu color patches came into being: An abstract painting in the widest sense (Fig. 8.5). It was fascinating and beguiling how my will got power over the brain machine. I chose pink, I chose a square, a blue one… moved the cursor to the right seven times, in between focused the color blue on the matrix, concentrated on the flashes, thinking 'square'….

Not the EEG lab was the workshop but my brain transformed into the artist's workshop of the third millennium for a short moment when I 'painted' the first picture worldwide without muscular power, without brush and colors. I myself was a cyborg. Soon my paintings became more complex, lost their algorithmic shape, were formally more condense, and showed initial artistic qualities (Figs. 8.6 and 8.7). I developed a certain ability and routine in dealing with the system. The BCI became more and more part of me. During the sessions my self-perception changed. There was a feeling as if my thoughts would leave my brain and start flying but only to finally turn around and enter into an alter ego. This other I now surfs through my gyri, senses my cortex, breaks into the darkest corners of my grey matter, watches me, and makes itself independent. My thoughts emancipate, distance themselves from me, and make aesthetic decisions wrapped in gamma band potentials crisscrossed through my personality. I don't perceive time and space. No passing and passing by, but only an eternal being: A moment of highest aesthetic sensation in the no man's land between brain and machine.

This short description shows that Brain Painting is not about creating nice things. Rather it became clear that the cerebral events and the events at the brain–machine interface *are* the artistic process. Is this the borderline between the idea and the work?

I have now spent more than 150 h wearing the BCI cap, sometimes up to 8 h with more or less no interruption, in the beginning in the EEG lab, later on also at home, and today anywhere. In connection with the 2012 exhibitions in Kunsthalle Rostock

Fig. 8.5 My first Brain Painting

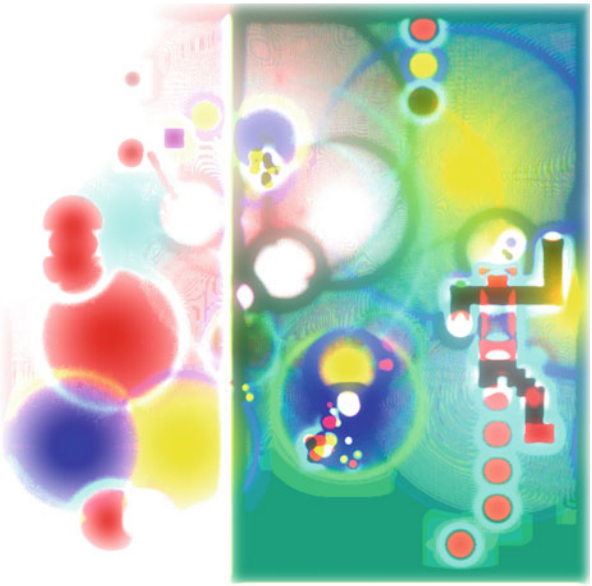


Fig. 8.6 Brain Painting no VII, inkjetprint on aludibond 100 × 100 cm, 2009

and in Ars Electronica Center Linz more than 200 private persons and 30 internationally renowned artists took part in Brain Painting. Ten ALS patients have brain-painted.

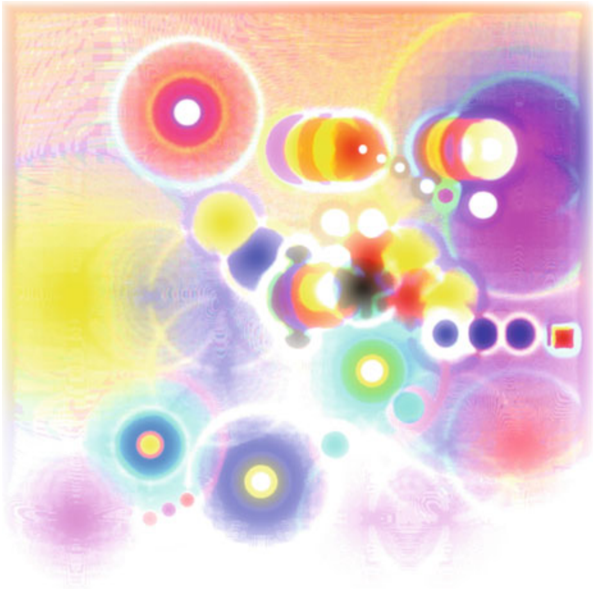


Fig. 8.7 Brain Painting no IX, inkjetprint on aludibond 100 × 100 cm, Berlin, 2009

Brain Painting is not only a platform where artists and scientists meet. In the first place it opens up a cosmos of questions comprising medical, socio-cultural, and artistic aspects. Given the wide scope of these aspects at the interface of art and science and the openness to understand this cooperation as the realization of an art project as well, *pingo ergo sum* is an experiment unique in the world. Art writes the screenplay. Society is on stage. An artist's workshop is the stage and becomes a scientist's lab. To engage with Brain Painting means to understand the arts differently, to free oneself from the idea that art is embodied in separate works displaying the ingenious human drive of expression. Here, art is not the destination but the journey, not a singular piece of evidence but a question about the process of becoming. Neither the beholder nor the researcher stand on the firm ground of usual cultural activities in line with our historical fundaments. They are rather in between art and science, concrete results and elusive thoughts, genesis and decay. They can not only see an experiment, but they are part of an experiment based on understanding the manifestation of creativity as being neither time- nor space-dependent.

The painted is no longer bound to a material substrate, but can be reproduced at various places in real time, i.e. at the moment of its origin in the artist's brain. It is a virtual appearance that, different from a singular space-dependent realization, brings time and space together. After completion the picture can be saved or printed, but on screen it disappears. The product is ephemeral; only the conviction of being able to make thoughts visible stays. This enables another global project opening besides the already existing digital worlds of finance and communication: The digital world of art. Following our technical evolution, art might become

Fig. 8.8 Christian Stock prepared for Brain Painting on Tuxer glacier

another no longer material but digital medium of our culture and could be moved both in expression and reception to any place in command of the necessary equipment. The further the de-materialization of events goes, the less evident is the spatial definition of a piece of art as such. In the logic of this development it seems obvious that a piece of art has no fixed spatial qualities but is rather a temporal experience. The object that is viewed becomes an ephemeral part of viewing itself. It exists at the moment of appearing.

2012, as a Brain Painting performance, the Austrian painter Christian Stock trekked to the Tuxer glacier (Fig. 8.8). Having arrived there he unpacked the Brain Painting equipment from his backpack, put on the EEG cap, and started 'painting'. Live and in real time the process of developing the picture could be monitored both in Ars Electronica Center Linz and in Kunsthalle Rostock. In addition, any user worldwide could follow this event via a live stream. The artist imagines the picture, it 'drops out' of the head, rolls down the mountain, and reaches the walls of the museum and the beholders' heads.

8.4 Extending 'Pingo Ergo Sum'

Brain Drawing (in cooperation with the University of Würzburg) and Brain Sculpting (in cooperation with the University of Rostock) followed after Brain Painting. Further similar procedures furnished with both artistic and scientific aura extend the label of 'pingo ergo sum'.

In 2012, as a direct cooperation between scientists and artists, Lars Schwabe (University of Rostock) and I founded the Art Research Lab (ARL). The scientific part of this lab works on the premise that perception and artistic expression are based on neuro-biological activity which can be made visible. In that sense, ARL is itself an image of the brain and its activities that 'drops out' of the brain. From the artistic point of view ARL is work in progress.

"My mirror neurons dance tango with me" is the poetic label of the project that is at the heart of ARL since 2012 while Brain Dancing is its scientific name.

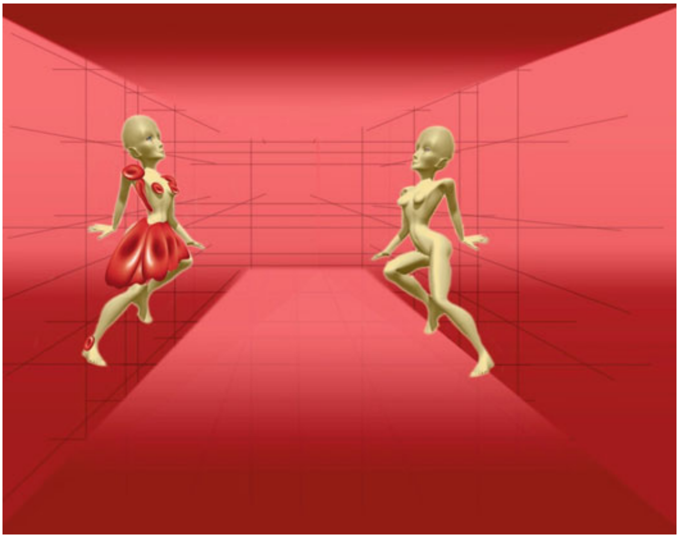


Fig. 8.9 Dancing avatar

Applied to Brain Painting or Brain Sculpting the aesthetic experience is to be found exactly at the brain–machine interface. With the Brain Dancing project Prof. Schwabe and I go even one avantgardistic step further. The project aims at enabling locked-in people to actively dive into virtual reality and there to dance tango together with a partner (Fig. 8.9). An avatar, taking on the role of the tango dancing partner, is controlled via shared control mechanisms according to implemented dance steps. The locked-in dancer extends the brain–machine interface, overcomes it, excorporates and de-materializes himself/herself, and mutates into an alter ego in a virtual space when slipping into a second dancing avatar. The emotional and erotic feelings associated with dancing tango are to be elicited by closing feedback loops. To do so we developed pneumatic and FES (functional electrical stimulation) dancing dresses (Fig. 8.10). An aesthetic whole will arise when action and perception start dancing.

The option of influencing biological beings technologically will change the human being into a cybernetic being, a cyborg, during the third millennium. Seen from an evolutionary perspective, the human being, then, would successively be changed and reduced in its physicality; as it is already anticipated in fashion when legs seem to be shortened. For what do we need arms conducting the partner or legs performing pirouettes? What, if we were to ‘kidnap’ several other of our senses to virtual reality by some ‘injections’? What if the dancers could no longer separate between top and bottom, between inside and outside? Would this help overcome the cerebral construction of reality?

Fig. 8.10 FES dancing dress

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Chapter 9
My BCI Vision

Sonja Balmer

9.1 About Me

My name is Sonja Balmer. I am a 40-year-old business graduate employee, artist, and author and in December 2010 earned a degree in animal psychology. I have been ill since childhood and for many years lived diagnosed with multisystem disorder, and between 2000 and 2012 with the diagnoses PLS (primary lateral sclerosis) and ALS (amyotrophic lateral sclerosis) – the latter ultimately a fatal disease. As however the progress of the deterioration process sometimes showed regressions and due to the many years of the manifestation, the form of muscle weakness, and the fact that other organs were also involved, in 2012 the explanatory model of mitochondrial disease was declared. Neither the diagnosis of multisystem disorder nor of ALS can be considered incorrect, especially as the electrophysiological tests that led to the ALS diagnosis confirmed that both the primary and the secondary motor neurons of the diaphragm are affected. With ALS one has no explanation at all (yet); in my case through certain additional laboratory findings the mentioned explanatory model mitochondrial cytopathy arose. I suffer from paralysis and muscle weakness with pain throughout my entire body and am artificially (invasively) ventilated by tracheostomy. Many organs are affected by the illness, which is associated with gene mutation: eyes, ears, ingestion, intestines, autonomic nervous system, central nervous system, kidneys, bladder, muscles, glands. I have often been on my deathbed, but always recovered and survived thanks to medicine and *joie de vivre*.

Between the ages of 14 and 31, I painted impressionist paintings and from 1998 to 2005 organized painting exhibitions and book readings throughout Switzerland. In my three books (Balmer 2002, 2006; Jenzer and Balmer 2008) I dealt intensively with key ethical questions in medicine, psychology, and care, as far as possible

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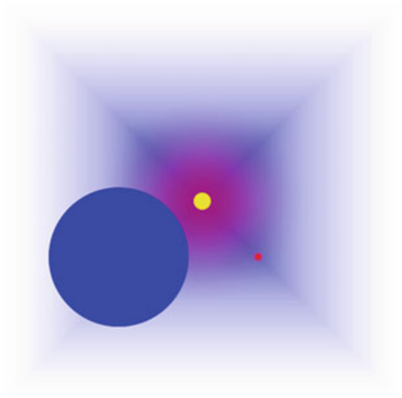
from a philosophical perspective. I plan to start a degree in psychology in 2014 and am currently teaching myself English and Latin.

9.2 My Path to BCI

The first time I heard of Brain Painting (see Kübler et al. 2008), I was in a dying phase, as I had given up on myself and everything around me. Afflicted by severe pneumonia, I was at a physical and psychological low point in my life. I hadn't only experienced pleasant encounters in the many years of my dependency. I had no energy left to enthuse myself for a life that was in no way "Sonja's". The inventor of brain painting, Adi Hoesle (cf. Hoesle 2008) had no chance of convincing me to live – not even his visit and not even his enthusiasm for brain painting. My grief over the lost impressionist painting was that profound. The disease progressed, although not as first thought. ALS generally leads to death within a few years, but I survived every dying phase that came, while everyone else around me died. I stood in public under enormous pressure to do what was expected of me: The toll of the fatal disease ALS – to die. The Sonja Balmer once full of *joie de vivre* despite the serious illness surrendered herself to her fate and wanted nothing more than simply to die. This fundamentally contradicted my philosophy. I was again reanimated, which triggered the turning point. Adi Hoesle stuck to his guns; from then on he supported me and gave me the courage to face life, visited me, wrote me e-mails. He showed me that I still have a mission and callings in life. He managed to make me grateful again for the gift of life. Shortly afterwards, Adi Hoesle visited me again. It was about a TV appearance on Swiss television, where I brain painted in front of the camera for the first time in my life. While as representative and spokesperson for other ALS patients I was a very public person, this was my first TV appearance for many years after the long withdrawal from the public sphere. Nobody can imagine the feelings that flooded over me after years ago giving up impressionist painting as a result of the paralysis: Butterflies in the stomach like previously in front of an oil painting, similar to love. Life is a miracle and I am someone who can kneel down in front of the miracle and marvel like a child seeing this wonder for the first time. That's how I felt (Figs. 9.1 and 9.2).

9.3 My World and My Art

Humans are highly communicative creatures and in the course of evolution will become ever more so. Today we are connected through Twitter, Facebook, e-mail, FaceTime, and so on and believe that we are so integrated that we are no longer lonely. Many people have 200–400 connections to so-called "friends" in their smartphones and view them as friends. Far from it! Communication is not only speech and writing but can be found in pictures, colors, photographs, and drawings.



Figs. 9.1 and 9.2 My first brain painting in front of running cameras

Art and painting is a form of communication for me, a way to voice myself externally. Wanting to create art comes from the more inner essence of mankind. It is a real, deep need to communicate something, to show something, to leave something behind, or make something visible. A creative urge that every artist understands, translates, realizes, and expresses in their own specific way. Art in all its forms gives us the unrestricted freedom to give utterance to our thoughts and feelings. The way in which one translates one's own creativity is something that needs to be sought.

Brain Painting allows me to communicate externally again via painting. Brain Painting shouldn't only be enjoyed by physically impaired people. So-called "healthy" people will also be inspired by the painting of a picture through nothing more than the concentrated power of thought from the depths of the brain.

Although brain painting lacks for example the smell of oil paints and turpentine or the feel of the brushstroke on the canvas, it achieves a direct connection to our creative thoughts. The path to painting is shortened and not disrupted by motor problems or blockades. BCI allows an undistorted reality. At the current time it is however not yet possible to paint in the precision that a painter of the impressionist style seemingly does or did. If however one looks very closely at a painting from Claude Monet, it is barely any different from the realization of an impressionist picture with brain painting. This confirms that (1) it is not only the result that is essential, but also the path to it, and (2) the viewing of a picture is always dependent on the perspective. Do I see that picture as a bird? As a bug? This consideration is essential not only in brain painting (Fig. 9.3).

Fig. 9.3 My second brain painting picture. As an impressionist painter I tried to depict a sunset at the horizon of a sea with a flying bird in the twilight. However, during the painting a memory of my near-death experience came up, the being between life and death, and I tried to depict what I felt

9.4 My Future and the Future of BCI

As long as I can communicate with my surroundings in the conventional manner, I want to mobilize all my energy to supporting the development of BCI. I am currently still able to use my multifunctional electric wheelchair including ventilator to travel outside into nature, where I gather many ideas. However I have found myself multiple times in the bad situation of the locked-in syndrome, from which I then recovered again. I know that the time may come when I do not recover from a locked-in state. I am friends with locked-in patients and their relatives.

It is today possible to use eye-tracking to control doors, windows, curtains, lights, and the computer, to write, or to activate the nurse call function. I have a device that contains all infrared codes: from the TV channels to the light and nurse call function. I imagine what it would be like to control my environment via BCI in order to acquire as much independence and self-responsibility as possible. If it is today possible to control this small, multiple-infrared device via eye-tracking and thus open a door, it must also be possible to do it via BCI.

In a few months I would like to leave the care home and move into my own apartment with 24-h care. I hope I can achieve this. I can look back on many years of experience of nursing management and medical care of my artificial ventilation as an outpatient. I imagine in my apartment, or in apartments generally, an “art room” in which I brain paint, write my books, communicate, tweet, e-mail, listen to music, relax, etc. All controlled by BCI. A videoconferencing link connects me to the outside world. But not only me. My visitors take part as well. We could even play games. As a more or less bedridden patient this would be the only opportunity for me to connect with the outside world. It would allow me to be autonomous and independent.

Bedridden patients can generally no longer go outside into nature. In this "art room" I picture 3D nature images and films that the patient can move via BCI controls. He travels with his bed along for example a virtual and acoustical farm track, perhaps even sensing the smell of the field. Via acoustic signals he hears the rustling of the trees and the chirping of the birds. This vision is not only pleasant, but provides spiritual and physical stimulation. Through the contact with the outside world and the artistic involvement and relaxation, hormones are distributed and the mental wellbeing is improved, and the immune response improved. For people no longer able to move themselves (for example can't breathe by themselves), the defense against infection (for example pneumonia) is strengthened. By recovering the psychological balance through BCI in the "art room", an equilibrium of the immune response can be achieved.

Working with BCI or even just imagining working with it (1) reduces my fear of at some point no longer being able to communicate externally and (2) excites me that I can participate in what is happening around me.

At the moment that the computer selects *the* brush, *the* stroke, *the* letter, *the* color, *the* door, *the* window, *the* piece that *I* ordered through the pure power of thought, I detect wonder and godly reverence. I feel as though I have gone back to the creation of the human brain. I feel as though I am part of evolution. The technology allows me to go on an evolutionary journey through time. The connection to our most primal cultural needs is unavoidable. With BCI one doesn't only advance to the future, but also engages with the past of human existence, thought, science, and progress. We should always take an example from nature, to which humans also belong. The differentiation between nature and technological development only exists at the surface. If we look deeper, we can see a pulsation in everything that we encounter in life: space pulses, a heart pulses, a plant pulses, and an EEG lead from a BCI also pulses. Everything comes and goes, grows and recedes, which seen from the outside always looks like pulsations. In a certain sense, nature communicates no differently than via a brain–computer interface. It is beneficial and we can profit from it without removing from it. We should handle nature as well as our own mental faculties with great reverence and always remember that mankind did *not* create the world but that we can learn from it to use constellations that are good for us. BCI is such a constellation. We should look after nature because we benefit from it daily. We should use it without abusing it. Humans belong to nature, and we should look after it, and we should look after ourselves. BCI is a technical opportunity to satisfy natural needs and so we should gratefully protect the nature that belongs to our age, such as plants, animals, people, cells, etc., as living beings. We would lose so much if we could only travel through space and time with BCI because we buried everything living that we could find in nature. Nature will always continue developing, and we haven't experienced or cherished anywhere near all of its facets. Evolution-related developments, technical developments like BCI, should therefore always be harmonized with our living existence. In the same way that body, spirit, and soul belong to mankind, so science, belief, technology, philosophy, a blade of grass, an animal, a person, bacteria, etc. are a part of nature.

If BCI can be seen as part of our nature, doors will open. However, BCI should always be subordinate to the will of the respective user. It would harm the meaning and purpose of BCI if it turns away from this and begins to try to read people's thoughts, to manipulate them. Until a few years ago seen only in science fiction movies, this form of exploitation and misuse of the technology and thus also of nature is no longer that far-fetched.

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Chapter 10
The Users' Perspective

Various Authors

10.1 Introduction

Research subjects in the sciences are usually people who are spoken about and not asked to speak themselves. Their personal views are not part of their role within a study. From the scientific and technological point of view this might be reasonable. However, research subjects are often the first contact laboratory matter has with everyday life and the reality outside the lab. As average citizens these prime users of new technologies can display in advance the impressions, feelings, and ideas new gadgets will cause in a population. And in the case of projects working with a special selection of people, research subjects' opinions might be seen as insights into the opinions of their peer group and allow information to be gained regarding the overall acceptance, demand, and usability of a technology. The following statements are extractions from interviews held in 2011 in Switzerland, Italy, and Germany. They originate from people who have been involved in brain-computer interface (BCI) research and have had the opportunity to use and to try out BCI-based devices of different sorts. Some of them are stroke patients who worked with assistive technology designed to help them regain lost motor functionalities. Others are motor-impaired people who went through a BCI training program. Those who successfully trained were given the opportunity to test several BCI applications, among them a telepresence robot, writing software, and entertainment software. Participation was not a success for all of the participants: Not everybody from the first group noticed a therapeutic effect, and not everybody from the second group achieved control over the interface. However, all of them had personal experiences with BCI technology and have their stories about it. This chapter will give them a voice and let them tell their stories. Their answers and comments to a range of questions are reported as they were given, and not modified and not included in a theoretical frame. The only editorial adaptation we necessarily had

Some anonymized information about the authors can be found at the end of the chapter; the editors contributed the introduction and compiled the answers.

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to make is the selection of interesting statements and where necessary the anonymization thereof. We present the material in the order of the questions we used to make the participants talk. The answers are chosen to display the spectrum of answers on each topic. We like to say thank you to all the participants in our interviews and to all our colleagues who held these interviews in the different countries and languages.

10.2 Questions and Answers

What did you know about BCI technology before?

Absolutely nothing. (13)
Before the experiment, nothing. (5)
I did not know about it, but I could imagine you can find devices that make life easier for people with disabilities. This did not seem impossible. (1)
I watched a TV show that was talking a little bit about this. (3)
Not that much, not that much. I knew that... I saw some documentary with some people who had an electrode in their brain to make a special device work. I never heard about non-invasive technology. (19)
What I know is enough, because I saw a lot of TV shows where they sometimes show how they move the brain through the scanner etc. So I was interested, I saw a lot, so I knew enough, but this thing I did, I'd never seen or tried. The study that was done here I had never done before. (4)

How well informed did you feel when you started participation in the BCI trials?

I made sure I knew everything. (15)
Very well informed. (14)
My doctor informed me about everything, and every day I had a lot of questions for the EEG technician. (11)
I was well informed, but it was difficult to bring it into practice and also to truly understand the explanations. They were not easy for me to understand. (3)
Not really. I expected something more global and more oriented towards real life – and I practiced only moving left, right, and ahead. (1)

What did you expect from this technology?

That it improves the life of anyone who is not independent. (19)
It may be good for people like me who have a disability and can no longer use their hands. (2)

I expected that it could help me in everyday life or help others. It is not fully developed at the moment, but I hope that it works to make things in life more quick and easy, of course. (7)

At first, I think, it was just the curiosity for the technology: to see what it looks like and what it is. (6)

For me, it was mainly to participate in a test and in something that could be useful for tetraplegics in general. Personally, as I have some mobility in the arms and a little in the hands, it was not directly useful for me, I think. (8)

My aim concerning this technology was that at the end I can by myself take a glass of water and drink from it, i.e. grasp the glass, bring it to my mouth, and put it down again. (18)

Well, not too much! I expected help, something that could add to the rehabilitation I already did. (17)

Well, I'm a guitar player. I'd like to play my guitar like before the stroke! I know it's so difficult but maybe this training can help in some way. (14)

I was hoping to bring things forward a bit and to provide help to those who might be in need of it. (9)

I expected this technology to succeed fully, and unfortunately this was apparently not the case. (4)

I expected a lot more but this was because I didn't know much about neural functioning! (12)

After you were asked to participate in the studies, which were your motivations to agree? Why did you become a participant in the BCI study?

First of all, I was curious about this study. And I wanted to see if I was able – if my brain was able – to give a command to a machine. (19)

To me it was very interesting and I wanted to discover the potentiality of my brain. (20)

The interaction between thought and technology has always interested me and I was very motivated for this reason. (7)

I wanted to discover whether I can think of something without making the movement. (2)

Out of curiosity, just to do something more, try to develop things. (9)

Because I was interested in seeing how you can make your brain work without the body being in movement. (10)

Well, my motivation for this study was... I'm actually an open person and have a good attitude and want to learn new things. (18)

Because I am interested in anything that is a little science, electronics, and other. I wanted to know exactly what is happening, what would happen, etc. (4)

Well, because I think it is interesting technology and it was fun to see what it is. Also later, well, there were exercises and it was nice and the atmosphere was very pleasant. So, this was the motivation. (6)

The training is quite boring, but I did it for science. (11)

I believe in the value of research and I think it is important to do something for it. (12)

I believe because I thought that it was important for me, for my hand, and for research too. (13)

I was hoping to be able to increase the use of my hand or otherwise to improve the movement in order to be as independent as possible. (15)

[. . .] in order to rehabilitate my hand, and I was happy to make my little contribution to science! (16)

The reason is also my health. I still have myotonic dystrophy and myopathy, and I have a problem in the muscles and, as I told myself, since I had problems with muscles, maybe one day it will be convenient for me to use it to move my legs or my arms or to move an object or the like, like vacuum cleaners that are remotely controlled now. (4)

All I wanted was to rehabilitate my left hand and given that BCI has no contraindications, I decided to participate. (17)

Can you describe what it is like to use a BCI-based device?

They put a cap on our head, apply gel to make the contacts work well, and then you sit in front of a computer to control the system. In principle, that's it. (8)

They put a cap with electrodes on the head and then there is a small box that linked us to the laptop and then there are two laptops – one is connected to the [university] and the other we are working on. No, it's good it's clear it's weird to be at a computer with a cap on your head. (2)

It's a simple way to imagine, I can't explain better. (14)

It is just. . .imagination! (17)

It is a very strong stimulus! (15)

Funny! It's funny and helpful. (19)

Yes, it's a little science fiction, a little supernatural, a little magic indeed. (9)

It is really complicated to control a device via a brain–computer interface. I found it really demanding because one has to concentrate so much. (18)

How did you experience the whole procedure of using a BCI device with all its necessary preparations and efforts?

Pretty good overall. (5)

Without problems. (10)

Very serene, therapists were very nice. Nothing bothered me in itself. (1)

Well, the stress is tolerable, actually it is not really stress, because I absolutely like to do it and I see it very positively. I'm totally motivated and it's really fun. (18)

I would not do it for all my life, but it was cool. (19)

Rewarding! But I expected it to be a little bit easier, because it is aimed at people with disabilities. (12)

Quite happily, even if it has been a little tiring for me. (15)

Some general discomforts but I overcame those discomforts: I'm talking about some little logistic discomforts like the transportation [. . .], washing hair after the session; the biggest discomfort was going out to do it. (20)

From the beginning, it is clear that it takes very, very long to install the system in the participants and there were some problems with the computers. It was not all good. (2)

[. . .] it was tiring: the cap, the electrodes, washing the hair each time. . .it was difficult for me. The training itself was relaxing! (17)

The cap was constricting. The gel was not very comfortable. The rest of the study needed a high level of concentration. It's not clear how to manage it. Besides this it was interesting like a new experience. (8)

Very annoying! I think it could be better if you can reduce it in some way. (11)

Did you experience the technology as helpful and useful? If yes: How did you benefit from BCI use? If no: What kinds of problems did you face?

Yes, after a few days I had a greater perception of my left hand, and I can use it in a more spontaneous way! (12)

Yes! The "illusion" of the movement of my own hand made me feel stimulated to continue the training. (13)

I appreciate the technology. I felt it to be useful for motor recovery. (15)

I had no visible physical improvements, so I don't know. . . (16)

It can, I think, provide assistance to people who are immobile in bed, who cannot move their arms, nothing at all. I think at this point it can be very useful. (5)

I think it will become very useful, maybe not directly for me. The cap is quite restrictive and not very practical, not very pleasant to use. But for people who have absolutely no arm mobility it is very useful. I think it should be further improved, but it is something really useful. (8)

I discovered myself to be clever. The stroke didn't slow me down. Problem: prolonged concentration. (20)

Yes, I think that this technology provides support and even though I was not able to make it work, I think it will help others. (7)

I think that the experience in general was helpful and useful to understand what is possible to do with a brain, with a brain at an interface. (19)

I found that it was a good exercise in concentration. Yes, in that sense it helped me. I was a little frustrated because I could not do it well. (10)

[. . .] it's all about concentration, it required a lot of concentration, but it is not really a problem for everyone. (9)

No, I had no problem, but at the same time I had no improvement. (11)

The problem I faced was that it was not adapted to my disability. Yes, it allowed me to discover that thinking of something could move an arrow on the screen. (2)

It is indeed very important that it works well, because without that the utility I could gain for myself, I do not see. [. . .] it should work, in my opinion, much better than it works here, every time I came here was a failure. (4)

Have you been generally satisfied with your experiences or did you experience disappointments? Please specify how far your expectations were met or frustrated

I'm completely satisfied. (15)

Ok, well, fully satisfied because I saw something interesting. (6)

Satisfaction: to be able to control it despite the stroke. (20)

As I had no expectations beforehand, and under no circumstances did I involve myself personally in the success or failure of the study, I had no feeling for or against this approach. I did it with good faith and according to what I can do. (1)

Yes, I am satisfied. I thought it was very interesting to develop that system, to achieve control over something only by thought, this was very interesting. Again, the cap could be improved. One might find another system that is less restrictive. But for the other things, no, I think it is a really useful technology. (8)

I enjoyed seeing that I could participate a little, but I could have done differently, perhaps if I could have practiced more at the beginning of the experiment. (3)

I feel no frustration or disappointment; it has been fun to participate even if sometimes it has been a little boring! (11)

I felt no disappointment because my expectations were not that high. (16)

Satisfied, I could measure if I could do it, I am ... I had a good impression. The negative is that because of my illness I could not continue to the end. (2)

Disappointed, yes, because I would have liked to contribute something, as I said before. But not personally, not for myself, not really. Rather concerning the advancement of the project, yes. Otherwise no. It was a good experience. (9)

Well I'm a little disappointed because I had no visible improvement. . .but I already knew that would not be easy. (13)

At first I was happy because it worked good, there were some interesting aspects. And later I was disappointed. Generally, now after all these sessions, I'm a little disappointed and I do not know if I'll come back, because that's up to you. (4)

Was there a specific act that you were able to do that surprised or astonished you?

No, no. (1)

No, it does not surprise me, there are opportunities with new technologies. (3)

A little, yes, I was surprised to be able to follow through. (5)

To imagine the movement while holding the movement itself, I never thought of being able to do it. (12)

Yes, I was surprised and amazed. I'm a little on another planet when with you. (10)

Yes, my own performance, I did not think I would be that good. (13)

I was surprised by the success of the training, I was so good. (15)

It's already amazing just to see that the mind can control a computer. (7)

Yes, I didn't expect to open and close my hand with my brain, just by using my imagination. (17)

What astonished me was the level of sensation I had when I imagined a movement, for example standing up or standing on tiptoes, because the movement is a movement which I did not know at all but which seemed to work well in my case. (6)

Did you experience a difference between using the BCI device and using more common tools or devices? If yes, how did you experience the difference?

I have not yet experienced any difference between the use of the BCI and the use of usual devices. (18)

Traditional is easier. [If so, how did you experience the difference?] Philosophically. (5)

The others don't need electrodes. The BCI cannot be used outside. (20)

Yes, it's a big difference, especially in terms of speed. And I think it's an additional option, it would be very useful for some things that are not possible with other tools. (7)

Yes, I see the BCI system requires a high level of concentration. If there were only such things . . . functional keys, it would be easier for me. (8)

How did you experience the role of your brain while using a BCI-based device?

It was the star of the project! (11)

Protagonist! (12)

I did everything with my brain. (17)

My brain was very stimulated by BCI. So it plays an important role, the brain is the core of the study. (15)

In any case, I challenged my brain and the machine did not bother me. And the fact that it did not really work did not cause any inconvenience. I trust in my brain. (1)

It was the first time I was using my brain in that way, it was very interesting. (3)

I was a little disappointed by my brain as it couldn't do what I expected it to do. (4)

Well, I think it went well. I think my brain did not explode, so it's ok. (6)

I think it made my brain work and I have experienced this role well. (7)

One has to try not to have negative thoughts, not to think only to control the system. Once again, it requires a lot of effort of concentration. And from one day to the other it is not always easy. There are days that are better than others. (8)

I had the feeling of being schizophrenic sometimes because I was using my brain as a slave. (19)

I had the impression that it makes me a little tired. (10)

Did you have the impression that you and the BCI-based device together form some kind of functional unit? Or, to put it in other words, did you experience the BCI device, the moment you used it, in any sense as part of you?

Yes, when I saw the fake hand opening and closing I felt it like a natural movement of my real hand. (13)

Yes, I felt like one with the tool. (15)

I do have the impression that the device and I are a unit; and the control actually works very well. (18)

I felt we were one entity when I could visually see what was happening on the computer, advancing, retreating and trying to put the arrows where needed. (3)

I think it was a part of me, yes [pause] because my brain was involved in it . . . did you read something by Isaac Asimov? (19)

No I would not say it was like this, then. But of course, we should try to make it a whole. (7)

No, I never got to this because of the technology; the lack of cybernetic interfacing is a practical obstacle. (12)

No, I never felt one with the BCI, it was just a way to work on my affected hand. (14)

No, never. It was me, I learned to use a tool for rehabilitation; the tool was just a way to reach rehabilitation. (11)

No, it is a communication device, it is not me! (20)

Not at all. (5)

While using the BCI device, could you directly concentrate yourself on the work you tried to do? In other words: Could you forget about the technology and the learned strategies of using it and just do what you wanted to do?

Yes, after a lot of training. (19)

Generally yes. It was fine. Well, I think I was a little tired at the end of the sessions, so it was a bit more difficult. But in general I think I managed more or less well to focus on work and exercise – more than on the technology. (6)

At first it was difficult. And a little later, I managed to focus well enough but I could be bothered with things quite easily. But overall I managed to focus well. The longer it lasted the more I was able to focus. [. . .] the more time passed the less I was bothered by the technology, the less I thought about it. (7)

Yes there have been times when the technology and I were linked. (11)

Yes, yes, I think I got it. There maybe was one time or another when I had negative thoughts, but overall I succeeded. (8)

Yes, definitely because I managed to concentrate well. (3)

No, actually the tool has the central role in the training and its role is central until the end of the entire training. (15)

No, it's not so easy to forget the technology and just focus on the hand. For me it's impossible. (14)

Imagine that the device you tested were to become a standard solution that is broadly used in everyday life. Could you imagine some specific problems that might result from such use?

No, I do not see any. (5)

Good question! Maybe that you become dependent or feel frustrated because the device is not developed further. (19)

That a patient must have a cap on his head all the time? It seems to me very complicated to set it up. Perhaps with sensors implanted throughout the year? I do not see much alternative. (1)

Yes, there are problems, bugs, and the computer program would have to be adapted to many disabilities. (2)

No, I don't....but you have to find a way to reduce the preparation time. (16)

I see the device as rather tedious for everyday use. (18)

The big problem I see is the use of the cap, which is not easy to apply. You have to have somebody for people with problems with their hands. I could not do it myself. Otherwise, for my personal use, I do not think it is really useful. (8)

Yes, having to wash the hair every time after the daily training! (12)

Do you think there should be special formal regulations concerning the use of BCI technology in general or the device you used in particular?

No, I do not see any reason. (7)

No. I use an electric chair in the street: It was difficult at first, but now I do not care. (1)

No, not of law but a brochure that clearly explains how to use it here. (2)

Yes, there must be mechanisms in place fitting with this new technology. (3)

Yes, I think that it is important to respect the patient [...] (17)

Now if we talk about other technologies in addition, like the lie detector or whatever, then I'm sure there must be laws. But for what I did here, there are no safeguards necessary because it does not influence the brain. It is we who need to influence the machine. I do not see, as long as it is not more like maybe some stuff like brainwashing or other [...] (4)

Since I'm a techie, I tend to say: we go and see how it works! It's cool. Eventually it's true that we can perhaps imagine some trouble that could happen. I don't know enough about how it works but I guess the data transmitted to the computer can probably be interpreted. I don't know but it's something that could potentially be possible in the future [...] (6)

Perhaps it is necessary to secure the system like wireless LAN in order to prevent hacking. We have to await further development to see whether this is really possible. (9)

Now, when the studies are over, do you feel relieved? Or do you regret that the studies are over?

I'm sorry that it is completed. (7)

I'm sorry that they are, I'm a little disappointed. I may have preferred to continue. But, hey, I'm not going to kill myself if I don't go on. I have other occupations and I can focus on them, but I'm disappointed. (4)

I already regret that the studies are over because I'm always expecting that I can discover something new. (19)

I enjoyed participating in the study and I'm not relieved that they are finished. (18)

Well, yeah, it was, it was cool, it's not a relief that I finished. When I finished it was clear that I wished, I would still do it, have fun with it. Because it was really nice. So when it was over I was a little disappointed but only a little, I'd say, because it was cool. (6)

I'm happy to have participated, and I hope my contribution will help someone else. (16)

Given the time I have, I am relieved not to go on with the study because I'm a very busy man. (1)

I would say that I was a little relieved to get to the end; it's a question of time and fatigue. (5)

Well, yes I feel relived but I'm glad to have participated. (17)

I'm relieved because I'm going home. (11)

I think I will feel relieved! Sorry for you but I have to go home. (14)

I'm untouched. (12)

If you look back to your participation, which are your personal conclusions or comments?

I think the simple ways on the table were not adequate. I repeat that I have found that the magnitude of the study was not according to what I expected. (1)

I would advise you to do it for all patients and adapt this special technology to the needs of each one. (11)

I would have liked to do more exercises in the beginning to see if I could pass on to the computer the feelings of the brain. I stayed a little bit stuck. (3)

I think there might have been more explanations and especially more training sessions. But since this is not the case, overall I'm glad I participated and I hope others will succeed and will make this project succeed. (7)

As for the comments with the helmet and the pads: I hope in the future development we will not be obliged to carry the whole system in order to make it work. This is my personal conclusion. (5)

I liked it because I wanted to see where I stood. For it is not easy to interact with the computer by thought. (2)

I think this is a very interesting system, which still requires some principle improvements: again, I refer to the cap. But for complete tetraplegic patients who have no movement in the arms, I think it is a technology that is very useful. (8)

It was interesting. If there was other stuff like this, I would probably also be a candidate to participate. (4)

It was a good experience! From a human and technological point of view! (20)

Authors

1. male, age 50, tetraplegia after Guillain-Barre disease, BCI training only
2. male, age 29, spinocerebellar ataxia with polyneuropathy, cervical dystonia, rubral tremor, and anemia, BCI training only
3. female, age 61, Landouzy-Dejerine myopathy, BCI training only
4. male, age 50, Steinert myopathy, BCI training only
5. male, age 59, C5 lesion, tetraplegia, BCI training and prototype testing
6. male, age 29, spinal amyotrophy type II, BCI training and prototype testing
7. male, age 52, C5 lesion, tetraplegia, BCI training only
8. male, age 41, C6 lesion, complete tetraplegia, BCI training and prototype testing
9. male, age 32, incomplete AIS B, tetraplegia, BCI training only
10. female, age 70, shoulder-hand syndrome (complex regional atrophy) following fracture of the left wrist, BCI training only
11. male, age 59, subacute stroke patient
12. male, age 40, subacute stroke patient
13. female, age 71, subacute stroke patient
14. male, age 54, subacute stroke patient
15. male, age 67, subacute stroke patient
16. male, age 59, subacute stroke patient
17. female, age 67, subacute stroke patient
18. male, age 40, C4/C5 lesion, tetraplegia, BCI training and prosthesis control
19. male, age 43, C5/C6 lesion, incomplete tetraplegia, BCI training and prototype testing
20. female, age 47, major impairment (ischemic stroke, right hand movement residual), BCI training and prototype testing

Chapter 11
Relatives' Report

17 January 2006: On this day my husband was diagnosed with amyotrophic lateral sclerosis (ALS). A finding that completely turned our previously carefree life upside down from one day to the next. My husband, born 1955, did not want to accept this diagnosis and so over the course of 2006 consulted a range of doctors as well as alternative practitioners and also tried out other possible cures such as traditional Chinese medicine (TCM), kinesiology, etc. – without success. It took nearly a year before my husband could come to terms with the ALS affection. In the following years, with ever increasing weakness, he coped with his fate with admiral composure – until his death in October 2011. My husband was a business graduate and worked in controlling. Although he used a wheelchair from January 2007, he was able to continue working until July of the same year. At home he spent almost the entire day on the computer. Initially he was still able to use his hands for this, but the power in his hands declined rapidly and so he had to operate the computer with the aid of a joystick and after a few months he had to use his chin to control the computer and manage his surroundings. In March 2008 he registered as a member of a forum of a society for people with muscle disorders, where he learned about a project about alternative communication options and brain–computer interfaces (BCI) and applied to take part. It started in autumn 2008. Psychologists came to our home for the BCI tests. They were all very friendly, courteous, and competent and working with them was an enrichment of our daily lives, both for my husband and for myself, especially as there were always different nationalities in the team.

Although the sessions were very exhausting for him and required an enormous amount of concentration, he always looked forward to the team arriving. This social contact provided for variety and above all for him it meant trying out new technologies. He was the person affected and so through his participation in the tests he wanted to use the opportunity to do something to improve the quality of life. My husband felt a real sense of achievement when, with the aid of BCI and the Internet,

The report comes from the wife (age 57, industrial clerk), who was assisted by her son (age 22, engineering student). They chose to write anonymously.

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he was able from his living room to make a robot at a Spanish university move. In the framework of the BCI studies he also worked with Brain Painting, which brought him a lot of pleasure and was a welcome diversion for him. Brain Painting was for him a great opportunity to do something artistic where both healthy and disabled people have the same opportunities.

My husband viewed BCI as a good concept, with many usage possibilities. However, he found the cap with the numerous electrodes, the gel as well as the light roughening of the scalp and the long preparation time this all required to be very annoying. With longer use or several periods of use in a short space of time, his scalp would without doubt have rebelled. He would have wished for an alternative to the cap, with fewer electrodes and less gel or none at all. He also thought that simpler cable management with easier and more user-friendly connection systems would be sensible for end users. He also believed that BCI, at least at that point in time, was too slow for daily use. For example, too much time had elapsed before a single command was forwarded to the computer. My husband would perhaps have considered using his own BCI had the speed and accuracy been improved. For me as the partner it was definitely a little strange using a BCI. But better communication with the use of BCI than no communication at all. I would have needed a corresponding set of instructions though. An eye-control system would perhaps have been more realistic in his case in terms of handling.

We hope that the studies in the field of BCI continue, so that affected people can improve their quality of life through this communication option and through the artistic activities.

Part III
Reflections

Chapter 12
A Tour of Some Brain/Neuronal–Computer Interfaces

Kevin Warwick

12.1 Introduction

For many years science fiction has looked to a future in which robots are intelligent and cyborgs – a human/machine merger – are commonplace. The Terminator, The Matrix, Blade Runner, and I, Robot are all good examples of this. Until recently however any serious consideration of what this might actually mean in the future real world was not necessary because it was really all science fiction and not scientific reality. Now however science has not only done a catching-up exercise but, in bringing about some of the ideas initially thrown up by science fiction, has introduced practicalities that the original storylines did not extend to (and in some cases still have not extended to).

What we consider here are several relevant experiments in linking biology and technology together in a cybernetic fashion. Key to this is that it is the overall final system that is important. Where a brain is involved, which surely it is, it should not be seen as a standalone entity but rather as part of the overall system – adapting to the system's needs.

Each experiment is described in its own section. Whilst there is clear overlap between the sections, they each throw up individual considerations. Following a description of each investigation some pertinent issues on the topic are discussed. Points have been raised with a view to near-term future technical advances and what these might mean in a practical scenario. It has certainly not been the case of an attempt to present a fully packaged conclusive document; rather the aim has been to open up the range of research carried out and to look at some of its implications.

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12.2 Robots with Biological Brains

We start here by looking at an area that might not immediately spring to mind. Initially when one thinks of brain–computer interaction then it is usually in terms of a brain already functioning and settled within a body. Here however we consider the possibility of a fresh merger where a brain is given a body in which to operate.

When one thinks of a robot it may be a little wheeled device that springs to mind (Bekey 2005) or perhaps a metallic head that looks roughly human-like (Brooks 2002). Whatever the physical appearance, our concept tends to be that the robot might be operated remotely by a human, as in the case of a bomb disposal robot, is being controlled by a simple computer program, or even may be able to learn with a microprocessor/computer as its brain. In all these cases we regard the robot simply as a machine. But what if the robot has a biological brain made up of brain cells (neurons), possibly human neurons?

Neurons cultured under laboratory conditions on an array of non-invasive electrodes provide an attractive alternative with which to realize a new form of robot controller. An experimental control platform, a robot body, can move around in a defined area purely under the control of such a network/brain and the effects of the brain, controlling the body, can be witnessed. This is not only extremely interesting from a robotics perspective but it also opens up a new approach to the study of the development of the brain itself because of its sensory-motor embodiment. Investigations can therefore be carried out into memory formation and reward/punishment scenarios.

Typically culturing networks of brain cells (around 100,000 at present) in vitro commences by separating neurons obtained from fetal rodent cortical tissue. They are then grown (cultured) in a specialized chamber, in which they can be provided with suitable environmental conditions (e.g. appropriate temperature) and nutrients. An array of electrodes embedded in the base of the chamber (a multielectrode array; MEA) acts as a bi-directional electrical interface to/from the culture. The neurons in such cultures spontaneously connect, communicate, and develop, within a few weeks giving useful responses for typically 3 months at present.

The culture is grown in a glass specimen chamber lined with a planar '8×8' multielectrode array which can be used for real-time recordings (see Fig. 12.1). It is possible to separate the firings of small groups of neurons by monitoring the output signal on the electrodes. In this way a picture of the global activity of the entire network can be formed. It is also possible to electrically stimulate the culture via any of the electrodes to induce neural activity. The multi-electrode array therefore forms a bi-directional interface to the cultured neurons (DeMarse et al. 2001; Chiappalone et al. 2007).

The culture can then be coupled to its physical robot body (Warwick et al. 2010). Sensory data fed back from the robot is subsequently delivered to the culture, thereby closing the robot–culture loop. Thus, signal processing can be broken down into two discrete sections: (a) 'culture to robot', in which live neuronal activity is used as the decision-making mechanism for robot control, and

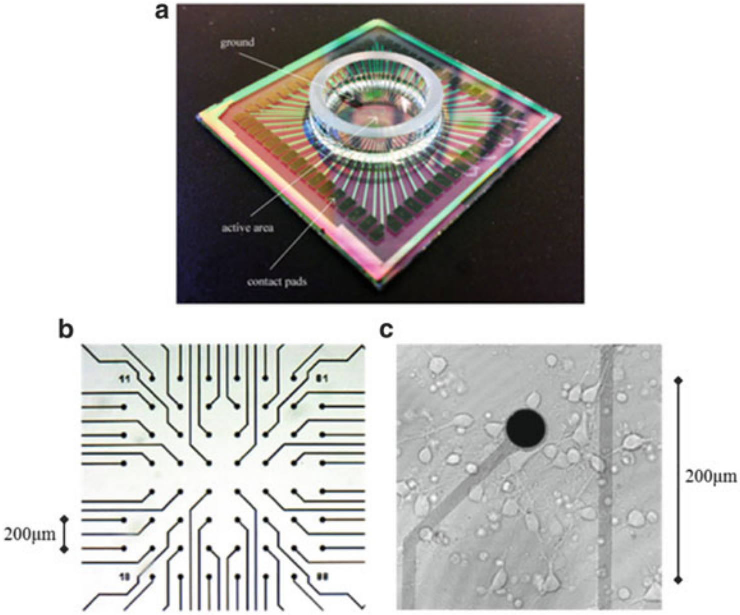

Fig. 12.1 (**a**) A multielectrode array (MEA) showing the electrodes; (**b**) electrodes in the center of the MEA seen under an optical microscope; (**c**) an MEA at ×40 magnification, showing neuronal cells in close proximity to an electrode

(b) 'robot to culture', which involves an input mapping process, from robot sensor to stimulate the culture.

The actual number of neurons in a culture depends on natural density variations in seeding. The electrochemical activity of the culture is sampled and this is used as input to the robot's wheels. Meanwhile the robot's (ultrasonic) sensor readings are converted into stimulation signals received by the culture, thereby closing the loop.

An existing neuronal pathway is identified by searching for strong relationships between pairs of electrodes. Such pairs are defined as those electrode combinations in which neurons close to one electrode respond to stimulation from the other electrode at which the stimulus was applied more than 60 % of the time and respond no more than 20 % of the time to stimulation on any other electrode. A rough input/output response map of the culture can then be created by cycling through all electrodes. In this way, a suitable input/output electrode pair can be chosen in order to provide an initial decision-making pathway for the robot. This is employed to control the robot body – for example if the ultrasonic sensor is active and we wish the response to cause the robot to turn away from the object being located ultrasonically (possibly a wall) in order to keep moving.

For experimentation purposes, the robot follows a forward path until it reaches a wall, at which point the front sonar value decreases below a threshold, triggering a stimulating pulse. If the responding/output electrode registers activity the robot turns to avoid the wall. In experiments the robot turns spontaneously whenever activity is registered on the response electrode. The most relevant result is the occurrence of the chain of events: wall detection–stimulation–response. From a neurological perspective it is of course also interesting to speculate why there is activity on the response electrode when no stimulating pulse has been applied.

As an overall control element for direction and wall avoidance the cultured network acts as the sole decision-making entity within the overall feedback loop. Clearly one important aspect then involves neural pathway changes, with respect to time, in the culture between the stimulating-recording electrodes.

Learning and memory investigations are generally at an early stage. However the robot appears to improve its performance over time in terms of its wall avoidance ability in the sense that neuronal pathways that bring about a satisfactory action tend to strengthen purely through the process of being habitually performed – learning due to habit. The number of confounding variables is however considerable and the plasticity process, which occurs over quite a period of time, is (most likely) dependent on such factors as initial seeding and growth near electrodes as well as environmental transients such as temperature and humidity. Learning by reinforcement – rewarding good actions and punishing bad – is much more of an investigative research effort at this time.

On many occasions the culture responds as expected, on other occasions it does not, and in some cases it provides a motor signal when it is not expected to do so. But does it 'intentionally' make a different decision to the one we would have expected? We cannot tell.

In terms of robotics, it has been shown by this research that a robot can successfully have a biological brain to make all its 'decisions'. The 100,000 neuron size is merely due to the present day limitations of the experimentation described. Indeed three-dimensional structures are already being investigated. Increasing the complexity from two dimensions to three dimensions realizes a figure of approximately 30 million neurons for the three-dimensional case – not yet reaching the 100 billion neurons of a perfect human brain, but well in tune with the brain size of many other animals.

This area of research is however expanding rapidly. Not only is the number of cultured neurons increasing, but also the range of sensory input is being expanded to include audio, infrared, and even visual. Such richness of stimulation will no doubt have a dramatic effect on culture development. The potential of such systems, including the range of tasks they can deal with, also means that its physical body can take on different forms. There is no reason, for example, that the body could not be a two-legged walking robot, with rotating head and the ability to walk around in a building.

It is certainly the case that understanding neural activity becomes more difficult as the culture size increases. With a three-dimensional structure, monitoring activity deep within the central area, as with a human brain, becomes extremely complex, even with needle-like electrodes. In fact the present 100,000 neuron cultures are already far too complex at present for us to gain an overall insight. When they are grown to sizes such as 30 million neurons and beyond, clearly the problem is significantly magnified. Looking a few years out, it seems quite realistic to assume that such cultures will become larger, potentially growing into sizes of billions of neurons. On top of this, the nature of the neurons may be diversified. At present rat neurons are generally employed in studies. However human neurons are also now being cultured, allowing for the possibility of a robot with a human neuron brain. If this brain then consists of billions of neurons, many social and ethical questions will need to be asked (Warwick 2010).

For example – If the robot brain has roughly the same number of human neurons as a typical human brain then could/should it have similar rights to humans? Also – What if such creatures had far more human neurons than in a typical human brain – e.g. a million times more – would they make all future decisions rather than regular humans?

12.3 Deep Brain Stimulation

Different types of brain–computer interfaces are employed either for research purposes or for standard medical procedures. The number actually in position and operating at any one time is steadily growing, a trend that is likely to increase in the years ahead.

As a case example, the number of Parkinson’s disease (PD) patients is estimated to be 120–180 out of every 100,000 people, although the percentage is increasing rapidly as life expectancies increase. For decades researchers have exerted considerable effort to understand more about the disease and to find methods to successfully limit its symptoms (Pinter et al. 1999), which are most commonly periodic (and frequently acute) muscle tremor and/or rigidity. Many other symptoms such as stooping may however occur in later stages of PD.

Several approaches exist to treat this disease. In its early stages, the drug levodopa (L-dopa) has been the most common one since 1970. However, it is found that the effectiveness of L-dopa decreases as the disease worsens and severity of the side effects increases, something that is far more apparent when PD is contracted by a younger person.

Surgical treatment, such as lesioning, is an alternative when drug treatments have become ineffective. Lesioning can alleviate symptoms, thus reducing the need for drug therapy altogether. An alternative treatment of PD by means of Deep Brain Stimulation (DBS) only became possible when the relevant electrode technology became available from the late 1980s onwards. From then on, many neurosurgeons have moved to implanting neurostimulators connected to deep brain electrodes positioned in the thalamus, sub-thalamus, or globus pallidus for the treatment of tremor, dystonia, and pain.

A typical deep brain stimulation device contains an electrode lead with four or six cylindrical electrodes at equally spaced depths attached to an implanted pulse generator (IPG), which is surgically positioned below the collar bone. DBS has many advantages such as being reversible. It is also potentially much less dangerous than lesioning and is, in many cases, highly effective. However, it presently utilizes a continuous current simulation at high frequency resulting in the need for regular battery replacement every 24 months or so. The cost of battery replacement, the time-consuming surgery involved, and the trauma of repetitive surgery of battery replacement severely limits the patients who can benefit, particularly those who are frail, or have problems with their immune system or are not particularly wealthy.

The obvious solution, namely remote inductive battery recharging, is fraught with problems such as the size of passive coil size that needs to be implanted and nasty chemical discharges that occur within the body – even then the mean time between replacements is only marginally improved. Another solution to prolong the battery life is simply to improve battery technology. However, the link between price of battery and battery life is clear. If we are considering here a battery that could potentially supply the stimulation currents required over a 10 or 20 year period then the technology to achieve this in a low cost, implantable, durable form is not on the horizon.

However ongoing research involving the author is aimed at developing an 'intelligent' stimulator (Pan et al. 2007; Wu et al. 2010). The idea of the stimulator is to produce warning signals before the tremor starts so that the stimulator only needs to generate signals occasionally instead of continuously – in this sense operating in a similar fashion to a heart pacemaker.

Artificial Intelligence (AI) tools have been shown to successfully provide tremor onset prediction. In either case, data input to the network is provided by the measured electrical Local Field Potentials obtained by means of the deep brain electrodes, i.e. the network is trained to recognize the nature of electrical activity deep in the human brain and to predict (several seconds ahead) the subsequent tremor onset outcome. In this way the DBS device is 'intelligent' when the stimulation is only triggered by the AI system.

Many issues exist with the AI system as much preprocessing of the brain data is necessary along with frequency filtering to minimize the difficulty of prediction. Comparative studies are now ongoing to ascertain which AI method appears to be the most reliable and accurate in a practical situation.

It is worth pointing out here that false positive predictions (that is the AI system indicating that a tremor is going to occur when in fact this is not the case) are not so much of a critical problem. The end result with such a false positive is that the stimulating current may be applied when it is not strictly necessary. In any event no actual tremor would occur, which is a good outcome for the patient in any case, however unnecessary energy would have been used – in fact if numerous false predictions occurred the intelligent stimulator would tend to operate in the same way as the present 'blind' stimulator. The good news is that results show that the network can be readily tuned to avoid the occurrence of most false positives anyway.

Missing the prediction of a tremor onset is though extremely critical and is simply not acceptable. Such an event would mean that the stimulating current would not come into effect and the patient would actually suffer from tremors occurring.

Whilst deep brain implants are, as described, aimed primarily to provide current stimulation for therapeutic purposes, they can also have a broader portfolio in terms of the effects they can have within the human brain. It is worth stressing however that in all cases further implantations are at this time forging ahead with little or no consideration being given to the general technical, biological, and ethical issues that pervade. It is perhaps time that such issues were given an airing.

The same physical stimulator that is used for the treatment of Parkinson's disease is also employed, albeit in fewer instances at present, for cases of Tourette's syndrome, epilepsy, and even clinical depression. In many people's eyes it is probable that the use of deep brain stimulators for the treatment of Parkinson's disease, epilepsy, or Tourette's syndrome is perfectly acceptable because of the standard of living it can effect for the individual recipient. However long-term modifications of brain organization can occur in each case, causing the brain to operate in a completely different fashion, e.g. there can be considerable long-term mental side effects in the use of such technology. The stimulators, when positioned in central areas of the brain, can cause other direct results, including distinct emotional changes. The picture is therefore not one of merely overcoming a medical problem – it is far more complex.

As described here, 'intelligent' deep brain stimulators are starting to be designed (Pan et al. 2007). In such a case a computer (artificial brain) is used to understand the workings of specific aspects of the human brain. The job of the artificial brain, as can be seen from the description of the experimentation, is to monitor the normal functioning of the human brain such that it can accurately predict a spurious event, such as a Parkinson's tremor, several seconds before it actually occurs. In other words the artificial brain's job is to outthink the human brain and to stop it doing what it 'normally' wants to do. Clearly the potential for this system to be applied for a broad spectrum of different uses is enormous.

12.4 General Purpose Brain Implants

In the previous section a description has been given of a brain–computer interface which is used for therapeutic purposes to overcome a medical/neurological problem. However even there it is possible to consider employing such technology to give individuals abilities not normally possessed by humans. Human Enhancement!

With more general brain–computer interfaces the therapy-enhancement situation is more complex. In some cases it is possible for those who have suffered an amputation or have received a spinal injury due to an accident to regain control of devices via their (still functioning) neural signals (Donoghue et al. 2004). Meanwhile stroke patients can be given limited control of their surroundings, as indeed can those who have for example motor neurone disease.

Even with these cases the situation is not exactly simple, as each individual is given abilities that no normal human has – for example the ability to move a cursor around on a computer screen from neural signals alone (Kennedy et al. 2004). The

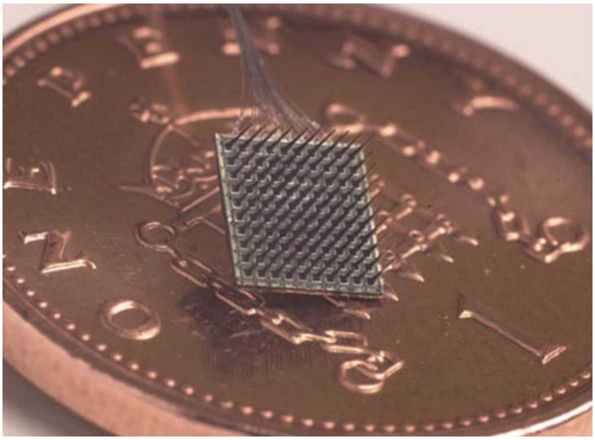

Fig. 12.2 A 100 electrode, 4×4 mm microelectrode array, shown on a UK 1 pence piece for scale

same quandary exists for blind individuals who are allowed extra sensory input, such as sonar (a bat-like sense) – it doesn't repair their blindness but rather allows them to make use of an alternative sense.

Some of the most impressive human research to date has been carried out using the microelectrode array, shown in Fig. 12.2. The individual electrodes are 1.5 mm long and taper to a tip diameter of less than 90 μm. Although a number of trials not using humans as a test subject have occurred, human tests are at present limited to two groups of studies. In the second of these the array has been employed in a recording only role, most notably recently as part of (what was called) the 'Braingate' system. Essentially electrical activity from a few neurons monitored by the array electrodes was decoded into a signal to direct cursor movement. This enabled an individual to position a cursor on a computer screen, using neural signals for control combined with visual feedback. The same technique was later employed to allow the individual recipient, who was paralyzed, to operate a robot arm (Hochberg et al. 2006). The first use of the microelectrode array (shown in Fig. 12.2) has however considerably broader implications which extend the capabilities of the human recipient.

Actually deriving a reliable command signal from a collection of captured neural signals is not necessarily a simple task, partly due to the complexity of signals recorded and partly due to time constraints in dealing with the data. In some cases however it can be relatively easy to look for and obtain a system response to certain anticipated neural signals – especially when an individual has trained extensively with the system. In fact neural signal shape, magnitude, and waveform with respect to time are considerably different to the other signals that it is possible to measure in this situation.

The interface through which a user interacts with technology provides a distinct layer of separation between what the user wants the machine to do and what it actually does. This separation imposes a cognitive load that is proportional to the difficulties experienced. The main issue is interfacing the human motor and sensory channels with the technology in a reliable, durable, effective, bi-directional way. One solution is to avoid this sensorimotor bottleneck altogether by interfacing directly with the human nervous system.

An individual human so connected can potentially benefit from some of the advantages of machine/artificial intelligence, for example rapid and highly accurate mathematical abilities in terms of 'number crunching', a high speed, almost infinite, internet knowledge base, and accurate long-term memory. Additionally, it is widely acknowledged that humans have only five senses that we know of, whereas machines offer a view of the world which includes infrared, ultraviolet, and ultrasonic signals, to name but a few.

Humans are also limited in that they can only visualize and understand the world around them in terms of a limited three-dimensional perception, whereas computers are quite capable of dealing with hundreds of dimensions. Perhaps most importantly, the human means of communication, essentially transferring a complex electro-chemical signal from one brain to another via an intermediate, often mechanical slow and error-prone medium (e.g. speech), is extremely poor, particularly in terms of speed, power, and precision. It is clear that connecting a human brain, by means of an implant, with a computer network could in the long term open up the distinct advantages of machine intelligence, communication, and sensing abilities to the implanted individual.

As a step towards a broader concept of brain–computer interaction, in the first study of its kind, the microelectrode array (as shown in Fig. 12.2) was implanted into the median nerve fibers of a healthy human individual (the author) during 2 h of neurosurgery in order to test *bidirectional* functionality in a series of experiments. A stimulation current directly into the nervous system allowed information to be sent to the user, while control signals were decoded from neural activity in the region of the electrodes (Warwick et al. 2003). In this way a number of experimental trials were successfully concluded (Warwick et al. 2004): In particular:

1. Extrasensory (ultrasonic) input was successfully implemented.
2. Extended control of a robotic hand across the internet was achieved, with feedback from the robotic fingertips being sent back as neural stimulation to give a sense of force being applied to an object (this was achieved between Columbia University, New York (USA) and Reading University, England).
3. A primitive form of telegraphic communication directly between the nervous systems of two humans (the author's wife assisted) was performed (Warwick et al. 2004).
4. A wheelchair was successfully driven around by means of neural signals.
5. The color of jewelry was changed as a result of neural signals – also the behavior of a collection of small robots.

In most, if not all, of the above cases it could be regarded that the trial proved useful for purely therapeutic reasons, e.g. the ultrasonic sense could be useful for an individual who is blind or the telegraphic communication could be very useful for those with certain forms of motor neurone disease. However each trial can also be seen as a potential form of enhancement beyond the human norm for an individual.

Indeed the author did not need to have the implant for medical purposes to overcome a problem but rather for scientific exploration. The question then arises as to how far should things be taken? Clearly enhancement by means of brain–computer interfaces opens up all sorts of new technological and intellectual opportunities, however it also throws up a raft of different ethical considerations that need to be addressed directly.

When ongoing experiments of the type just described involve healthy individuals where there is no reparative element in the use of a brain–computer interface, but rather the main purpose of the implant is to enhance an individual's abilities, it is difficult to regard the operation as being for therapeutic purposes. Indeed the author, in carrying out such experimentation, specifically wished to investigate actual, practical enhancement possibilities (Warwick et al. 2003, 2004). From the trials it is clear that extrasensory input is one practical possibility that has been successfully trialed, however improving memory, thinking in many dimensions, and communication by thought alone are other distinct potential, yet realistic, benefits, with the latter of these also having been investigated to an extent. To be clear – all these things appear to be possible (from a technical viewpoint at least) for humans in general.

As we presently stand, to get the go-ahead for an implantation in each case (in the UK anyway) requires ethical approval from the local hospital authority in which the procedure is carried out, and, if it is appropriate for a research procedure, also approval from the research and ethics committee of the establishment involved. This is quite apart from devices agency approval if a piece of equipment, such as an implant, is to be used on many individuals. Interestingly no general ethical clearance is needed from any societal body – yet the issues are complex.

12.5 Non-invasive Brain–Computer Interfaces

The most studied brain–computer interface is perhaps that involving electroencephalography (EEG) and this is due to several factors. Firstly it is (as the heading says) non-invasive, hence there is no need for surgery with potential infection and/or side effects. As a result, ethical approval requirements are significantly less and, due to the ease of electrode availability, costs are significantly lower than for other methods.

It is also a portable procedure, involving electrodes which are merely stuck on to the outside of a person's head and can be set up in a lab with relatively little training and little background knowledge and taking little time – it can be done then and there, on the spot. As a consequence of this to some researchers, not so well versed in the field, one sometimes often encounters the feeling that BCI = EEG.

The number of electrodes employed for experimental purposes can vary from a small number, four to six, to the most commonly encountered 26–30, to well over 100 for those attempting to achieve better resolution. As a result it may be that individual electrodes are attached at specific locations or a cap is worn in which the electrodes are prepositioned. The care and management of the electrodes also varies considerably between experiments from those in which the electrodes are positioned dry and external to hair to those in which hair is shaved off and gels are used to improve the contact made.

Some studies are employed more in the medical domain, for example to study the onset of epileptic seizures in patients, but the range of applications is widespread. A few of the most typical and/or interesting are included here to give an idea of possibilities and ongoing work rather than for a complete overview of the present state of play.

Typical are those in which subjects learn to operate a computer cursor in this fashion (Trejo et al. 2006). It must be pointed out here however that, even after significant periods of training (many months), the process is slow and usually requires several attempts before success is achieved. Along much the same lines, numerous research groups have used EEG recordings to switch on lights, control a small robotic vehicle, and control other analogue signals (Millan et al. 2004; Tanaka et al. 2005). A similar method was employed, with a 64-electrode skull cap, to enable a quadriplegic to learn to carry out simple hand movement tasks by means of stimulation through embedded nerve controllers (Kumar 2008).

It is possible also to consider the uniqueness of specific EEG signals, particularly in response to associated stimuli, potentially as an identification tool (Palaniappan 2008). Meanwhile interesting results have been achieved using EEG for the identification of intended finger taps, whether the taps occurred or not, with high accuracy. This is useful as a fast interface method as well as a possible prosthetic method (Daly et al. 2011).

Whilst EEG experimentation is relatively cheap, portable, and easy to set up, in a completely different light, yet still within the category of non-invasive techniques, both functional magnetic resonance imaging (fMRI) and magnetoencephalography (MEG) have also been successfully employed. fMRI brain scans use a strong, permanent magnetic field to align nuclei in the brain region being studied to ascertain blood flow at specific times in response to specific stimuli. As was reported earlier they can therefore be used as a marker to figure out where there is activity in the brain when an individual thinks about moving their hand.

The equipment is however necessarily cumbersome and relatively expensive. As a result of the cost and equipment availability, experimentation in this area is by no means as widespread as that for EEG. Results have nevertheless been obtained in reconstructing images from such scans (Rainer et al. 2001) and matching visual patterns from watching videos with those obtained in a time-stamped fashion from the fMRI scans being recorded (Beauchamp et al. 2003).

12.6 Subdermal Magnetic Implants

One final area to be considered here is that of subdermal magnetic implants (Hameed et al. 2010). This involves the controlled stimulation of mechanoreceptors by an implant manipulated through an external electromagnet. A suitable magnet and implant site are required for this along with an external interface for manipulating the implant. Clearly issues such as magnetic field strength sensitivity and frequency sensitivity are important.

Implantation is an invasive procedure and hence implant durability is an important requirement. Only permanent magnets retain their magnetic strength over a very long period of time and are robust to various conditions. This restricts the type of magnet that can be considered for implantation to permanent magnets. Hard ferrite, neodymium, and alnico are easily available, low cost permanent magnets suitable for this purpose.

The magnetic strength of the implant magnet contributes to the amount of agitation the implant magnet undergoes in response to an external magnetic field and also determines the strength of the field that is present around the implant location.

The skin on the human hand contains a large number of low threshold mechanoreceptors that allow humans to experience in great detail the shape, size, and texture of objects in the physical world through touch. The highest density of mechanoreceptors is found in the fingertips, especially of the index and middle fingers. They are responsive to relatively high frequencies and are most sensitive to frequencies in the range 200–300 Hz.

For reported experiments (Hameed et al. 2010), the pads of the middle and ring fingers were the preferred sites for magnet implantation. A simple interface containing a coil mounted on a wire frame and wrapped around each finger was designed for generating the magnetic fields to stimulate movement in the magnet within the finger. The general idea is that the output from an external sensor is used to control the current in the wrapped coil. So as the signals detected by the external sensor change, these in turn are reflected in the amount of vibration experienced through the implanted magnet.

A number of application areas have already been experimented on, as reported in Hameed et al. (2010). The first is ultrasonic range information. This scenario connects the magnetic interface to an ultrasonic ranger for navigation assistance. Distance information from the ranger was encoded via the ultrasonic sensor as variations in frequency of current pulses, which in turn were passed on to the electromagnetic interface.

It was found that this mechanism allowed a practical means of providing reasonably accurate information about the individual's surrounding towards navigational assistance. The distances were intuitively understood within a few minutes of use and were enhanced by distance "calibration" through touch and sight.

A further application involves reading Morse signals. This application scenario applies the magnetic interface towards communicating text messages to humans using an encoding mechanism suitable for the interface. Morse code was chosen for encoding due to its relative simplicity and ease of implementation.

In this way text input can be encoded as Morse code and the dots and dashes transmitted to the interface. The dots and dashes can be represented as either frequency or magnetic field strength variations.

12.7 Conclusions

In this chapter a look has been taken at several different types of brain–computer interface. Experimental cases have been reported on in order to indicate how humans, and/or animals for that matter, can merge with technology in this way – thereby throwing up a plethora of social and ethical considerations as well as technical issues. In each case reports on actual practical experimentation results have been given, rather than merely some theoretical concept.

In particular when considering robots with biological brains, this could ultimately mean perhaps human brains operating in a robot body. Therefore, should such a robot be given rights of some kind? If one was switched off would this be deemed as cruelty to robots? More importantly at this time – should such research forge ahead regardless? Before too long we may well have robots with brains made up of human neurons that have the same sort of capabilities as those of the human brain – is this OK?

The section on deep brain stimulation looked at some of the issues raised by seemingly therapeutic-only implants such as those used for the treatment of Parkinson's disease – a relatively standard procedure. However, not only does the present implant throw up possible problems concerning responsibility if a malfunction occurs but when an intelligent, predictive implant is employed should this be acceptable, even for therapeutic reasons, when a computer brain is outwitting a human brain and stopping it doing what it naturally wants to do? If you cannot do what your own brain wants you to do, then what?

Meanwhile in the section on a more general purpose invasive brain implant as well as implant employment for therapy a look was taken at the potential for human enhancement. Extrasensory input has already been scientifically achieved, extending the nervous system over the internet and a basic form of thought communication. So if many humans upgrade and become part machine (cyborgs) themselves, what would be wrong with that? If ordinary (non-implanted) humans are left behind as a result then what is the problem? If you could be enhanced, would you have any problem with it?

Then came a section on the much more standard EEG electrodes which are positioned externally and which therefore are encountered much more frequently. Unfortunately the resolution of such electrodes is relatively poor and they are indeed only useful for monitoring and not stimulation. Hence issues surrounding them are somewhat limited. We may well be able to use them to learn a little more about how the brain operates but it is difficult to see them ever being used for highly sensitive control operations when several million neurons feed into the information transmitted by each electrode.

Finally a quick look was taken at subdermal magnetic implants. This type of connection has, until recently, been investigated more by body modification artists than scientists and hence application areas are still relatively sparse. Whilst involving an invasive procedure it is still relatively straightforward in comparison with for example deep brain stimulation or multielectrode arrays fired into the nervous system. It is expected therefore that this will become an area of considerable interest over the next few years with many more potential application areas being revealed.

As well as taking a look at the procedures involved, the aim in this article has been to consider some of the ethical and social issues as well. Some technological issues have nonetheless also been pondered on in order to open a window on the direction that developments are heading. In each case however a firm footing has been planted on actual practical technology rather than on speculative ideas. In a sense the overall idea is to open up a sense of reflection such that further experimentation can be guided by the informed feedback that results.

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Chapter 13
Philosophical Reflections on Brain–Computer Interfaces

Guglielmo Tamburrini

13.1 BCI as an Exemplary Case Study in the Philosophy of ICT

A Brain–Computer Interface (BCI) processes brain activity online and identifies patterns in this activity that can be used for communication, control, and, more recently, monitoring purposes (Wolpaw and Wolpaw 2012). BCI systems are prime examples of the actual and potential changes that novel information and communication technologies (ICT) are impressing on human–machine interactions, on public debate about the promotion and regulation of technological innovation, and on rational and irrational attitudes towards technological development. This contribution examines the impact that BCI systems are having on these aspects of human life from distinctive philosophical perspectives.

To illustrate, consider the question "Are there good reasons to believe that my BCI system will do the right thing in its operational environment?" The special epistemological interest of this question depends on the *adaptive* character of both BCI systems and the operational environment they are immersed in. Indeed, BCI architectures crucially involve a *learning* component, that is, a computer program which is trained to adapt to and identify activity patterns in the central nervous system (CNS). Since an adaptive BCI interacts with a CNS, in other words with the most complex adaptive system we are acquainted with, their sustained interactions give rise to both theoretical and practical impediments in the way of predicting exactly what a BCI system will do in its intended operational environment. These epistemological issues are addressed in Sect. 13.2.

Epistemological reflections on the expected behavior of BCI systems bear on a variety of issues in applied ethics. Retrospective responsibility and liability

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problems are significant cases in point. The epistemic predicament affecting programming engineers, manufacturers, and users of BCI systems alike looms large on such questions as “Who is morally responsible for unpredicted damage caused by a BCI-actuated device?” and “How are liabilities and compensations for that damage properly distributed?” The connections between epistemology and ethics in BCI contexts are addressed in Sects. 13.3 and 13.4.

BCI research is paving the way for unprecedented forms of human–machine interaction. Notably, BCI systems enable one to establish communication channels with the external world *without requiring any voluntary muscular movement* on the part of their users. However, current limitations of BCI communication channels in the way of bit-rate transfer suggest that only special categories of healthy users may benefit in the near future from BCI systems. It has been proposed, for example, that astronauts might be one of these categories, insofar as mental teleoperation enables one to govern external semi-automatic manipulators in hampering microgravity work conditions (Millán et al. 2006).

In the light of current BCI strengths and weaknesses, the wider groups of users who are likely to take advantage of BCI systems in the near future are formed by people affected by severe motor impairments. Notably, BCI systems may mitigate excruciating communication and action barriers experienced by persons affected by Locked-In Syndrome (LIS) and other clinical conditions bringing about very limited or no residual capabilities for voluntary movement. By the same token, however, BCI experimentation and trials may induce unrealistic expectations in these remarkably vulnerable groups of persons. The ethical implications of this state of affairs are examined in Sect. 13.5 in the context of the ethical principles of respect for persons and medical beneficence.

Groundbreaking experimental trials showed that some persons diagnosed to be in a vegetative state were capable of answering correctly yes/no autobiographical questions by producing the required brain activity patterns (Owen et al. 2006; Monti et al. 2010). Similar brain activity patterns can be used to operate a BCI system. Accordingly, it was suggested that BCI systems may enable one to test whether conscious states occur in behaviorally unresponsive persons and to open, in the case of positive test outcomes, a unique communication channel with them. These envisaged uses of BCI systems give a new twist to the epistemological problem of assessing the soundness of inferences from behavioral observations to the attribution of conscious states to other human beings (or, more generally, to other entities). Here, inferences to consciousness are based on empirical premises involving BCI-detected patterns of brain activity rather than overt verbal behaviors or bodily movements (Owen et al. 2009). It transpires that basic distinctions drawn in the philosophy of mind about different aspects or varieties of consciousness help one to clarify empirical and conceptual problems arising in connection with these inferences, the correctness of their conclusions, and their ethical implications (Tamburrini and Mattia 2011). These various issues are examined in Sect. 13.6.

The new forms of human–machine interactions that are enabled by BCI systems give rise to special expectations about ICT technologies and their envisaged benefits for human life. In making public statements about their goals and achievements, scientists cannot count on the shared background of tacit knowledge which shapes communication styles within their own scientific communities. Accordingly, the ethically praiseworthy goal of transferring correct and accessible information to the general public raises the formidable challenge of adapting communication styles to the needs of much broader audiences of non-specialists. This issue is examined in Sect. 13.7 in connection with different sorts of psychological attitudes, both rational and irrational, that BCI systems may give rise to.

On the whole, these various observations suggest that one may expect substantial rewards from an examination of BCI systems from the distinctively philosophical perspectives of epistemology and scientific method, ethics, philosophy of mind, and philosophical psychology. It is to this task that we now turn, starting from the vantage point offered by epistemology and scientific methodology.

13.2 Epistemological Reflections on Adaptive BCI Systems

Interaction between a BCI system and its user starts from the user performing a *mental task*. The user's brain activity is *recorded* during task performance, and processed online in order to *recognize* the presence of features that one *translates* into control signals for an external device. Finally, the user obtains (usually perceptual or linguistic) *feedback* about the outcomes of this repeatable interaction cycle.

This closed-loop functional scheme can be multiply realized in ways that are conditional on available kinds of BCI hardware and software; on the invasive or non-invasive character of brain signal recording devices; on the use of synchronous or asynchronous interaction protocols; and on the variety of brain signals that are acquired and processed. Additional taxonomies of BCI systems arise on the basis of a variety of informative distinctions, which include those between dependent and independent, active and passive, and hybrid and non-hybrid BCI systems (Wolpaw et al. 2002; Wolpaw and Wolpaw 2012).

In synchronous communication protocols, the mental effort required of the human user is locked to the presentation of some perceptual stimuli. For example, letters of the alphabet are consecutively flashed on a screen, and the user must concentrate on the letter he wants to select and write by means of a BCI-actuated word processor. In asynchronous communication protocols, users voluntarily initiate and pace their mental efforts. For example, one may choose to imagine some specific body movement or to carry out an arithmetic operation or another mental task taken from a fixed list in which each task is associated with the performance of an action. Imagining a specific body movement (as opposed to executing an arithmetic operation) is meant to transmit, through the BCI identification of some of its characteristic neural correlates, the command that action A (as opposed to action B) must be planned and carried out by an ICT or robotic device.

A BCI system relies on some suitable classification rules in order to distinguish between the neural correlates of different mental states. This classification rule is usually generated by means of a supervised machine learning process (Müller et al. 2008), which involves the use of a training set formed by examples of recorded brain activity and their correct classification.

How reliable are learned classification rules in their identification of BCI user intents? This epistemological problem is addressed by extensive testing of learned rule performance or theoretical assessments of learning outcome reliability. Both approaches involve distinctive background assumptions about the significance of training data and the stability of the stochastic phenomenon one is dealing with. Indeed, reliability estimates obtained by testing the performance of learned rules are contingent on the assumption that both training and testing data are representative of a stochastically stable phenomenon. Similarly, probabilistic bounds on error frequency that one establishes within the more abstract mathematical framework of statistical learning theory (Vapnik 2000) are contingent on the background assumption that training inputs be independently drawn from a fixed probability distribution.

The background assumptions that are involved in both empirical testing and theoretical assessments of learned rule reliability are difficult to buttress when the classification of neural correlates of cognitive processing is at stake. Indeed, a variety of contextual factors jeopardize the stability of recorded brain signals. These factors notably include increased familiarity with the mental task, mental fatigue, variable attention level, and the reproducibility of initial conditions by means of technical set-up procedures that are carried out at the beginning of each BCI session. Briefly, both empirical and theoretical evaluations of the reliability of learned classification rules are based on the fulfillment of boundary conditions on brain processing and signal recording that are difficult to isolate, control, and reproduce (Tamburrini 2009). In turn, this epistemic predicament gives rise to ethical tensions between autonomy promotion and protection in practical applications of BCI systems, and especially so in connection with groups of users affected by severe motor impairments.

13.3 Protecting BCI User Autonomy

There are persons who can hardly turn *any* intention to act into appropriate sequences of bodily movements. This condition is dramatically witnessed by people affected by LIS, who preserve a basically intact mind trapped in an almost or completely paralyzed body – a butterfly in a diving bell, to use the words with which Jean-Dominique Bauby graphically conveyed his dramatic condition (Bauby 1997). In this condition of generalized motor impairment, human agency *as such* is mostly or completely compromised.

There is a direct conceptual connection between the protection of human agency as such and the protection of human dignity. The concept of agent – that is, the concept of an entity that is capable of performing a repertoire of actions guided by desires, intentions, and beliefs about the world – plays a central role in both Kantian and neo-Aristotelian accounts of human dignity. According to Kantian approaches, the intrinsic worth of human beings is ultimately grounded in their capability to act as *homo noumenon*, by endorsing rationally and conforming their behaviors to the maxims of practical reason (Rothaar 2010). And according to neo-Aristotelian accounts based on actualizations of human capabilities, the exercise of practical deliberation, control over one's own environment, and engagement in social activities is conducive to realizing a dignified human life (Nussbaum 2006, 77–78 and 161). Clearly, both conceptions of human dignity afford ethical motivations for protecting a generalized capability to perform actions, whose vulnerability is dramatically underscored by the sweeping action impairments occurring in LIS and other pervasive motor disabilities.

By learning how to use BCI technologies, people affected by LIS once again acquire a *general-purpose* capability to act. Indeed, BCI-actuated devices presently include robotic manipulators, virtual computer keyboards, robotic wheelchairs, internet surfing systems, photo browsing, and virtual drawing and painting systems (Millán et al. 2011; Wolpaw and Wolpaw 2012). Thus, by restoring generalized capabilities for action, BCI technologies for functional substitution are instrumental to human dignity protection through the intermediary of human agency protection.

BCI communication and control protocols require that human users surrender to a computational system both user intent identification and low-level control of action. Therefore, the protection of disabled user autonomy *by means of* BCI systems requires that users rely on a machine for their intent identification and fulfilment. In particular, this sort of intent identification is needed to manifest concretely one's own legal capability by, say, engaging in e-banking transactions on the internet, expressing informed consent, and writing a testament. One should be careful to note, however, that BCI-recovered autonomy engenders the problem of protecting user autonomy *from* errors affecting the behaviors of BCI systems. For example, one may appeal to the sources of BCI misclassifications examined above in order to question the identity between the action intended by the BCI user and the action actually performed by a BCI-actuated device. Therefore, the protection of BCI user autonomy provides ethical motivation for BCI research to develop suitable intent-corroboration procedures, especially in the case of legally binding contracts and transactions.

Additional issues concerning the protection of autonomous action *from* behavioral errors of BCI systems arise in connection with shared control of action in BCI-actuated robotic systems (Tamburrini 2009; Santoro et al. 2008). The limited capacity of BCI communication channels confines direct BCI user control to high-level commands only. As a consequence, BCI-actuated robots (such as robotic wheelchairs and robotic arms for grasping and manipulating) are autonomous in their control of both low-level actions and ancillary tasks such as the avoidance of unforeseen obstacles (Millan et al. 2004; Galán et al. 2008). Autonomous robotic action may give rise to discrepancies between user intent and actual trajectories of robotic systems, in view of perceptual and planning errors, sensitivity to small perturbations of initial conditions, and sensor noise piling up in series of sensory readings (Nehmzow 2006).

13.4 Ascribing Responsibilities and Liabilities

A BCI-actuated robotic wheelchair may roll down a staircase on account of user intent misinterpretation or inaccurate sensory readings. And a robotic arm responding to a request to fetch a glass of water may fail to perceive and bump into another person standing in the room. How are responsibilities and liabilities sensibly distributed in view of the fact that programmers, manufacturers, and users are not in the position to predict exactly and certify what BCI-actuated robots will actually do in their intended operational environments? (Clausen 2008, 2009; Tamburrini 2009; Grübler 2011; Holm and Teck 2011; see also Chap. 14) Clearly, those who failed to predict damaging events arising from BCI operation cannot be held morally blameworthy, provided that they properly attended in their different capacities to every reasonable design, implementation, testing, and operational issue. Nevertheless, even in the absence of moral responsibilities deriving from negligence or malevolent intentions, caused damage and corresponding compensation claims call for a proper ascription of liabilities (also known as objective responsibilities).

In developing liability policies for BCI-actuated robots, one may note that some predictive failures arise there from learning, reasoning, and action planning capabilities that BCI systems share with human beings and other biological systems. In the light of this positive analogy between BCI systems and biological systems, one may suggest an extension to BCI-actuated robots of liability ascription criteria one adopts for damages deriving from unpredictable behaviors of biological systems. This suggested extension puts the inability of BCI users to predict exactly and control the behavior of brain-actuated robots on a par with the inability of dog owners to curb their pets in every possible circumstance; with the inability of employers to predict exactly and control the behavior of their employees; and even with the inability of parents to predict and control the behavior of their children. Parents are held to be vicariously liable for many kinds of damage caused by their children, just as pet owners are liable for damage caused by their pets, and employers are liable for certain types of damage caused by their employees. Judging by this yardstick, users should be held liable for damaging events resulting from hardly predictable behaviors of their BCI systems.

The suggestion of holding users liable for BCI-engendered damage is vulnerable to ethically motivated criticism, insofar as this criterion may lead to discrimination in assistive technology access between those who can and those who cannot afford insurance and compensation costs. As an alternative, one might shift the burden of economic compensation onto BCI manufacturers. Indeed, in view of their expected profits, producers of goods are often held liable for damaging events that are difficult to predict and control. This liability ascription policy is aptly summarized in the Roman juridical tradition by the formula *ubi commoda ibi incommoda*.

The suggestion of ascribing liability to BCI producers is exposed to ethically motivated criticism too. Indeed, the risk of high compensation costs may discourage investments in research and development (R&D) towards marketable BCI systems, with the effect of diverting resources that are badly needed to launch a pioneering BCI industry. As a consequence, tensions are likely to arise between liability policies transferring compensation costs to BCI producers, the demands of beneficence in bioethics, and consequentialist evaluations of broader societal benefits that are expected to flow from BCI technological innovation.

These various observations suggest the opportunity of developing a more complex governance framework for BCI-engendered retrospective liabilities. Since BCI technological risk comes with beneficial opportunities for groups of disabled people and broader societal benefits in the way of technological innovation, one might allow for the socialization of risks associated with BCI systems, distributing insurance and compensation costs across a variety of stakeholder groups and governmental agencies.

13.5 Informed Consent and Respect for Persons

Along with healthy participants, research trials on the BCI-enabled replacement of motor functions may enroll people who have lost most of their abilities to communicate and act. These disabled participants may come to view a BCI research trial as a unique and last resort to overcome their communication and action barriers. These expectations might be so compelling in the dramatic human condition of severely paralyzed persons that they prevent a proper appreciation of the facts that one must know before participating in BCI experimentation (Haselager et al. 2009; Vlek et al. 2012). Accordingly, specific information aimed at anticipating and mitigating similar psychological attitudes must be included in setting up informed consent questionnaires and protocols for BCI experimentation. In particular, one should properly emphasize and carefully illustrate the phenomenon of BCI illiteracy, that is, the incapability to operate a BCI, which is estimated to affect 15–30 % of potential users, and for which effective remedies are still to be found (Vidaurre and Blankertz 2010). In addition to this, one has to provide more standard information about the likely absence of personal advantages flowing from participation in research trials, about psychological risks of depression which may derive from retracting BCI use at the end of time-limited studies, and about foreseeable discomfort in the care of disabled participants which may derive from prolonged operation and maintenance of BCI systems (Schneider et al. 2012).

It was pointed out above that machine-to-human adaptations deriving from computational learning are sources of distinctive risk and ethically motivated concern. Potentially deleterious changes in the CNS resulting from *human-to-machine adaptations* are even more important sources of risk and ethical concern about the physical and mental integrity of persons.

Psychological rewards and punishments deriving from the observation of BCI interaction outcomes are known to affect CNS activity patterns. As a matter of fact, an operant conditioning process usually intervenes to change brain activity if the user obtains negative feedback information, that is, information about occurring discrepancies between expected and actual outcomes of his interaction with the machine. As a result of operant conditioning, brain activity patterns change in ways that have been found to facilitate ensuing machine classifications. Accordingly, as the overall functional implications of these adaptations are not fully understood and difficult to predict, one cannot rule out generic risks of detrimental effects on states of mind and behaviors of intensive BCI users (Schneider et al. 2012). Thus, every BCI candidate user must be properly informed of potentially detrimental effects of BCI-induced brain adaptations and plasticity (Dobkin 2007).

Unlike BCI systems for communication and control, some experimental BCI rehabilitation therapies for improving motor functions *target directly* brain areas, with the principal aim of modifying their structure and functions (Shih et al. 2012). One strategy for post-stroke motor rehabilitation involves a BCI system monitoring damaged brain areas which normally control movements that are impaired after brain injury. The BCI system provides appropriate feedback according to whether activation patterns in the targeted brain areas come closer to normal or not (Grosse-Wentrup et al. 2011; Pichiorri et al. 2011; Daly and Sitaram 2012; Mattia et al. 2012; Várkuti et al. 2013). Similarly, BMCI systems (with the letter "M" in the acronym standing for *muscle*) combine the analysis of brain signals and electromyographic signals to stimulate increasingly correct activity patterns in both brain and muscles (Bermudez et al. 2013). Ethical concerns about BCI systems directly fostering brain plasticity arise, at a general level, from awareness of limited etiological understanding of deleterious effects, if any, of these experimental therapies.

Additional ethical issues arise in connection with the use of *invasive* versus *non-invasive* BCI systems. Operation of invasive BCI systems requires the implant of electrodes in the cortex and the deployment of apparatus for electrocorticography (ECoG) or intracranial electroencephalography (iEEG) on the exposed brain surface (Moran 2010). In general, invasive BCIs enable one to achieve, in contrast to non-invasive ones, better signal spatial resolution and signal-to-noise ratio leading to improved control of peripheral devices. Among the non-invasive systems, those relying on electroencephalography (EEG) as a recording method afford better performances in terms of signal temporal resolution, cost, and practicality of use. Potential users of BCI systems must be informed of comparative advantages and disadvantages of invasive and non-invasive systems, including relevant facts about characteristic risks of invasive systems in connection with implant stability, reversibility, and infection. Interestingly, empirical data from interviews administered to people affected by Amyotrophic Lateral Sclerosis (ALS) suggest a definite preference for non-invasive systems, notwithstanding the functional advantages of invasive BCI systems which derive from better spatial resolution and signal-to-noise ratios, and corresponding disadvantages of non-invasive systems in the way of slower operation and more error-prone control (Birbaumer 2006a, b).

13.6 The Protection of Agentivity and Consciousness

Some explanations of the inability to learn how to operate BCI systems suggest that teaching people affected by LIS and other severe motor disabilities how to use a BCI system before they completely lose muscle control may contribute to protecting their agentivity and possibly to preventing their purposeful thinking from waning. Experimental studies show that among patients affected by Amyotrophic Lateral Sclerosis (ALS) and trained with a non-invasive BCI, none of those who were trained after entering a complete locked-in state (CLIS) were able to acquire stable communication abilities (2006a). Birbaumer (2006b) advanced two competing explanations for this observation. According to the first explanation, the onset of CLIS is accompanied by a generalized decline in perception, thinking, and attention abilities. It is this decline which prevents CLIS patients from learning to use a BCI, and therefore learning how to use a BCI cannot counteract this progressive and generalized decline.

Birbaumer's second explanation hinges on the hypothesis that the development and sustained preservation of purposive thinking crucially involves a reinforcement stage, concerning the verification of intended consequences of actions. This hypothesis is advanced in the framework of so-called motor theories of thinking, according to which thinking develops as a means for – and is sustained by – effective animal motion: "As early as the 19th century, the 'motor theory of thinking' hypothesized that thinking and imagery cannot be sustained if the contingency between an intention and its external consequence is completely interrupted for a long time period" (Birbaumer 2006b, 481). The reinforcement stage required by motor theories of thinking is hardly ever accessed in a CLIS subject. The sequence intention-action-consequence-verification cannot be enacted autonomously; it is occasionally completed through the intermediary of caretakers who happen to fulfill the patient's current desire. Therefore, thinking and imagery are no longer sustained, and the related ability to learn and operate a BCI fades away in a CLIS patient.

A third explanation of the inability of disabled people with no remaining muscle control to learn and operate BCI systems hinges on the theory of learned helplessness (Seligman 1975). A human may learn to behave helplessly in the face of adverse conditions that he cannot modify, and will fail to alter this response even though a new opportunity subsequently arises to help oneself and obtain positive rewards.

If the second explanation is correct, then learning how to use a BCI before the onset of CLIS may prevent the extinction of thinking and imagery, insofar as the sequence intention-action-consequence-verification is preserved through BCI operation. And if the third explanation is correct, then learning how to use a BCI before the onset of CLIS may prevent the insurgence of the condition of learned helplessness as an overwhelming obstacle towards BCI use at a later time. In either case, one should teach BCI operation to persons who may subsequently enter the CLIS state so as to preserve their status of agents. Thus, medical beneficence provides ethical motivations for probing the effectiveness of these therapeutic interventions and for testing their theoretical premises in motor thinking and learned helplessness hypotheses.

Each one of the above applications of BCI systems presupposes the possession of a wide variety of mental capabilities on the part of their prospective users. These mental requirements are usually satisfied by people affected by LIS. In contrast to this, it is far from obvious that persons affected by disorders of consciousness possess the mental capabilities that are needed to operate a BCI. However, groundbreaking experiments (Owen et al. 2006; Monti et al. 2010) involving groups of persons who were diagnosed to be in a vegetative state (VS) or a minimally conscious state (MCS) unexpectedly suggested the possibility of using BCIs to communicate with people affected by disorders of consciousness.

In these experiments, VS and MCS patients were verbally instructed to perform a motor imagery task (playing tennis) or a spatial imagery task (visiting rooms in their home) in order to convey their "yes" or "no" answer, respectively, to questions posed by experimenters. From an analysis of functional magnetic resonance imaging (fMRI) scans taken upon administering autobiographical questions (e.g., "Is your father's name Thomas?" and "Do you have any sisters?"), regional brain activations were reliably and repeatedly found to correspond to correct imagery-conveyed answers in a small proportion of those patients.

Several extensions of this communication protocol have been proposed and discussed. These extensions concern a variety of dialogical purposes, ranging from subjective symptom reporting to informed consent, and even to continued medical care decision-making. It was suggested, for example, that "patients could be asked if they are feeling any pain, and this information could be useful in determining whether analgesic agents should be administered" (Monti et al. 2010). Moreover, it was claimed that "the first and obvious use of mental signaling by means of fMRI could be to preserve the patient's autonomy by querying his or her wishes regarding continued medical care" (Ropper 2010). Understanding which aspects of consciousness must be present for these interactions to take place, and how to detect them in behaviorally unresponsive patients who satisfy the medical criteria for being diagnosed as VS or MCS is a formidable scientific problem (Nachev and Husain 2007). A limited contribution that philosophy can provide towards the conceptual clarification of this problem is based on distinctions between aspects and varieties of consciousness that are routinely made in the framework of contemporary philosophy of mind. In particular, *phenomenal*, *access*, and *narrative* forms of consciousness appear to be selectively involved as preconditions for genuine communication about pain reporting, informed consent, and continued medical care (Tamburrini and Mattia 2011; Tamburrini 2013).

Roughly speaking, *access consciousness* is identified with the ability to introspect one's own mental states and to make the introspected mental states available for modification by reflection (Block 1995). The *introspective* and *reflective components* of access consciousness do not necessarily come together in conscious mental life, insofar as one may introspect, say, one's own desire without being able to modify it by reflection: irresistible desires and incorrigible perceptual illusions that are introspectively accessible are significant cases in point.

The subjective feel or experiential dimension of one's own mental states is not captured by the notion of access consciousness. The capability to experience what it is like to be in a certain mental state is identified with another variety of consciousness. This is *phenomenal consciousness* (Nagel 1974), whose manifestations comprise perceptual experiences (like tasting something) and bodily experiences (like pain).

Let us finally observe that mental states can be recalled and unified as a narrative of episodes, which are experienced and accessed from the unitary perspective of the individual self by taking into account their causal and semantic connections. This ability to organize, access, and experience from a unitary subjective perspective a series of mental states is often referred to as *narrative consciousness* (Ricoeur 1990; Merkel et al. 2007).

Let us now bring these distinctions to bear on envisaged BCI communication with persons affected by disorders of consciousness. According to the definition advanced by the International Association for the Study of Pain (IASP), the term 'pain' denotes "an unpleasant sensory and emotional experience associated with actual or potential tissue damage, or described in terms of such damage." Thus, being in pain involves having an *experience* of the qualitative feel of pain or, in other words, to possess phenomenal consciousness in connection with the bodily experiences that one calls pain. Accordingly, in order to deal competently with pain questions one must be endowed with some form of phenomenal consciousness.

Let us now turn to consider informed consent about medical treatment or participation in research trials. This kind of communication is usually motivated on autonomy protection grounds, and the individual autonomy one is presupposing there involves the capability to act on one's own desires. Since, however, agents who are driven by a strong desire or impulse to act fail to qualify as autonomous in the etymologically grounded sense of being *self-ruled agents*, individual autonomy additionally requires the ability to endorse, modify, or reject one's own desires to act. Briefly, autonomous decision-making involves full access consciousness ascriptions, insofar as an autonomous agent must be able to introspect and perform reflective interventions of various sorts on his own mental states.

Even more comprehensive consciousness ascriptions appear to be presupposed in communication concerning continued medical care. An expressed preference to discontinue medical care must be pondered over, remain open to revision for some time ahead, and be typically reinforced in iterated interviews. Accordingly, one is presupposing that the recipient of continued medical care questions is endowed with memory continuity of the sort that allows one to recall previously expressed preferences, if any, their motivations, and their evolving patterns from one interview to the next. Briefly, by raising questions about continued medical care, one is pragmatically assuming that their recipient is capable of putting together a narrative of reflective and deliberative episodes from a unitary first-person perspective. These abilities are typically associated with the *narrative* variety of consciousness.

The empirically elusive and formidable problem of detecting whether a person diagnosed to be in a VS or MCS still possesses the required varieties of consciousness calls for a cautious attitude in the process of evaluating the purported significance, if any, of the results in Monti et al. (2010) for BCI dialogical communication about pain reporting, informed consent, and continued medical care. And a cautious attitude is similarly required to communicate BCI research to stakeholders and to deal sensibly with both rational and irrational expectations that BCI systems may give rise to.

13.7 Communicating BCI Research Programs and Achievements

BCI systems prompt a special sense of wonderment which is related to the fact that no speech, no gesture, and no voluntary muscular movement are required to actuate user intents.

> I have mixed attitudes towards technology. I use it and take it for granted. I enjoy it and occasionally am frustrated by it. And I am vaguely suspicious of what it is doing to our lives. But I am also caught up by a wonderment at technology, a wonderment about what we humans have created. Recently researchers at the University of Pittsburgh developed technology that allows a monkey with tiny electrodes implanted in its brain to control a mechanical arm. The monkey does this not by twitching or blinking or making a slight movement, but by using its thoughts alone. The technology has obvious promise for impaired people. But that is not what causes me wonder. I wonder that we can put together circuits and mechanical linkages – in the end pieces of silicon and copper wire, strips of metal, and small gears – so that machinery responds to thought and to thought alone (Brian 2009, 9).

Along with reactions of wonderment, psychological responses to BCI systems present an intriguing combination of fantasies, worries, and rational and irrational expectations. Indeed, the openings of several popular science and media reports leverage on the “magic” allure of BCI technologies and their alleged ability to respond to the force of thought only. A reflection on these various mental attitudes is crucial to appreciate the symbolic roles of novel technologies in contemporary society, and their influence on public debate and decision-making about technological research, development, and dissemination. In particular, an understanding of generative mechanisms underlying unrealistic expectations about BCI systems is crucial to develop effective BCI research communication strategies, and to build mutual trust between scientists, users, and other groups of stakeholders. Let us consider, from this perspective, psychoanalytic mechanisms that may contribute to explaining the “magic” appeal of BCI systems (Scalzone and Tamburrini 2012).

In his *Thoughts for the Times on War and Death*, Sigmund Freud remarked: “It is an inevitable result of all this that we should seek in the world of fiction, in literature and in the theatre compensation for what has been lost in life [. . .] For it is really too sad that in life it should be as it is in chess, where one false move may force us to resign the game, but with the difference that we can start no second game, no return-match. In the realm of fiction we find the plurality of lives which we need." (Freud 1964, vol. 14, 291).

Psychologically compensating scenarios once explored in literary work only are now in the purview of technological research programs promising substantive extensions and enhancements of human capabilities. These scenarios impinge on the general public through their dissemination in the media and popular science reports. But what is the psychological basis of compensation-seeking attitudes towards technology? Freud's theory of narcissism makes an explanatory basis available for understanding the compensating psychological role of technologies in general, and BCI presentations which strike the chord of the "force of thought" in particular. According to Freud, children in a normal stage of their development entertain primitive beliefs characterizing animistic conceptions of the world. These animistic beliefs, notably concerning magic wish-fulfilling and the omnipotence of one's own thoughts, lead one to overestimate the capability to bend external reality to one's own desires by the force of thought only. Adults give up these narcissistic beliefs in their conscious life, coming to terms with the reality principle and acknowledging death as inevitable. But these repressed beliefs persist and operate unconsciously in adult life. In particular, one unconsciously seeks compensations for the conscious acceptance of the reality principle and the attending psychological blows for naïve self-love. Thus, in particular, descriptions of BCI technologies may provide some such compensation – an opportunity for what Freud called a fictitious "return match" or "second game" – taking the form of illusory enhanced control of the external world by magic wish-fulfilling.

This interpretation of psychological responses towards BCI systems suggests that public statements of researchers about their research goals and activities may inadvertently become a powerful source of irrational attitudes towards technological progress. These irrational attitudes are more likely to emerge as a response to popular expositions emphasizing the promises of scientific research programs, but neglecting to emphasize information which is needed to gauge the distance between promises and the actual results of research activity. The ambitious long-term goals of research programs play significant motivating roles within communities of scientists and may suggest fruitful lines of inquiry, even though their promises cannot be attained without making substantial and unforeseeable progress with respect to currently available models and techniques. However, the dividing line between concrete achievements and long-term or visionary goals of a research program is not invariably clear to the non-specialist. Therefore, the ethically praiseworthy goal of furnishing correct and accessible information to the general public raises the formidable challenge of adapting the communication styles that scientists use within their communities so as to anticipate and avoid the insurgence in the general public of disproportionate and irrational expectations towards technological development.

Ethical motivations for carefully drawing the distinction between envisaged long-term goals of a research program and its tangible results have emerged in connection with several developments of BCI research. Thus, in communicating the research goal of making a variety of BCI technologies and systems available to people affected by LIS, one ought to emphasize properly problems of BCI system reliability, cognitive decline in LIS patients, the incidence of BCI illiteracy, and the generalizability to clinical contexts of results obtained in research trials involving healthy subjects only. Moreover, one must specify BCI costs and benefits with respect to alternative communication methods for persons who retain some communication capabilities, say by moving their eyes or eye-lids.

The need for responsible communication strategies emerges even more evidently in connection with the suggestion of using BCI for communicating with and promoting the autonomy of people affected by disorders of consciousness. Assessing whether persons affected by disorders of consciousness still possess the required varieties and degrees of consciousness is a scientifically formidable and empirically elusive problem. Accordingly, one ought to adopt an extremely cautious attitude in communicating to psychologically vulnerable families of people affected by disorders of consciousness the aims of these studies and their envisaged implications in therapy and quality of life improvement. There, the development of an effective and responsible communication strategy may take advantage of the above philosophical analyses of consciousness with their clarifying distinctions that are closer to common sense conceptualizations of the phenomenon of consciousness.

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Chapter 14
Brain–Computer Interfaces and User Responsibility

Fiachra O'Brolchain and Bert Gordijn

14.1 Introduction

In the not-too-distant future, if you meet someone you feel you ought to recognize but do not, you need not fear social embarrassment. The information you require can be beamed directly to your field of vision. You approach your house carrying shopping, but cannot reach for your keys; you will be able to unlock the door via thought alone. You wish to communicate silently with your comrades in the midst of the battle? You will be able to transmit your thoughts directly to them. You might wish to experience the dark waters at the bottom of the ocean – you will be able to "experience" this from the comfort of your living room. The development of brain–computer interfaces (BCIs) suggests all these possibilities.

Brain–computer interfaces (or brain–machine interfaces) harness the electromagnetic signals produced by the brain to enable users to control external, artificial objects. These technologies acquire and process signals generated by the user by accessing the electrical signals in the brain and sending them to a computer, which in turn interprets the signals and translates them into commands that are sent to an external device. In effect, they allow people to control external devices using only the power of their thoughts. Currently, neural signals are captured by attaching electrodes to the scalp, inserting electrodes onto the cortical surface, or using intracortical electrodes. Depending on the sophistication of the technology, the controlled "device" might be a cursor on a computer screen, an artificial avatar, a wheelchair, a prosthetic limb, a vehicle, a drone, a weapon or weapons system, or a robot. Early therapeutic examples of BCIs include BrainGate1, which allowed Matt Nagle, who had become paralyzed from the neck down after being stabbed, to control lights, operate external devices such as a television, and operate a prosthetic hand (Harris 2011; Martin 2005). Research into neurotechnologies stemming from

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the original BrainGate is continuing at Stanford University and Massachusetts General Hospital (http://www.braingate2.org). Although BCIs were initially intended to be used for therapeutic purposes, they are increasingly being developed for other markets, such as entertainment and the military. The Californian company NeuroSky, which proclaims its duty as bridging "the gap between technology and the body," (http://www.neurosky.com) released a consumer-based EEG in 2007 and later partnered with Mattel and the producers of Final Fantasy. The Australian company Emotiv Systems released an EEF device in 2009 which was designed for use with games on Windows PCs (http://www.emotiv.com). In 2012, the Austrian company g.tec released a BCI that can be used at home to control computer games and apps and, reportedly, has an accuracy of 99 % (http://www.gtec.at). The rapid evolution and entrance of BCI technologies into new consumer markets requires ethical consideration. We focus on responsibility not only because BCIs are already entering the market, but because BCI use will affect the Aristotelian conditions of responsibility (knowledge and control) and extend the range of human abilities in novel ways.

Our focus in this chapter is on the responsibility of BCI users. Firstly, we will briefly introduce BCIs. Then we will outline the concept of responsibility. After that we will discuss three novel aspects of BCIs that will have an impact on user responsibility. These are the issues of control of external things via the mind alone, the possibility of subconscious thoughts as actuators of BCI devices, and mind-melding via BCIs. Following that we outline and assess different claims advanced in the scholarly debate regarding the impact of BCIs on the extent and the allocation of user responsibility.

14.2 BCIs

Brain–computer interface research has therapeutic origins and was first aimed towards helping people with severe physical impairments (Harris 2011). For instance, BCIs have been developed to allow paraplegics to manipulate cursors on computer screens, thereby granting them the ability to interact with the Internet and so communicate with other people (Harris 2011). This relationship with the external device distinguishes the BCIs discussed in this chapter from other types of innovative neurotechnologies such as deep-brain stimulation (DBS) or functional magnetic resonance imaging (fMRI) devices in that it enables the user to *actively* control an external device using their thoughts or to directly receive information from an external device. Although fMRI machines and DBSs are, in a literal sense, brain–computer interfaces, they are not focused on in this chapter, because they do not permit the user to consciously control an external device. Instead, this chapter will be concerned with non-invasive BMIs, as these are the most likely to be widely utilized first (assuming that brain surgery remains a serious operation preferably avoided).

That said, BCI research is not confined to therapeutic aims. As well as enabling people to control artificial limbs and other therapeutic ends, BCIs may also allow us to direct vehicles, drones, or robots from far afield. (Nissan teams up with EPFL for futurist car interfaces, http://actu.epfl.ch/news/nissan-teams-up-with-epfl-for-futurist-car-interfa.) As well as allowing people to control external devices via thought alone, BCIs will also allow people to receive – directly to the brain – feedback from external devices. There already exists a "SmartHand", a robotic prosthetic hand. This hand allows its user – Robin af Ekenstam – to control the finger movements of the prosthesis with his brain. The motion of the hand is relayed to the user brain so that he has feedback and can actually feel the movement of his hand (Science Daily 2009), whilst researchers at Chalmers University of Technology have made advances in implantable robotic arms that can be controlled by thoughts (http://www.chalmers.se/en/news/Pages/Thought-controlled-prosthesis-is-changing-the-lives-of-amputees.aspx). The US Defense Advanced Research Projects Agency (DARPA) is also involved in BCI research (Hoag 2003). One of the DARPA BCI projects is focused on developing a novel type of binoculars that operates as a BCI – the Cognitive Technology Threat Warning System (CT2WS). When the user scans the horizon using the BCI binoculars, the machine scans both the user's brainwaves and the horizon. It is capable of detecting a specific type of brainwave, a P300, which is involved in stimulus evaluation and categorization that is triggered when the user subconsciously detects a threat. The BCI will then inform the user of this threat quicker than they would have been aware of it themselves (Schermer 2009). DARPA have also been developing "Silent Talk", which aims to develop user-to-user communication on the battlefield through EEG signals of "intended speech" (Defense Advanced Research Projects Agency 2009). Yet another area of research is neurofeedback, which involves presenting, in real time, information about the state of the brain. It aids people in attaining the most beneficial state of mind, e.g. entering the zone, in sports (Vernon 2005).

Furthermore, the entertainment industry has already developed consumer-grade BCI devices (cf. Emotiv EPOC, NeuroSky, and gtec's intendiX SOCI). The intendiX SOCI, which was released in 2012, allows users to employ BCIs to control avatars in games such as World of Warcraft. Other possible commercial uses include interacting with a car (École Polytechnique Fédérale de Lausanne News 2011) or controlling a smart home, i.e. a home in which the devices and systems (ventilation, security, lighting etc.) are integrated and capable of communication with each other (Edlinger et al. 2011). More speculative future uses of BCIs might enable users to directly connect to the Internet, the uploading of dictionaries or online encyclopedias, and possibly direct brain-to-brain communication (Gordijn and Buyx 2010). For obvious reasons, non-invasive BCIs, which record brain activity through techniques such as EEG, magnetoencephalography (MEG), and positron emission tomography (PET), are more likely to be used by the general population than invasive BCIs. Some BCIs will be unidirectional (permitting only output signals from the brain), while others will be bidirectional (enabling signals to be inputted into the brain and distributing signals from the brain).

14.3 Concept of Responsibility

We normally consider adults above a specific cognitive threshold to be moral agents. We can ascribe moral responsibility to agents when we can say that they are worthy of praise or blame for their actions. Usually, responsibility is only ascribed to an agent under specific conditions. In short, people can be held responsible for outcomes insofar as they cause them and do not act in ignorance or under compulsion. This is, at least, the Aristotelian perspective and the view that we will rely on in this chapter, due to its prominence in the Western tradition. Aristotle outlined specific conditions under which it is appropriate to hold a moral agent responsible for an action (or for a vice or virtue). Aristotle's general proposal is that one is an apt candidate for praise or blame if and only if the action and/or disposition is voluntary (Aristotle 1985, Bk 3 I-V). So, if a mechanical fault causes my car to crash despite my best efforts at controlling it, I will not be held responsible. According to Aristotle then, a voluntary action has two distinctive features. First, there is a control condition: The action must have its origin in the agent. That is, it must be up to the agent whether to perform that action — it cannot be compelled externally. Moreover, there should be a causal connection between the person and the outcome of the action. Second, Aristotle proposes an epistemic condition: The agent must be aware of what it is she is doing or bringing about (Aristotle 1985, Bk 3, I-V). So, if I am flying home from a holiday somewhere tropical and an insect gets into my luggage unbeknownst to me and causes an infestation upon my return, I cannot be held responsible for this.

In short, if a person is to be considered morally responsible for a particular event or action, that person must have been able to exert some kind of influence on that event and must have known that in doing so a certain consequence would most likely have ensued. If a person could not have acted differently and was unable to influence the course of an event, or if they acted on the basis of false information, it makes no sense to hold them morally responsible for the outcome of that event.

14.4 Three Novel Aspects

In one sense, the use of BCIs will present no new problems of user responsibility. BCIs are, of course, tools. They are products of technological development. They can, in principle, enable us to do things that we otherwise could not do. In a very general sense, then, they are no more novel than any other new tool or invention. At this level of abstraction, then, the issues of *responsibility* are no more interesting than those associated with the introduction of new technologies of the past, for example paper, the watermill, gunpowder, cars, or electrical circuits. Analyzing the use of BCIs at this level of generality, however, obfuscates a great many interesting details. Viewed with sufficient abstraction, BCIs are just tools like any other. Nonetheless, if you leave the high level of abstraction and zoom in on real world details of BCIs, interesting novel aspects pop up. These novel aspects have implications for responsibility. It is essential to examine these issues in greater detail due to the swift development of BCIs and their emergence into public life, the novel means of interacting with the world that they will facilitate, and the ways in which they will affect our control and knowledge of not only the world around us, but also of ourselves. In this section, we introduce three novel aspects of BCI technology that will have implications for responsibility.

Control over external things with our thoughts instead of our bodies. Throughout most of human evolution, we have been limited in our actions by our physical bodies. Tool use has extended the range of our actions, but the ability to interact with the world using only our thoughts will be different in kind. Firstly, we are accustomed to our interactions with the world being dependent on physical movement through the body. To be sure, our technological development has meant that greater and greater effects can be achieved with comparatively less physical effort, to the horrific point where a single push of a button on a keyboard can result in the death of many people. Nonetheless, this still requires some bodily movement. The control of objects that are not physically connected to us in any way will be something very different. One might wonder, for example, whether we will have the same sort of control over our thoughts actuating external actions on objects as we are used to exerting over our bodies. The ability to control technological devices or the environment around us using only our thoughts is simply not something with which humans are familiar. It might turn out, for example, that on average we have less control over our thoughts than we have over our bodies as actuators of gadgets. Also, we might learn that it is easier to multitask commanding various gadgets simultaneously with the body than with thoughts. Such findings would obviously have implications for our ideas about BCI user responsibility.

Use of subconscious events as actuators of action. That BCIs will be capable of picking up subconscious thoughts means that further issues of user responsibility will come to the fore. If an accident occurs as a result of a BCI's response to the subconscious thoughts of its user, there is a clear problem of responsibility. It would be difficult to hold the user responsible as they would neither know what they were thinking nor did they have any control over their subconscious thoughts triggering certain actions. The capability of BCIs to pick up on subconscious brain activity will complicate our conception of agency in a fundamental way.

Mind melding. This admittedly speculative scenario arises if we consider the potential BCIs provide for a number of minds to connect to each other and simultaneously access each other's thoughts (McGee and Maguire 2007). Projects such as DARPA's Silent Talk can be seen as prototypes of technologies that will facilitate mind-to-mind communication. The possibility of instantaneously exchanging conscious thoughts with others might blur the distinction between the individual self and the collective online community. Furthermore, if a number of people are permanently connected to the same databases and information feeds, their uniqueness in terms of exclusively possessing specific information would be reduced. Determining the individual consciousness in such a situation may become increasingly difficult (Gordijn 2006, 730). In conjunction with virtual realities as well as enhancement technologies, it is possible to envisage a scenario in which people would collectively participate in a joint emotional/psychological experience. In such cases, determining the individual would again be problematic, and thus assigning individual responsibility would be challenging. That people would wish to participate in such a scenario is feasible. The experience might involve the loss of the sense of individuality and the attainment of a sense of being part of something greater, feelings that people have used narcotics for over the millennia. Such experience might become addictive. People might also participate in group thinking in order to achieve goals in virtual reality games or to solve complex problems. The popularity of social networking sites such as Facebook might provide a clue as to how BCIs may be used in future. Rather than simply sharing photos, videos, and comments, people may in future choose to share, via BCI connections, emotional states and experiences directly. If we extrapolate further from this scenario, it is worth considering whether groups connected by BCIs will be able to make collective decisions and take collective actions. In such an entirely new scenario, it might become impossible to determine which individual is responsible for which thought and, ultimately, for actions. BCIs used in this manner will challenge not only our concepts of responsibility but also of the person and of agency. Supposing that BCIs do enable minds to connect together to perform tasks, it will be essential to understand whether the decisions are an aggregative phenomenon (the combined decision of a group) or the result of some sort of gestalt mind that transcends the contributions of individual members but is nevertheless capable of intentionality. This will, in turn, have important implications for the allocation of user responsibility.

In sum, it is clear that BCIs may present some new aspects that might have an impact on user responsibility. These are the control of external things with our thoughts rather than our bodies, the use of subconscious events as actuators of action, and the melding of individual minds. With non-BCI devices, in contrast, the ascription of responsibility is relatively clear. So long as the tool is functioning correctly, the user will be held responsible for their actions. If the tool malfunctions or is damaged, thus causing it to inflict harm, then responsibility will most likely be ascribed either to the manufacturer or to those in charge of maintenance of the device or to whoever damaged the device.[1] In the following sections we will provide a discussion of ways in which these novel aspects of the technology will impact on, first, the extent of responsibility and, second, the allocation of responsibility.

[1] Incidentally, this might of course still result in the well-known 'many hands' problem, the difficulty in the identification of moral responsibility in situations in which many people were involved in collectively causing an event. This concept initially was applied to the work of public officials in the creation of a policy (Thompson 1980) but has lately been applied in engineering and computer ethics. Mistakes arising from computer errors are usually the result of an accumulation of mistakes, making it difficult to attribute the catastrophe to any one individual (programmer, engineer, manufacturer, or user).

14.5 Extent of Responsibility

On the one hand, BCIs enable us to act at a distance, to control, via our thoughts, things that previously required physical interaction. On the other hand, BCIs also threaten to enable mind control by third parties or, in certain circumstances, significantly reduce our ability to control objects, or even ourselves. Moreover, they may even reduce our knowledge of the ways in which our intentions will be actuated in the world if BCIs pick up on subconscious thoughts.

14.5.1 Claim 1: BCIs Can Reduce the Extent of Responsibility

The advent of BCI-controlled devices can lead to a reduction of responsibility in a variety of ways. We focus on subconscious decisions, hacking the mind, information overload, and societal disruption.

Subconscious decisions. BCIs acting in response to subconscious actuators would significantly reduce the extent of an agent's responsibility. Given that the agent would neither have control over, nor knowledge of, their subconscious thoughts, there is a problem in holding them morally responsible for the actions resulting. Thus an agent might be causally responsible for the actions of their device, but due to lack of control and knowledge over their subconscious mind, not morally responsible.

Hacking the mind. BCIs may also lead to a more sinister threat to a user's responsibility: the threat of "hacking". BCIs process signals from the brain and translate them into commands to which the device responds (Martinovic et al. 2012). In order for this to be possible, connections need to be made between the user's brain and the computer. One fear is that this connection would not simply be a one-way connection, and that signals could be sent to the person's brain via the BCI. This is not as far-fetched as it may seem. There currently exist a number of technologies designed to influence behavior by directly influencing the brain. Deep brain stimulation (DBS) technologies are an obvious example. These devices use electrodes implanted in the thalamus in order to treat diseases such as Parkinson's and other movement-related conditions and have been suggested as a treatment for psychiatric disorders (Weaver and Follett 2009). Devices that stimulate the vagus nerve – believed to modulate perceptions of hunger and satiety – have also been developed for clinical use (Foster 2006). Less invasive technologies such as transcranial magnetic stimulation (TMS), which causes depolarization or hyperpolarization in the neurons in the brain, can also stimulate the brain. TMS devices are being used in the treatment of depression (George et al. 2000).

The conjunction of neurotechnologies that enable us to communicate with brains remotely and technologies that enable us to directly influence the functioning of a brain mean that it might in principle be possible to remotely stimulate areas of the brain in order to influence the user (McGee and Maguire 2007). Halperin et al. (2008) have illustrated that in certain scenarios devices that communicate wirelessly with external machines (such as pacemakers, defibrillators, and, most interestingly for our purposes, neurostimulators) can be influenced externally. The researchers showed that implantable cardioverter defibrillators (ICDs) disclose unencrypted sensitive information and they demonstrated a *reprogramming* attack that changed the operation of the device. They illustrated that an ICD "can be made to communicate indefinitely with an unauthenticated device, thereby posing a potential denial-of-service risk" (Halperin et al. 2008, 2).

Similarly, BCIs will potentially provide those with malicious intent with the means to target people's brains (Martinovic et al. 2012). Hackers might transmit images to the BCI user's brain and then extract knowledge from the subconscious brain activity of the user, just as the BCI binoculars utilize the P300 brain response. By recording the P300 experiences, hackers might be able to mine a great deal of data about the person (Anthony 2012). In such a scenario a person using a brain–computer interface might divulge private or secret information without realizing that they are doing so. As such, they could not be held responsible for this.

Furthermore, researchers have illustrated that it is possible to control rats via remote control, by stimulating electrodes implanted in their brains (Lang et al. 2011; Talwar et al. 2002). If it becomes possible to hack into a BCI without the user knowing, it might perhaps be possible to send commands (of greater or lesser complexity) to that person or to alter their moods in relation to the performance of an action. It is conceivable that mood-altering non-invasive brain–machine interfaces will be feasible at some point in the future, thus increasing the risk that hackers (or governments) will be able to use people's BCIs to subconsciously influence and control them (cf. Gordijn and Buyx 2010).

Clearly, if this scenario is possible and if a person is hacked they will have reduced control over their actions and will consequently have less responsibility for their actions.

Information overload. A similar, if less insidious, way in which BCIs could lead to a reduction in a person's responsibility for their actions is if the BCI overloads the user with information, confusing them and increasing the difficulty of selecting the relevant information required for specific actions and situations. This scenario can be seen to result in the diminution of the epistemic condition of responsibility, as an increase in unfiltered data does not necessarily lead to greater understanding of the relevant facts. Simply put, an increase in sensory data might just as easily confuse the recipient as help them in understanding the situation. It is easily conceivable that someone might become overwhelmed or confused by the information provided by their BCI.

Societal disruption. There is also a risk of societal disruption. Suppose a society comes to depend on BCIs to a large degree, with most citizens utilizing them. In the event of a cyber attack or some other unforeseen event, BCIs might be disrupted or disabled. In this scenario, such an event would significantly limit individuals' knowledge and control of their world around them. This problem would be exacerbated if the societal infrastructure was designed to cater for a population with BCIs.

Indeed, the skills needed for life without BCIs might atrophy if BCIs become prevalent. For instance, if surgeons became dependent on using BCIs and lost the skills (or simply never gained the experience) of performing surgery without a BCI, the consequences would be grave (at least in the short term). If a surgeon were to lose access to a BCI at a delicate point in surgery, the surprise might result in a mistake. Even if this were not to happen, the loss of the BCI would presumably mean the surgeon is no longer as capable as they were. Indeed, such surgeons might, due to inexperience of operating without BCIs, be below the baseline set by contemporary surgeons. Such limitations on control and knowledge would significantly reduce the capacity of these individuals to act in fully responsible ways as they would not possess the knowledge to act in such a world without BCIs nor would they possess the control they are accustomed to. Of course this fourth example differs from the previous three in that it involves a reduction of responsibility not as a direct result of BCI use but as a consequence of the interruption or loss of the same.

14.5.2 Claim 2: BCIs Can Extend Responsibility

The abilities granted to users by BCIs will, in certain situations, mean that they will have a greater degree of responsibility than people currently possess. Someone with locked-in syndrome would be able to operate an artificial limb or at least manipulate a computer avatar. In the most obvious case, by extending the ability of paraplegics or those with locked-in syndrome to act in the world, BCIs extend their responsibility. However, the ways in which BCIs could extend human capacities beyond the normal range raise more interesting issues of responsibility.

With BCIs a person will be responsible for more things, more actions, than any current person can be held responsible for. Any agent with a BCI will have the opportunity to receive information from the device or influence events, even if they are not physically present. In these situations, physical absence might no longer be considered sufficient to exempt the agent from responsibility. Accordingly, even prosaic tasks like a journey to the shops might involve greater degrees of responsibility. Suppose a person has a BCI device that allows them to control the environment and various objects in their house or apartment. Absence from the abode to go to the shops would no longer mean they are not responsible for events in the house, assuming they are receiving information from the house and are able to influence it. This will, most obviously, have implications for insurers. However, the increase in responsibility might have psychological impacts, such as increasing stress or a reduction in the ability to unwind or escape.

A person may even be in control of a number of different devices simultaneously. The increase in *control* will lead to an increase in responsibility. People will be considered to have a greater degree of responsibility for their actions as BCIs will provide them with more information and guidance. Visual images from sensors on a vehicle could be relayed directly to the visual centers of the brain.

Were the technologies to continue to develop, BCIs would provide more information for anyone in control of a vehicle or, for example, for surgeons performing complex operations. Those with access to BCIs will have more information available to them and so can be said to have a greater degree of responsibility. The increase in *information* will mean that more actions will fall under the epistemic condition.

BCIs will, in theory, be able to provide significantly more information for users than people can currently gain. For example, car drivers will receive information from the car or receive warnings if they are becoming drowsy; soldiers would be able to "see" the images that drones or their comrades can see; police will be able to access information from security systems; aviators will be able to receive feedback from sensors on their planes (Hoag 2003) and so on. If BCIs fulfill this potential, individuals will have access to far more relevant knowledge about the context of their actions and, depending on how the computer system processes the information, about the impact of those actions. By increasing both the control and knowledge of the situation, BCIs will extend people's responsibility.

An example of the way in which BCIs might extend responsibility can be observed in military scenarios. BCI-equipped soldiers operating in urban environments would have many advantages over soldiers currently operating in similar environments. BCIs could enable the soldiers on the ground to access visual information from drones or similar external devices. Indeed, BCIs may even be capable of providing direct brain-to-brain communication. DARPA has been developing a "Silent Talk" project that will enable soldiers to communicate through subvocalized speech (Kotchetkov et al. 2010). In these situations, the soldiers would be able to determine the whereabouts of their enemy despite ground-level visual obstructions. These technologies could in principle provide soldiers with information regarding whether people they encounter are armed threats or not. Increasing the information available to troops in combat zones means that these troops will have a greater degree of responsibility than troops currently have, in that they will have a greater awareness of what it is they are doing, what their options are, and what their actions are likely to achieve. If one were to be optimistic, enhancing soldiers' abilities to recognize enemies, to assess threats, and to comprehend changing circumstances in the sphere of combat might result in fewer civilian casualties and less unnecessary destruction of property.[2]

The use of neurofeedback is also likely to extend responsibility in medical spheres. Some evidence is beginning to emerge regarding the usefulness of neurofeedback in medicine (Koberda et al. 2012). Were it proven to be effective, it might have many beneficial applications. Surgery is an obvious but speculative example. Assuming that neurofeedback can help people enhance their performances, e.g. getting into the "zone" in sports, then it might also help surgeons reach a state of complete concentration and focus. Technologies similar to DARPA's

[2] Of course, this assumes that the soldiers will be relatively virtuous. Enhanced communication between troops could equally benefit terrorists or any group with malevolent intentions.

Cognitive Technology Threat Warning System (see above) might also play a role in non-military fields, including medical fields. Any task that involved scanning large amounts of visual data could harness the subconscious power of the brain, or of brains, in order to track P300 brainwaves and alert the user to something significant. This would increase the responsibility of the user in that they would have greater knowledge regarding the task at hand. Interestingly, in this scenario, *reward* for the action might have to be shared with those who subconsciously helped in the identification of the object of the project even though they would not fulfill the Aristotelian conditions of responsibility (control and knowledge). So, while these people would not be morally praiseworthy, they would be due some reward for their role in the task.

14.5.3 Assessment

It is obvious that BCIs will both increase the extent of our responsibility in some scenarios and reduce our responsibility in other scenarios. That BCIs might make mind control a real possibility is frightening. The feasibility of hackers taking over a person's mind by utilizing a BCI will need to be assessed at an early stage of the development of BCIs. This is particularly urgent if BCIs are to be made available to the general public. Even if hackers were not able to control the person, they may be able to garner private information or control the person's device. Furthermore, hackers are not the only concern. There is no reason to presume that governments will refrain from using utilizing these technologies and the opportunities they provide. That users of BCIs are secure from these threats ought to be a priority for their developers.

The problems associated with atrophy may be unavoidable but preparation might lessen the risk of societal disruption. An increased reliance on technological systems leaves us vulnerable to a diminution of the conditions necessary for responsibility, i.e. knowledge and control, if the technological systems are disrupted. If societies were to become dependent on BCIs in the same way we are currently dependent on the Internet, any disruption of their use would result in severe limitations on the knowledge and control to which people would have grown accustomed. Increased reliance on BCIs, just like any increased dependence on technological systems, leaves us at risk of having the conditions necessary for responsible action reduced suddenly.

The ways in which BCIs might extend responsibility hold out much promise. The liberty that BCIs will bring to those with locked-in syndrome and others with similar conditions will improve their lives immeasurably. That soldiers, police, doctors, civilians etc. will have more knowledge and control over their lives and actions is surely welcome. However, there are aspects that might also be considered troubling. That individuals will be able to act at great distances using only their minds significantly increases their power. If BCIs are to become widespread, it will be essential to determine how easy it is for people to control their thoughts, and how well BCIs can interpret these thoughts. As mentioned earlier, this is a very novel phenomenon. Research will have to be done in order to determine whether and to what extent and for what purposes these devices should be made available to the general public. For instance, it might emerge that BCI-controlled devices are very difficult to control due to people being unable to control their own thoughts or due to difficulties in the translation of electrical signals. If that were to be the case, it would be sensible to prohibit people from using BCIs to control devices that can cause extensive harm to others, such as cars, heavy machinery[3] etc. BCIs might then be limited to being links between the person and the device in order to increase knowledge, or to access the Internet, rather than to control dangerous external devices. It is true that people will have more responsibility, but whether they will act in a more responsible manner is not at all certain. Essentially, BCIs, like many novel technologies, present a dual-use dilemma. Whilst they will offer many therapeutic and social benefits, they will also provide those with malevolent aims with greater control and knowledge, and thus with greater capabilities to cause harm.

The psychological effects of an increase in responsibility might also be worth considering. Being able to leave responsibility behind, if only for a short walk to the shops, is surely an important element of people's lives. Email and mobile phones make it increasingly hard for contemporary people to leave work behind, as they are, or are expected to be, almost always available. BCIs are likely to exacerbate this, as now a person will be able to receive a constant stream of information from a large number of devices, or even their homes, and will be able to, and possibly expected to, continue to influence or control the activities of these devices. This is not to say that the use of BCIs ought to be curtailed; it is simply worth noting that increasing the extent of responsibility may have personal and social consequences such as increases in distress or a reduction in the time and social space available in which people can relax.

14.6 Allocation of Responsibility

In discussions of responsibility and novel neurotechnologies, there has been a great deal of focus on ways in which new neurotechnologies might aid in the determination of responsibility (Vincent 2009, 2010). Novel neurotechnologies are of great interest to people concerned with determining criminal responsibility, as they might be useful in determining whether a person is telling the truth or not. Also BCIs might have an impact on the allocation of responsibility. We first examine ways in which BCIs might problematize the allocation of responsibility (the problem of

[3] This would not mean that BCIs could not still be used in conjunction with these technologies, e.g. to inform smart cars about the mental state of the driver.

many hands, the responsibility gap, subconscious actuators, and mind-melding) and then ways in which BCIs might facilitate the allocation of responsibility.

14.6.1 Claim 3: BCIs Problematize the Allocation of Responsibility

Simply put, the use of BCIs might, by increasing the complexity of the causal chain of events, make it more difficult for people to determine who was responsible for an event after it takes place. Firstly, there is *the problem of many hands*. Secondly, there is the problem of the *responsibility gap*.

The problem of many hands. This issue arises from the fact that in a complex system, a chain of events, or a chain of systems, many people might have a share in any action that leads to undesirable (or desirable) occurrences. Accidents can occur as a result of programming faults, engineering faults, errors in the maintenance of the machine, as well as mistakes in the storage and retail of the machine. If some mishap were to occur as a result of the actions of the external device controlled by a BCI, the problem of many hands would come into play regarding the allocation of responsibility. With the development of learning machines, the machine itself might be considered as another "hand" in the problem of many hands. Learning machines can make decisions and act independently of human intervention. Furthermore, the rules by which they decide how to act are not fixed during the production process and develop over the course of the machine's existence. That machines might now act independently of human intervention, constituting another "hand", makes the allocation of responsibility more difficult due to what has been described as the "responsibility gap".

The responsibility gap. This phrase was originally advanced in relation to the increased use of computers in everyday life and essential systems (Matthias 2004). It argues that the entry of computers into decision-making processes significantly distorts the usual means of ascribing responsibility. As discussed earlier, responsibility is ascribed to agents when two conditions are met: knowledge and control. The increasing use of machines, *particularly* of machines that are capable of independent learning, may lead to a loss of both main aspects of responsibility. The evolution of programming techniques (from procedural programs, to neural networks, to genetically evolved software) has resulted in machine systems that adapt their behavior towards optimal capability through repeated interaction with their environment or through the use of genetic algorithms that alter the machine's coding and consequent behavior. Necessarily, the actions of these computers will not be as predictable as regular machines. In such scenarios, responsibility ascription is more difficult and may be impossible. If a machine acts in a way that neither the manufacturer nor the owner of the machine can predict or control, neither the manufacturer nor the owner of the device can be held responsible for its actions (Matthias 2004).

A number of scholars addressing BCIs have explored the responsibility gap in relation to BCIs (Tamburrini 2009; Clausen 2009; Holm and Voo 2011; Grübler 2011). The issue of the responsibility gap in relation to BCIs with autonomous learning capabilities or intelligent supervisory systems has led to the question of whether the user is still autonomous and morally responsible for the actions of the device (Lucivero and Tamburrini 2008). Potentially, situations may arise when neither the user nor the programmers or designers of a BCI can be held morally blameworthy for a damaging act performed by a brain-actuated mobile device (Tamburrini 2009).

Grübler explains that as a result of the vulnerability of BCI interaction routines to changing conditions, the ability of target devices to learn, and the varied division of control between the agent and the machine, an opaque understanding of the user's control of the device has developed. Ultimately, however, Grübler argues that the lack of causal control does not hinder the ascription of moral responsibility. In instances when people choose to use BCIs, then, they can be held responsible for their overall use of the BCI. He contends that the user of the BCI is interested in and responsible for the whole performance of the BCI. That the BCI is controlled (or supposedly controlled) by person's brainwaves makes no moral difference in this scenario (Grübler 2011). Clausen (2009) argues that the responsibility gap is not a practical problem in relation to BCIs as certainty regarding actions is not always necessary for ascribing responsibility. Utilizing the concept of diachronic responsibility, which allows for the attribution of responsibility to someone for something for which they might not be directly blamed, Holm and Voo also contend that the responsibility gap is not a problem in relation to BCIs (Holm and Voo 2011).

Subconscious actuators. The role of subconscious actuators in BCIs may pose problems for the allocation of responsibility. Take a scenario discussed by Tamburrini (2009) in which the subconscious processing power of brains is used as part of a BCI system in human–machine cooperative problem solving. This scenario envisages large numbers of people plugged into a machine that uses BCIs to harness the processing power of the human brain to perform tasks with greater efficiency. The machine will use the subconscious processing power of the people plugged into it to scan large amounts of data, for instance satellite photographs. P300 brain signals will be produced when patterns are recognized, unbeknownst to the people whose brains are actually producing them. If innocents were killed as a result of a drone strike in response to a threat "recognized" by people's P300 brain signals, it would be most difficult to determine exactly where the fatal error occurred (Tamburrini 2009).

In individual cases in which an accident occurred as a result of the actions of a BCI-actuated device, it would be necessary to determine whether the device acted as a result of a subconscious thought of the user or otherwise. Given that agents do not have control over their subconscious thoughts, finding them liable in such circumstances might be impossible. With neither control of their thoughts, nor knowledge of what they were going to think, these individuals would not be morally responsible for such an event. As such, no one would be morally responsible, making the allocation of moral responsibility impossible.

Mind-melding. The more fanciful scenario of mind-melding also creates problems for the allocation of responsibility. Were minds to meld, each individual's consciousness would merge with every other consciousness. It is impossible to know what such an experience would entail. If such an event were possible, it would be a unique phenomenological experience; the gulf between current individual human consciousness and such a collective consciousness might be as vast as between current humans and chimpanzees. Assuming that it did not result in madness and a melded consciousness was capable of intentional action, problems arise regarding the allocation of responsibility to the collective. It will be essential to decide whether responsibility is distributed amongst the individual members of the collective (and if so how this is to be done) or whether the collective, if capable of intentionality, can be held responsible without the individual members being responsible. The existence of some sort of gestalt mind, made up of individual consciousnesses but capable of intentionality (and possibly acting in a way alien to the individuals involved) would automatically problematize the allocation of responsibility.

14.6.2 Claim 4: BCIs Will Make It Easier to Allocate Responsibility for Actions

BCIs either interpret the brain signals of the user in order to control the device in question or relay signals from the device to the brain of the user. Assuming that BCIs retain a record of the signals received from the brain, it seems that it might be possible to determine which parts of the user's brain were active at any given time. This may be somewhat limited as a BCI will not need to register and interpret all brain activity in order to be functional, so only certain aspects of brain activity need to be recorded. Yet such a record will have many uses for the allocation of responsibility. If it is possible to determine which parts of the brain were active when an action was undertaken it may be possible to determine whether or not a person can be held responsible for a specific action. It might be possible to determine whether they did something intentionally or by accident. As noted, BCIs do not need to record or interact with all brain activity. However, with more advanced BCIs (perhaps encompassing miniature MRI scanners), it should in principle be possible to register and record substantial amounts of brain activity.

There is already a debate regarding the possibility that neuroimaging could be used to reveal which brain mechanisms are required for responsible moral agency (Kotchetkov et al. 2010). Indeed, fMRI scans might be capable of determining whether a person possessed or lacked a certain capacity essential for moral agency at the time of the decision (Vincent 2009). If technological assessments of brain states become acceptable guides to a person's legal responsibility for an action, it follows that the information gleaned from BCIs might also be used in determining legal responsibility if they are capable of providing enough data on the brain states of users.

Consider a military scenario once again. BCI-enabled troops are involved in a massacre of civilians. They claim they were fired upon first. If these troops are connected together, so that they can communicate silently and receive information from a drone, the BCI will have a record of the information they were processing. As such, it should be possible to determine whether or not they were fired upon, what choices they had prior to firing their own weapons, and how much time they had to process the information they were given. Not only that, but it would in principle be possible to determine their emotional states, by recording both biometric data (muscle contraction, heart rate etc.) and EEG data about neural correlate of mental states[4] (Tamburrini 2009). Moreover, it may be possible to determine which individuals used their weapons, and which parts of their brains were active at the time. In principle, then, it should become easier to determine whether soldiers etc. are guilty of specific crimes in warzones.

14.6.3 Assessment

Whether or not it will be possible to allocate responsibility for actions will be a key factor in the development and possible commercialization of BCIs. Clearly, in cases in which BCI-controlled devices are involved in accidents, it will be essential to determine whether the event occurred as a result of the conscious intentions of the user, the subconscious intentions of the user, or a problem with the machine. Without this, we will be faced with a scenario in which it will be impossible to allocate responsibility. If this allocation problem occurred frequently, it would have most serious social implications and would be a major argument in favor of prohibiting widespread use of BCIs: People's powers and abilities would have been extended (including their ability to do harm) but the possibility of ascribing responsibility for many of their BCI-facilitated actions would not exist. For reasons of public safety (as well as for legal reasons), such a scenario would surely present too many risks to justify the widespread use of BCIs.

For example, the problem of many hands and the problem of subconscious thoughts as actuators, if insoluble, would lead to a problem of moral hazard, in which people with BCIs, knowing that they will be able to blame a malfunction in their BCI for any wrong they do (even if done intentionally), choose to act unethically as a consequence. So, it is in the interests of the developers of BCIs

[4] Computer systems that combine biometric data and EEG data would of course have many civilian applications, e.g. managing stress. These data would be useful for people developing lifelog technologies.

and those who want to commercially release them to ensure that it will be possible to retrospectively determine responsibility.

It is not clear to us that the responsibility gap has been solved. Allocating responsibility to the agent for the actions of the BCI device as a whole (i.e. diachronic responsibility) does not alleviate the risk that the computer will either mistranslate the user's brain states or will misinterpret these brain states resulting in an unintended action. The consequence might be as trivial as clicking a cursor on the wrong link, or as serious as bombing the wrong location. Nor does it alleviate the risk that the BCI device will be actuated by the subconscious thoughts of the user, over which the user has no control. If this were to happen, it would be very difficult to ascribe responsibility to the agent: They would have had no knowledge of their subconscious thoughts, nor control over them, yet the events would have been triggered by their thoughts. These practical problems require further exploration before BCIs become an integral part of the daily life of society.

Connecting minds will also present novel problems of responsibility. The increasing complexity, arising from many participants, in the causal chain leading to an action will make it much more difficult to trace the origin of specific commands or decisions. In this scenario, the concept of collective responsibility will come to the fore as BCIs might make collective activities more feasible and more potent. However, there is the problem of how responsibility should be distributed amongst the collective participants. If the connected group as a whole causes harm, does each member bear equal responsibility or will it be possible to find some more blameworthy than others? There is a further, related problem associated with mind-melding. Normally it is thought that groups, as opposed to individuals, cannot form intentions. BCIs may change this so that a group is capable of intentionality and can act and cause harm. If this is the case, then it will be essential to determine whether the group as a whole is a different phenomenon to the aggregated individuals and whether responsibility should be allocated to this "gestalt mind." It might be the case that people, when connected together, have an entirely different phenomenological experience to anything they experience as individuals, and thus act in a way alien to their intentions as discrete individuals. If responsibility is allocated to this gestalt mind, it is not clear what sort of responsibility, if any, the individuals comprising the mind should bear.

If it is true that BCIs will make it easier to allocate responsibility, however, then some of these problems may not arise. The pace of development of neuroimaging technologies suggests that it might be possible to determine the brain activity that set any chain of events associated with a BCI in motion. Something akin to an airplane's black box might be necessary if BCIs are to be in general circulation. By recording the decision-making processes, from the brain of the user through to the functioning of the device, users, designers, and the public at large would be assured that responsibility for the actions of these powerful devices can be determined. This might also alleviate the fear that a person would be held responsible for the actions of a hacker. The recording of people's brain states of course has disquieting implications, such as governments or corporations being able to retrieve the brain signals of any individual using a BCI. Therefore, it would be pivotal to develop appropriate firewall technologies accompanying BCIs in order to prevent hacking in all its various forms. If it is not possible to allocate responsibility with acceptable probability the use of BCIs may have to be curtailed, as users would fear being blamed for something they feel they were not responsible for, designers and producers of BCIs would fear litigation if users claimed that the machine malfunctioned, and so on.

14.7 Conclusion

Our analysis has outlined three novel problems associated with responsibility and BCIs, explored the different ways in which BCIs will both extend and reduce the extent of moral responsibility, and examined problems associated with the allocation of responsibility in relation to BCIs. The therapeutic promise of BCIs initiated their development, but the entertainment industries and others quickly took them up. As such, it is likely that they will be a common feature of future societies.

The novel aspects of BCIs outlined above (control of external things, subconscious actuators, and mind-melding) mean that current conceptions of moral responsibility may not easily be applicable. Certainly, the increased knowledge that BCIs might enable is likely to extend our responsibility. That doctors, soldiers, scientists, and regular car drivers will be able to receive feedback regarding their activities and information to guide their choices will enable them to act more responsibly. Additionally, the possibility of controlling external things with nothing more than our thoughts will enhance our responsibility, as our power to affect the world will have increased vastly. People will have more control of the environment around them and more knowledge with which to make decisions.

Some serious problems must be addressed though. It will be essential that BCIs do not allow hacking or mind control from third parties. That hackers, governments, or corporations might be able to send signals via BCIs to a user and thereby control their thoughts and actions is nightmarish to contemplate. Not only would this threaten the possibility of responsible action, privacy, and liberty, but it would also threaten the possibility of discontent with the loss of these values. It must also be ensured that BCIs do not respond to subconscious thoughts in a dangerous fashion. A BCI-controlled car responding to an angry impulse has the potential to cause a disaster. As such, some sort of time-lapse safety measure may be required in certain BCIs. Furthermore, that BCIs respond to subconscious thoughts also, as discussed above, complicates the allocation of responsibility, as the user would neither have knowledge of, nor control over, their subconscious thoughts.

In order for BCIs to gain widespread acceptance, the allocation of responsibility must be possible, so as to ensure that people are not being held responsible for actions of their devices over which they had no control. Developers ought to seriously consider the creation of something like an airplane's black box, so that responsibility can be properly allocated. Such a device would need to be of sufficient sophistication to enable people to determine the origin of any action, and whether that origin was external, subconscious, or conscious. However, the creation of a record of a person's thoughts and mental life raises profound problems of liberty and autonomy, which must be addressed in the scholarly discussion.

Finally, if mind-melding – people being able to share thoughts and emotional states and experience each other's experiences simultaneously – were to be made possible by BCI devices a robust conception of collective responsibility would be essential. In addition, such a development would raise philosophical issues of phenomenology, authenticity, privacy, and consciousness far beyond the scope of this chapter.

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Chapter 15
On Human–Computer Interaction in Brain–Computer Interfaces

Gerd Grübler and Elisabeth Hildt

15.1 Introduction

Research in brain–computer interfaces (BCIs) is motivated by the hope to implement this technology into the everyday lives of severely impaired people (Birbaumer 1999, 2006; Dornhege et al. 2007; Daly and Wolpaw 2008; Mak and Wolpaw 2009; Millán et al. 2010; McCullagh et al. 2010; Zickler 2009).

In addition to scientific BCI research, there is a growing interest in reflections on the anthropological, social, and ethical implications of BCI technology (Fenton and Alpert 2008; Haselager et al. 2009; Tamburrini 2009; Hildt 2010; Nijboer et al. 2011). From an anthropological point of view, of particular interest are questions that relate to human–computer interaction in BCIs. Is it adequate to describe this interaction between man and technical device as mere tool use comparable to the use of a drilling machine or a mobile phone? Or is it more adequate to assume man and technical device to form some sort of functional unit or hybrid? Are there reconfigurations taking place (Suchman 2007)? Can the technical device be integrated into the body's representation?

Furthermore, human–computer interaction in BCIs points to a human future scenario of cyborgs discussed by transhumanist positions: The vision of the biology of human beings being more and more substituted by technology, which may even end up in the vision of taking over the whole human body through technology. Taking into account that the European tradition of anthropological thinking has taken the human being to be in a rather impaired and incomplete condition, constantly in need of culture and technology, it might be an interesting question

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whether the substitution of parts of the body by technological devices would fight or rather serve the human essence.

In what follows, this chapter first reflects on the role of neurotechnology and human–computer interaction in transhumanist thinking. Then, some phenomenological positions are introduced that might serve as a basis for reflecting upon human–computer interaction in BCIs. In this, the concept of "transparency" is considered of particular interest. Afterwards some empirical results of a pilot study which investigated people's experiences concerning human–computer interaction in BCI use are presented and discussed against the theoretical background.

15.2 Transhumanism

Imagine the perfect BCI device: All technical trouble is overcome, the devices are reliable, smart, and cheap, the number of potential applications is unlimited, and the users learn to operate them easily. Is this not the opportunity to overcome all the disadvantages of our fleshly existence and to replace the body with technical devices driven by thoughts only? Could not a brain alone, connected via several interfaces to worldwide sensors and tools, live a rich and interesting life? And could not even the brain itself, the last remaining part of the body, eventually be replaced by more durable hardware? Could not mankind, as the next step in evolution, transform itself into a web-like superorganism?

This thinking is characteristic of the movement of transhumanism (Hayles 1999; Pepperell 2003; Graham 2004; Miah 2008; Birnbacher 2008; Krüger 2004; Herbrechter 2009). Transhumanism is the idea that the current constraints of being human can be overcome by technological means and that humans could be transformed into other, 'better' beings. There may be different branches and strategies of transhumanism (biochemical ones, electronic ones), but at their core they commonly aim at enhancing the mind, increasing pleasure, and overcoming death. Many of them consider leaving the body as we know it behind and moving the mind to a more durable basis. To refer to only one example, could we not upload the human mind to a supercomputer and by doing so, although leaving all the flesh behind, nevertheless save the actual, the 'real', human being? (Moravec 1988; Kurzweil 1999; Tipler 1994; Bostrom 2008, 2009) Many well-known scientists and engineers are representatives of the transhumanist movement. For an appropriate example in the BCI context, one might think of Artificial Intelligence (A.I.) researchers like Marvin Minsky or Hans Moravec. In a programmatic article Minsky (1994) claims: "To lengthen our lives, and improve our minds, in the future we will need to change our bodies and brains. [. . .] We must then invent strategies to augment our brains and gain greater wisdom. Eventually we will entirely replace our brains [. . .]" Minsky expects that researchers "will also conceive of entirely new abilities that biology has never provided. As these inventions accumulate, we'll try to connect them to our brains [. . .] In the end, we will find ways to replace every part of the body and brain – and thus repair all the defects and flaws that make our lives so brief."

Positions like this raise several anthropological questions. Are these transhumanist visions overambitious or impossible? Is there an aspect of 'human essence' that cannot or should not be touched by technical manipulation? Can humans, may they invent and engineer as they like, ever escape their general situation by technical means? Or will those technical means always remain makeshifts of an assistive, compensatory character? Can humans achieve any design by technical means, even the complete reshaping of themselves?

We can expect, roughly said, two types of answers, stressing either particular essential features of the human being or the non-fixed character of human existence. Defenders of the opinion that there are at least some essential features that might be considered to be 'eternal' would say that of course man has some options and some degrees of freedom, but he cannot escape his essential corset. The other way of thinking accepts only openness as an appropriate description and suggests implicitly that in principle man always has the option to change himself more or less completely.

No doubt, both paradigms are vulnerable to criticism. It would be hard for the eternal-features paradigm to present only one feature that has not been changed or even lost in at least some people in history. On the other hand, the option paradigm has to concede that the freedom of man is *in fact* limited by many undeniable conditions. These conditions might be altered at some point, but now, right now, they *are* present and *do* limit human activities.

It is relevant that the transhumanist visions express a current ideal or future scenario, and that research in telepresence, cyberspace, BCI, and whole-brain emulation can be considered to be in line with, if not already quite close to, these visions. From a transhumanist perspective, BCI technology can in some respects be seen as a step towards the aim of overcoming the bodily existence of the human being. As an interface between brain and computer ('wetware' connected to hardware), BCI technology in some sense illustrates the transhumanist ambition of replacing biological structures by technological enhancements (Grübler 2012). So the question arises: Can BCI applications really substitute parts of the body?

In the following, this core question will be further elaborated on the basis of some positions in philosophical anthropology.

15.3 Human–Computer Interaction

During recent years increasingly intensive discussions about the way people interact with machines have taken place (cf. Suchman 2007). Typical instances that have been used to illustrate arguments and interpretations are media use and human–computer interaction. However, for the theoretical backing of these discussions much older models and theories were used. The most prominent ones come from Edmund Husserl (1976) and Maurice Merleau-Ponty (1962). The latter argued that (even primitive) tools and devices people use are integrated in their bodily experiences and modify the way they construe 'their' world. Contradicting the 'objectivist' point of view – the readymade body uses a readymade tool to manipulate the readymade world – this phenomenological point of view stresses the undivided unit the human being practically forms with the world he or she is actively engaged in. On the basis of this kind of thinking the extension of the body or the incorporation of tools in several fields of prosthetics or cyberspace applications was spoken about (Clausen 2006; Hildt 2010). It has, for instance, been argued that prostheses become part of the users (e.g. McDonnell et al. 1989; Hochberg and Taylor 2007). This seems to support the idea that human beings may be altered by technological means and that they might drift away from their current state of being. In addition, it was further argued that there is an important difference between the inclusion of technical devices into the body and the extension of the body via technical devices (De Preester and Tsakiris 2009). According to this thesis, the body seems to have an internal, inborn model allowing for an integration of artificial limbs as far as they emulate the complete biological body. Only artificial parts of that kind can be experienced as parts of that body.

In the context of human–machine interaction, Martin Heidegger's reflections on tool use are also of interest. With regard to tool use, Heidegger (1962, §16) described a mechanism of status change which sometimes happens to things we deal with in the world. These things, like tools for instance, are invisible in use, transparent. Their ontological status is 'ready-to-hand.' But sometimes one might be unable to do the planned work because the tool is broken or out of order. In such cases, the tools lose their character of being 'ready-to-hand' and are now only 'present-at-hand.' Then, the practical context of a transparent use is destroyed. The tool is a mere object now, a piece of matter. Of course, the body is not a broken tool, but there are some similarities in structure: We usually do not focus on the body or on the tool we use, but just do whatever we want to do. We are engaged in the world. The body as well as the tool are invisible in use, transparent. That means that we fully concentrate ourselves on the 'work' we try to do. Controlling the body or the tool is not what we have in mind, but doing the 'job'. A trivial example is bicycling: We just go to the left or go to a certain destination without thinking about the details.

All technology that enables transparent practice has at least the potential for success. If BCI technology allows for activities that 'feel' like this we would say that the substitution of the body's motor activities is successful. If, on the other hand, it turns out that in BCI use the technology will always remain an issue that stands between man and his 'work', this practice would be very different from our regular experiences in normal life.

Based on phenomenological observations like these, the notion of transparency has become relevant especially within several theories of media use and in the field of cyberspace or telepresence. Here, transparency has already been an issue in several empirical investigations (cf. Murray and Sixsmith 1999; Dolezal 2009). Tentatively, one might summarize the results as follows: The more technologies connect visual feedback consistently with motor activity, the greater their potential for becoming transparent.

For BCIs the former is not given by definition. The question, therefore, is whether they nevertheless have the potential for transparent practice. Or should this not be the case for reasons of principle? At least there are several theories claiming that personal life, self-consciousness, and the sense of one's own actions is primarily mediated by motions (so called motor theories). For instance, on the basis of a survey of modern studies, Tsakiris and Haggard (2005) conclude: "Overall, the 'agentic self' seems to be constituted by voluntary movement [. . .]" and "[. . .] in both phylogenetic and ontogenetic terms, perception and cognition begin with movement" (404). The core question here is, then, whether it is really the movements as such or rather the realization of intentions which, technologically mediated and without any self-movement, have the effect of maintaining all these self-constituting phenomena.

Given these theories, it is an interesting question how BCI users experience BCI use: Do BCIs have the potential to become transparent in use? In order to approach an answer to this question, semi-structured interviews were undertaken in a pilot study. Some of the results of this pilot study will be presented in the next section.

15.4 Some Empirical Results

To find out more about these questions concerning human–computer interaction, participants in non-invasive EEG-based BCI studies were asked about their experiences with BCI use (cf. also Grübler et al. 2014): 20 persons (15 male, 5 female, aged 29–71) in three countries took part in semi-structured interviews. Seven of them are stroke patients who went through a BCI-based experimental rehabilitation. Thirteen are motor-impaired people who did BCI training sessions and, if they achieved control over the interface, tested prototypes for communication, entertainment, or telepresence. Six out of these thirteen users had been training successfully and went on testing prototypes, while seven dropped out after several training sessions without achieving command over the interface. Most of the participants used the strategy of motor imagery, i.e. they imagined movements to trigger the functions of the devices. Only one participant used the P300 approach, which capitalizes on rather passive (reactive) potentials for choosing functionalities on the screen.

The interviews consisted of 23 questions, of which only two are of interest here, however. One of them is: "Did you have the impression that you and the BCI-based device together form some kind of functional unit? Or, in other words, did you experience the BCI device, the moment you used it, in any sense as part of you?" The other question of interest is: "While using the BCI, could you directly concentrate yourself on the work you tried to do? I mean: Could you forget about the technology and the learned strategies of using it and just do what you wanted to do?" Both questions, using different wording, ask for issues related to transparency.

Concerning the first question, four participants answered that they had the impression of forming a unit with the technology; all the others rejected this. A 71-year-old stroke patient who had trained to move a virtual hand on the screen said: “Yes, when I saw the fake hand opening and closing I felt it like a natural movement of my real hand.”

A participant who did BCI training said: “I felt we were one entity when I could visually see what was happening on the computer, advancing, retreating, and trying to put the arrows where needed.” Another participant who successfully tested a BCI prototype reported: “I think it was a part of me, yes [pause] because my brain was involved in it [. . .].”

In contrast, a person who did not manage to control the BCI said: “Not at all, because [the device] did a bit what it wanted, my brain just as it wanted while I was focusing. And then with all the failures there all the time [. . .]. So I cannot say we were really hooked atoms, him and me.”

Another interviewee said after BCI training: “I considered it to be more like a tool, like a computer keyboard, like an aid.”

While only four users said they had the impression of forming some kind of functional unit with the BCI device, 15 participants said that they were able to concentrate on their ‘work’ while using the BCI and that they could forget about the technology and the learned strategies. As an example we cite a 43-year-old tetraplegic who used the BCI to control a telepresence robot by motor imagery (in his case moving hands). After receiving a confirmative answer, the interviewer added an in-depth question: “If you now want to move the bar [i.e. the bar on the computer screen that is used for training and feedback] left or right or turn the robot left or right, do you think about ‘robot turning left or right’ or do you think about ‘right hand movement and left hand movement’?” The user’s answer was: “No, I’m thinking about the hardware. . . not about me.”

Some participants stressed that they were able to forget about the technology after having had several training sessions and before fatigue set in. For example, one interviewee said after prototype testing: “Generally yes, it was fine, well then I think I was a little tired at the end of the sessions, so it was a bit more difficult but in general I think I managed more or less well to focus on the work and exercise more than on the technology.”

Another participant, when asked whether he was able to forget about the technology and the learned strategies of using it, and just to do what he wanted to do, said: “It was difficult but that’s what I was trying to do. But it is true that the more time passed, the less I was bothered by the technology, the less I thought about it.”

In sum, the preliminary results obtained point to some ambivalence concerning the question of transparency in BCI use. Whereas some participants clearly report the impression of having formed a functional unit with the technical device or the impression of having been able to forget about the technology, others rejected these aspects. One reason for this may be that both the questions were rather abstract, so that possibly not every participant clearly understood what we were asking for. In addition, it seems plausible to assume that the impression of transparency in BCI

Table 15.1 Some examples of pairs of answers given by individual participants

Did you have the impression that you and the BCI-based device together form some kind of functional unit? Or, in other words, did you experience the BCI device, the moment you used it, in any sense as part of you?	While using the BCI, could you directly concentrate yourself on the work you tried to do? I mean: Could you forget about the technology and the learned strategies of using it and just do what you wanted to do?
Not at all...	Yes, absolutely...
No, never. It was...me, I learned to use a tool...	Yes, that was quite easy for me.
No, I never got to this...	Yes, there were times when the technology and I were linked.
No, never. It was always a means to achieve a goal...	Yes, it has been easy for me.
No, never. It has always been a means to achieve a goal.	Yes, it has been easy to learn a strategy and then use it.
No, it is a communication device, it is not me!	Yes. Nothing else to say.

use is tightly linked to the experience of having control over the BCI (which was not the case in all of the subjects). Nevertheless, according to the answers obtained by some of the participants in this pilot study, it seems that transparency is a phenomenon that can be observed in BCI use.

Furthermore, if one compares the answers the individual participants gave to each of the two questions, a considerable inconsistency attracts attention: Whereas a majority of the participants said that they were able to concentrate on their 'work' and to forget about the technology, when we asked whether they felt themselves to be a functional unit with the technology, most persons hesitated to agree. Since both questions related to transparency in BCI use, this inconsistency seems rather surprising. This can be seen more clearly when placing the answers coming from one and the same person side by side (see Table 15.1).

We can see participants on the left side of the table harshly oppose something that they seem to embrace on the right side. It seems that they are reluctant towards ideas like "forming some kind of functional unit with a technical device" which may imply "melting with technology" or "becoming part of a hybrid". Instead, they seem to prefer to describe their interaction with the technology rather as 'controlling a tool'. It may be speculated that one reason for this may be that phrases like 'forming a functional unit with a technical device' raise negative feelings or fears linked to ideas such as technicalization or cyborgization that might imply losing one's essence or identity.

15.5 Conclusion

Concerning the empirical pilot study reported here, our impression is that the results point towards the potential of non-invasive EEG-based BCI technology to become 'transparent' in use. The users were, partially, able to control their environment –

even without motor activities – and focus on their aims and intentions. This emulates the way we normally act in the world. Therefore, the substitution of parts of the body seems to be possible to a certain extent. Human practice and human essence might be flexible enough to realize a 'full' life on the basis of other, unusual interaction strategies.

It is an interesting by-product of the interview study to see a tendency in the participants to distance themselves from technology, to avoid ideas relating to forming a functional unit or becoming part of some man–machine hybrid.

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Chapter 16
BCI and a User's Judgment of Agency

Rutger Vlek, Jan-Philip van Acken, Evine Beursken, Linsey Roijendijk, and Pim Haselager

16.1 Introduction

BCI is an umbrella term (Nijboer et al. 2011) for several techniques where "covert mental activity is measured and used directly to control a device such as a wheelchair or a computer" (van Gerven et al. 2009). When the user performs a mental task his brain activity is measured, analyzed in real time, and used as a control signal for a device. The device then provides feedback to the user. Control is achieved through the classification of the detected activity and the mapping of this activity to an action.

In this chapter we want to explore how the insertion of a BCI in between thought and action may affect a user's sense of agency (SA), defined by Gallagher (2000) as: "The sense that I am the one who is causing or generating an action" (15). We will argue that, at least theoretically, it is possible that BCI-mediated action can leave a user uncertain as to whether or not he was the agent. We will discuss two pilot experiments we performed that illustrate how this theoretical possibility can be empirically investigated. The first experiment focused on the possibility that a user may claim to have been the agent of a BCI-mediated action, while this actually was not the case (the user had the *illusion of agency*). The second experiment examined the effect of the *transparency of the mapping* between the mental task and the performed action on this agency illusion. We will close by discussing briefly some of the potential implications of a user's uncertainty about being an agent in the process of learning to use a BCI and the potential moral and even legal implications concerning responsibility for action (Haselager 2013).

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16.2 BCI and Agency: The Theoretical Issues

A person's sense of agency has been discussed increasingly over the last decade (see for example Blakemore et al. 2002; 2003; Wegner 2003a; de Vignemond and Fourneret 2004; Tsakiris et al. 2006; Pacherie 2007; Moore and Haggard 2008). On the one hand, someone might think he is doing something, though in actual fact he might merely be undergoing an event, witnessing its effects on him, but not being a cause of it. Wegner (2003a, 9) has classified this as a case of illusion of control, where someone has the feeling of doing something, but is not actually doing it. On the other hand, someone might think he is not doing something, while in fact he is. Wegner classifies this as a case of automatism: "The case of no feeling of will when there is in fact action" (Wegner et al. 2003, 9). The basic distinction is between doing something without realizing this (e.g. one's brain states being the cause of a specific event) and thinking that one is doing something without actually doing so (one's brain states not being the cause of the event).

Recently, two aspects of SA have come to be distinguished: A pre-reflective as well as a reflective SA (Gallagher 2012). Several concepts for the two different types of SA are in use and the ones best suited to give a rough, intuitive understanding are provided by Synofzik et al. (2008): pre-reflective, non-conceptual SA can be seen as *Feeling of Agency* (FoA) while a reflective, conceptual SA is labeled *Judgment of Agency* (JoA). For the FoA the most prominent models are derived from the so-called *comparator model* by Frith (1987, 2012; Gallagher 2000), while one model out of several for the JoA has been proposed by Wegner and Wheatley (1999). Although both aspects need to be studied, we decided to focus on the reflective and inferential processes involved in a participant's judgment about whether they caused or generated a BCI-mediated action.

Beginning at the end of the last century, psychologist Daniel M. Wegner published several articles on various aspects and manipulations of persons judging themselves to be the agent or 'author' of an action, i.e. judging that it was their conscious will that caused it. In their 1999 work Wegner and Wheatley looked for the sources involved in the creation of this impression. Ownership of action (or, following Synofzik et al. 2008, 'judgment of agency') arises when three preconditions are met: A thought is perceived as willed when the thought precedes the action at a proper interval (called the *priority principle*), when the thought is compatible with the reaction (*consistency principle*) and when the thought is the only apparent cause of the action (*exclusivity principle*). The *consistency principle* is especially interesting in the context of BCI. In much research, imaginary movement is used as the mental task to drive a BCI (van Gerven et al. 2009). A subject is for instance imagining left versus right hand movements. These imagined movements lead to reasonably easy to detect oscillatory neuronal patterns in right and left motor areas, which can then be used for example for the movement of a cursor on a screen. This new mapping between mental task and actuator output needs to be learned. At first participants will be uncertain which of their imagined movements will result in which exact movement of the cursor on screen. It is through double-checking the correlation between performed mental task and cursor movement that, through repetition, a consistent picture will form, reinforcing their judgment that they are the agents of the action.

It may be useful to examine how these principles help to explain the results of a BCI experiment by Lynn et al. (2010). This experiment has shown that it is possible to generate illusory intent for BCI applications – participants reported that they deliberately caused the movement of an object on a screen after being asked to try moving it as often as possible even though the movement they saw during the experiment was completely pre-rendered and allowed for no interaction. The principles help to explain this as follows. The object moved after participants allegedly began "emitting the intention of moving the line", which is in line with the *priority principle*. The object traversed the screen in a way that the participants had been led to expect through their briefing and appeared to do so consistent with their prior knowledge of, and their experience with, the BCI of Lynn et al., thus satisfying the *consistency principle*. Finally, the participants were the only visible actors, satisfying the *exclusivity principle*.

16.3 Experimental Inspiration

We wanted to illustrate how the theoretical possibility of a user's mistaken JoA could be studied experimentally. In order to do this we chose an experimental setup that remained as close as possible to one of Wegner's most vivid experiments concerning the illusion of agency. In "Vicarious agency: Experiencing control over the movements of others", Wegner et al. (2004) describe an experiment called 'helping hands'. This experiment is conducted with two people, of which one would randomly be assigned to be the participant while the other would be assigned to the role of the so-called 'hand helper'. Participants would watch themselves in a mirror while another person (the 'hand helper') stood behind them. This helper would be hidden from view in the mirror, except that he extended his hands forward on each side where normally the participant's hands would appear. The hand helper then performed a series of hand movements. Both the hand helper and the participant were wearing a headphone through which they heard instructions that sometimes were the same, and sometimes different. In Wegner et al. (2004), three different experiments were discussed. Only the first one is relevant for our purposes here. It had two conditions, a preview condition (in which the participant heard the same instructions as the hand helper) and a non-preview condition (in which the participant heard no instructions at all, but the helper still did). Results were gathered using a questionnaire with questions about how much control or conscious will the subject experienced. The answers could be rated on a Likert scale from 1 to 7. Mean vicarious control ratings were computed by taking the mean of the answers of two questions: "How much control did you feel that you had over the arms movements?" and "To what degree did you feel that you were consciously willing the arms to move?". In the preview condition, the mean vicarious control ratings reported by the subject were significantly greater (with a mean of 3.00, $SD = 1.09$) than in the non-preview condition ($M = 2.05$, $SD = 1.61$, $t(31) = 26.8$, $p < 0.02$). Although a rating of 3 on a scale from 1 to 7 (with 1 meaning no control) is still relatively low, according to Wegner the results indicate that the participants hearing the instructions just before the action "expressed an enhanced feeling that they were able to control and will the arms' movements" (Wegner et al. 2004, 841). These results show that participants in the preview condition experienced significantly more vicarious control over (indicating that the subject felt more authorship for) the movements of someone else than participants without preview. The most interesting finding of this experiment is that people experienced some sense of agency over the movements of others even though they knew someone else executed the instruction.

In this experiment two principles to make judgments about action are applied: The priority principle and the consistency principle. According to the priority principle the thought should occur before the action. In the preview condition this principle is applied (the participants thought follows the instruction), contrary to the non-preview condition in which no instruction is given and therefore no instruction-related thought occurs. The consistency principle means that the thought should be consistent with the action. This principle is applied in the consistent preview condition, but not in the non-consistent preview one (in which the instructions did not match the actions).

16.4 Experiment 1

In this experiment (see van Acken 2012 for further details), we set up a nonfunctional brain–computer interface that replaced the 'hand helper'. More specifically, we employed an electroencephalogram (EEG) hooked up to a computer that controlled the movements of a robot hand displayed on a screen in front of the subject. The signals picked up by the EEG were allegedly able to control the gestures of a virtual hand, presented on the display. In truth the participants did little more than watch a series of movies. Their EEG was measured for further research, but was not used to actually control the feedback during the experiment.

Participants would hear one of two commands, either "*thumbs up*" or "*okay*". They were told that the *vivid thought* of moving one of their hands without actually moving it (i.e. imagined movement) would be picked up by the EEG cap on their head. Upon hearing "*thumbs up*" they had to imagine moving their left hand up and down, which would in turn cause the virtual hand to perform a "*thumbs up*" gesture. Upon hearing "*okay*" from the speakers the participants had to think about moving their right hand up and down, in turn causing the virtual hand to perform the "*okay*" gesture.

Each session consisted of 60 trials, of which 30 instructed right hand imagined movement, and 30 left hand imagined movement. The order of the trials was randomized. There were two sessions in total, with two different delays between the instructions and the hand movement on screen. The session we are focusing on here had a 2.5 s delay between the onset of the audio cue and the onset of the hand movement. This delay was based on the fact that most BCIs do not react immediately but with a slight delay. Although participants were told their EEG readings would be used by the BCI to control the hand movements visible on the screen, in actual fact they were looking at fixed short movies. These movies were set to display the hand moving conforming to the audio cue 90 % of the time, and non-conforming 10 % of the time. These percentages were chosen to approximate high-level EEG-based BCI performance levels. Thus, occasionally participants would hear the "*thumbs up*" cue but see the hand perform an "*okay*" sign or vice versa. After the session participants filled in a questionnaire. We computed the participants' JoA using the following questions of Wegner et al. (2004): 'How much control did you feel that you had over the hand's movement?' and 'To what degree did you feel you were consciously willing the hand to move?'.

We performed a pilot version of this experiment with six participants (all students, three male, three female, mean age of 22.3 years, all but one right-handed, two with prior BCI experience) as part of a bachelor thesis project at the Department of Artificial Intelligence at the Radboud University Nijmegen. We examined the mean vicarious control ratings and found $M = 5.00$, $SD = 0.316$ for the 2.5 s preview condition. As the number of participants in this pilot is low ($n = 6$) we do not make any claim about significance levels. All the same, the mean vicarious control ratings reported by the participants are higher than found by Wegner et al. (2004). At the least it seems to suggest that under certain circumstances one cannot discard the option that users in a BCI context might experience an illusion of control, i.e. judge that they are the author of the act, and thereby have a sense of agency concerning actions they do not perform.

It is valuable to consider how the principles underlying judgments of agency apply to the BCI scenario of experiment 1. As in every setting the hand moved after the audio cue that served as the start signal for the participants to begin with their imagined movement, we argue that the *priority principle* holds. As the participants knew they were the only actors involved during each trial, the *exclusivity principle* holds. The answers by participants concerning how they felt about the experiment after each session seem to support this: Among the answers were phrases like "I think I did something wrong a few times, I really thought about moving my left hand but the virtual hand did the okay sign". Phrases to indicate a perceived co-authorship from the EEG system would likely have gone more along the lines of "I thought about X but *it* did Y" where *it* may be replaced by BCI, EEG, or a related term, attributing some agency to *it*. As for the *consistency principle* one might argue that it holds here since the mapping from audio cue to imagined movement to the movements of the digital hand stayed consistent except in the case of error. With all three principles accounted for – even if some might be rather weak – all sources for a JoA according to Wegner and Wheatley (1999) are present. It seems plausible to say that a BCI setting allows for stronger *exclusivity*, roughly equal or lower *priority*, and – due to the, say, novelty of the task our participants had to perform – somewhat weaker *consistency* than comparable experiments reported by Wegner et al. (2004).

16.5 Experiment 2

Experiment 2 (see Beursken 2012 for further details) focused on the effect of the transparency of the mapping between mental task and performed action on the user's JoA. The mapping between the mental task and the performed action is called transparent when the performed action conforms to the mental task. For example, normally when we think about grasping a glass (e.g. we want to grasp it) in order to grasp the glass, the thought and action 'fit' one another. In a BCI context this is rarely the case, particularly because one wants to use mental tasks that provide the largest contrast in brain signatures between them. Often left versus right hand imagined movement is used in order to for example move a cursor on the screen upwards or downwards, or having a hand-like effector opening or closing a grasp, which does not correspond directly to the imagined movement performed during the mental task.

Experiment 2 had a similar setup to experiment 1, but used two robot hands (a left and a right hand) instead of one. It had two conditions, one transparent and one non-transparent. In the transparent condition, the audio instruction, mental task and performed action conformed to each other. For instance, when the audio instruction 'left hand up' was given, the participant had to imagine moving his left hand up and down. The left virtual hand would in return move up. In the non-transparent condition, two possible audio instructions were given: '*thumbs up*' or '*okay*'. When the instruction 'thumbs up' was given, the participant had to imagine moving his left hand up and down. The virtual hands would in return make a thumbs up sign. When the instruction 'okay' was given, the participant had to imagine moving his right hand up and down. The virtual hands would in return make an okay sign. As in experiment 1, the gestures of the virtual robot hands were preprogrammed, which means that the participants were not in control, even though they might think they were.

We performed a pilot experiment to investigate transparency as part of a bachelor thesis project at the Department of Artificial Intelligence at the Radboud University Nijmegen. There were eight participants (four females and four males), between the ages of 19 and 25. None of them reported to have experience with BCI (though three reported to have experience with EEG). Six of them were right-handed, and two were left-handed. The experiment had a within-subject design in which each subject performed a session of each condition (the order was randomized and counterbalanced). Each session contained 60 trials (30 left hand and 30 right hand, randomized over the experiment). As in experiment 1 we also chose to simulate a BCI performance of 90 % correct.

As in experiment 1, the user's JoA is computed using the following questions: 'How much control did you feel that you had over the hand's movement?' and 'To what degree did you feel you were consciously willing the hand to move?'. We compared these ratings (one for each condition) using a paired-samples t-test. Mean vicarious agency ratings were higher in the transparent condition (M = 4.188, SD = 1.710) than in the non-transparent condition (M = 3.688, SD = 1.557), but this difference was not significant ($t(8) = 15.28$, $p = 0.17$ (2-tailed)). Thus, the transparency of the mapping between the mental task and the performed action did not significantly influence the user's JoA. However, the ratings are found to be in the right direction (higher in the transparent condition than in the non-transparent condition). The results support those of experiment 1, in that they are higher than those reported in Wegner et al. Again we refrain from making any claims about significance here because of the low number of participants.

16.6 Differences Between the Two Experiments Potentially Relevant to JoA

In order to obtain a better understanding of how the context of a BCI setting can be of influence on a user's JoA, it is interesting to consider why the vicarious agency ratings in experiment 1 have a higher mean ($M = 5.00$) than in the transparent and non-transparent condition of experiment 2 ($M = 4.19$ and $M = 3.69$, respectively). This difference is especially interesting since experiment 1 used a non-transparent set-up. To explain these results we noticed the following differences that might have played a role:

Showing live recordings of the data recorded by the electrodes to the participant. In experiment 1, the live recordings of the electrodes were shown to the participant during the setting up of the EEG equipment. The participants were asked to blink their eyes and clench their teeth, while the EEG waves were shown on the screen in front of them. In this way they saw direct feedback from their brain. This may have had a significant influence on the participants. Even though this does not immediately show that the BCI performs well, it might help to convince the participant that the EEG signals are used for controlling the BCI output. In experiment 2, no such live recordings were shown to the participants and this might result in lower reinforcement of the suggestion that the user actually controls the output.

Availability of the instructions during the experiment. In experiment 1, the instructions were available on paper during the experiment, allowing the participant to look at the paper to see what needed to be imagined when a certain instruction was heard. Showing the instructions does not make the mapping between the mental task and performed action more transparent, because the mental task and performed action still do not conform to each other. However, showing the instructions may compensate for the lack of transparency between the mental task and performed action by reducing the memory load.

Number of virtual robot hands. In experiment 2 two virtual robot hands were used (to associate with left and right hand imagined movement), while in experiment 1 only the right hand was used. One might consider that one versus two virtual robot hands had an influence on the JoA and that two virtual robot hands can better reflect reality, since participants have two hands and both hands were used for imagination. This would suggest that the participant might have felt more control (because the consistency principle can be better applied here) and would therefore have given higher ratings. However, the results contradict this; in experiment 1 higher ratings were found than in experiment 2. We are at a loss how to explain this except for the suggestion that the difference in results is caused by one of the other differences between the experiments.

To summarize, probably the first difference (showing live recordings) has a large impact on the JoA. The difference in the number of virtual robot hands gives slightly contradictory results, since we expected the participant to feel more control over two virtual robot hands than over one. Showing the instructions during the experiment (difference number two) could have helped the participant to internalize the mapping between the mental task and the performed action better. This could give the participant the idea of having more control. Unfortunately more than one difference is found between the experiments, so that we cannot attribute the difference in results to one specific cause. We analyzed these issues in such detail to provide an example of how subtle details of the context in which a BCI is used may be of influence on a user's JoA. Further studies need to take this into account.

16.7 Conclusion

First of all, our pilot studies seem to indicate that it is possible to measure a user's JoA in a BCI context. Furthermore, in both experiments a JoA rating was found that was relatively high (i.e. above the 50 % point of the 1–7 Likert scale). While it thus seems possible to evoke an illusion of agency, two important questions remain: (1) What are the potential implications of unjustified JoAs? And (2) could a manipulation of a user's JoA be beneficial to BCI use and, if so, under what circumstances?

Imagine a user – let's call him Frank – trying to perform an action through the assistance of a BCI. Frank is imagining his left hand moving, in order to have a robot hand picking up a cup of hot coffee so that a person (Louis) sitting nearby can get it. Something goes wrong and the coffee spills over Louis, resulting in damaged clothes and slight skin burns in the process. Does Frank feel responsibility – as distinct from being (legally) responsible – for the outcome of his attempt? If our investigations are on the right track, it may be that Frank may feel that he himself did something wrong (e.g. in his performance of the mental task), while actually he (his brain states) played no causal role in the unfortunate outcome. That is, it may have been that he performed the mental task correctly, but some aspect of the BCI was not working properly. Though Frank did not really do it, he may feel he did, and feels the guilt and perhaps pays damages accordingly. Importantly, there may be inconspicuous aspects of the context in which Frank is using the BCI that may strongly influence his feeling of responsibility. Our analysis and experiments tentatively suggest that BCI users may be well advised to carefully (re-)consider whether their first assessment of responsibility is correct.

From a legal perspective, there might be important implications as well (see Tamburrini 2009 for a brief discussion of potential liability issues). According to the legal dictum used in American criminal law 'actus non facit reum nisi mens sit rea', the act does not make a person guilty unless the mind is also guilty. An important condition for Frank having a guilty mind ('mens rea') is that he is aware that he is acting in a specific way, while doing it. An act performed by sleepwalking, for instance, is considered to be involuntary, which may exempt a person from at least part of his responsibility for the outcome. In the case of acts leading to undesired consequences (such as in the case of Frank with the spilling of coffee), a legally important criterion is negligence. Negligence arises when the accused unintentionally committed the criminal act without exercising the care that a reasonably prudent person would exercise in similar circumstances. As some of the participants indicated after the experiments we performed, Frank might be blaming himself for not exercising reasonable care while using the BCI (e.g. reports himself to have been distracted), thereby admitting to a legally relevant error that he actually did not make.

Regarding the second issue, perhaps surprisingly there could actually be some benefits of a higher JoA in BCI users. For instance, an unjustified JoA could have stimulating effects in the often difficult initial phase of learning to use a BCI. It might help participants to pass the stage where one has no idea what one is doing or whether what one is doing is right. Moreover, a heightened JoA might evoke some sense of ownership towards the BCI, which could trigger the so-called *mere ownership effect* (Beggan 1992). That effect states that the attitude towards an object gets more positive if one owns the object compared to the attitude towards the same object if one does not own it. As such *the mere ownership effect* could in turn lead to a more positive evaluation of the BCI by the user. A user that likes his BCI might be more forgiving towards errors. In addition, positive affect (alongside glucose and resting) is known to replenish mental resources to an extent and motivate subsequent task engagement (e.g., Tice et al. 2007; Thoman et al. 2011); training or using a BCI would feel less tiresome for users who view *their* BCI in a positive light. For both the positive and negative reasons, and for the theoretical interest of sense of agency in its own right, we would like to suggest that it is important to further study the effects of BCI use on judgments of agency.

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