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Abstract: This deliverable describes the current state of the roadmap document.

Keywords: Roadmap

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[1] Public

[2] Restricted to other program participants

[3] Restricted to a group specified by the consortium

[4] Confidential, only for members of the consortium

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1 Introduction

This document reflects the current progress of BNCI Horizon 2020. It contains mainly sections derived from material which was developed in the three work packages WP2, WP3, and WP4. The first public draft of the roadmap (due by the end of M12) might and most likely will be different from what is available right now, since we will incorporate feedback by our consortium and our advisory board to create a more streamlined and easy-to-read version of this document. We will also make the first public draft considerably shorter. Concerning the layout, we have created a template in the appendix which illustrates how the final document could look like.

2 The Project

Brain-computer interfaces (BCIs) have become a popular topic for research in recent years. A BCI is a communication device which allows people to control applications through direct measures of their brain activity. A BNCI (brain/neuronal computer interaction) system extends a BCI by including other physiological measures such as muscle or eye movement signals. The number of BCI research groups around the world, peer-reviewed journal articles, conference abstracts, and attendance at relevant conferences are indicators of the rapid growth of this field. With dozens of companies and research groups actively participating in the development of BCIs and related technologies, collaboration, a common terminology, and a clear roadmap have become important topics.

To provide a solution to these issues, the European Commission funded the coordination action Future BNCI in 2010/2011. This project was the first effort to foster collaboration and communication among key stakeholders. BNCI Horizon 2020 aims to continue and improve upon the efforts initiated by Future BNCI.

A main result of BNCI Horizon 2020 will be a roadmap for the BCI field. This roadmap can support the European Commission in their funding decisions for the new framework program Horizon 2020. More specifically, we will focus on consolidating recent results in BNCI research and on investigating new BNCI activities and synergies with relevant fields. We will discuss potential new applications leading to the enhancement of functions for healthy people as well as people with motor, sensory, cognitive and mental disabilities. Furthermore, we will elaborate on key technological advancements necessary to achieve future goals, and we will touch upon other key topics including ethics, societal needs for and acceptance of BNCI systems, user-centered approaches, evaluation metrics, and the transfer of technology from research labs to the market.

BNCI Horizon 2020 will foster communication, collaboration, and dissemination of information; create public awareness of BNCIs by organizing a retreat-style conference specifically for companies and end users; actively support the foundation of an official BCI Society; create and maintain a website for researchers, reviewers, the industry, end users, and the general public; and involve both academic and industrial key stakeholders as well as end users and end user associations.

All these areas are important to further advance this still young and growing research field into a full-fledged major research discipline. A clear and comprehensive roadmap produced by BNCI Horizon 2020 will lay the foundations for, and impact on, a (continued) dominance and clear visibility of European research groups in the future. In addition, the roadmap will display opportunities, but also limitations and constraints, for the industrialization and commercialization of BNCIs.

3 The Consortium

Our consortium includes eight major European BCI research institutions, three industrial partners, and two end user organizations (one of which is also a research partner).

- Technische Universität Graz, Graz, Austria
- École Polytechnique Fédérale de Lausanne, Lausanne, Switzerland
- Julius-Maximilians-Universität Würzburg, Würzburg, Germany
- Fondazione Santa Lucia, Rome, Italy
- Universitair Medisch Centrum Utrecht, Utrecht, The Netherlands
- Technische Universität Berlin, Berlin, Germany
- Barcelona Digital Centre Tecnològic, Barcelona, Spain
- Guger Technologies OG, Schiedelberg, Austria
- Universiteit Twente, Twente, The Netherlands
- Eberhard-Karls-Universität Tübingen, Tübingen, Germany
- Institut de Neurorehabilitació Guttmann, Barcelona, Spain
- enablingMNT GmbH, Berlin, Germany

4 What is a BCI?

A brain-computer interface (BCI) is a device that enables communication without movement (Wolpaw et al., 2002). Since people can use BCIs to communicate via thought alone, they may be the only communication system possible for severely disabled users who cannot speak or use keyboards, mice, or other interfaces. Figure 1 illustrates the basic principle of a BCI.

Most BCI research focuses on helping severely disabled users send messages or commands. However, this is beginning to change. Some companies have begun offering BCI-based games for healthy users, and other groups are developing or discussing BCIs for new purposes and for new users.

There are often a lot of misunderstandings about what BCIs can and cannot do. BCIs do not write to the brain. BCIs do not alter perception or implant thoughts or images. BCIs cannot work from a distance, or without your knowledge. To use a BCI, you must have a sensor of some kind on your head, and you must voluntarily choose to perform certain mental tasks to accomplish goals.

In the most commonly adopted definition, any BCI must meet four criteria (Pfurtscheller et al., 2010). First, the device must rely on direct measures of brain activity. Second, the device must provide feedback to the user. Third, the device must operate online. Fourth, the device must rely on intentional control. That is, the users must choose to perform a mental task, with the goal of sending a message or command, each time they want to use the BCI.

A more recent definition describes a BCI as follows (Wolpaw and Wolpaw, 2012): *A BCI is a system that measures central nervous system (CNS) activity and converts it into artificial output that replaces, restores, enhances, supplements, or improves natural CNS output and thereby changes the ongoing interactions between the CNS and its external or internal environment.* This definition includes BCIs that do not require intentional control, which are sometimes referred to as passive BCIs (Zander and Kothe, 2011). A BNCI (brain/neuronal computer interaction) system extends a BCI by including other physiological measures such as muscle or eye movement signals. However, such systems are sometimes also referred to as hybrid BCIs or multimodal BCIs.

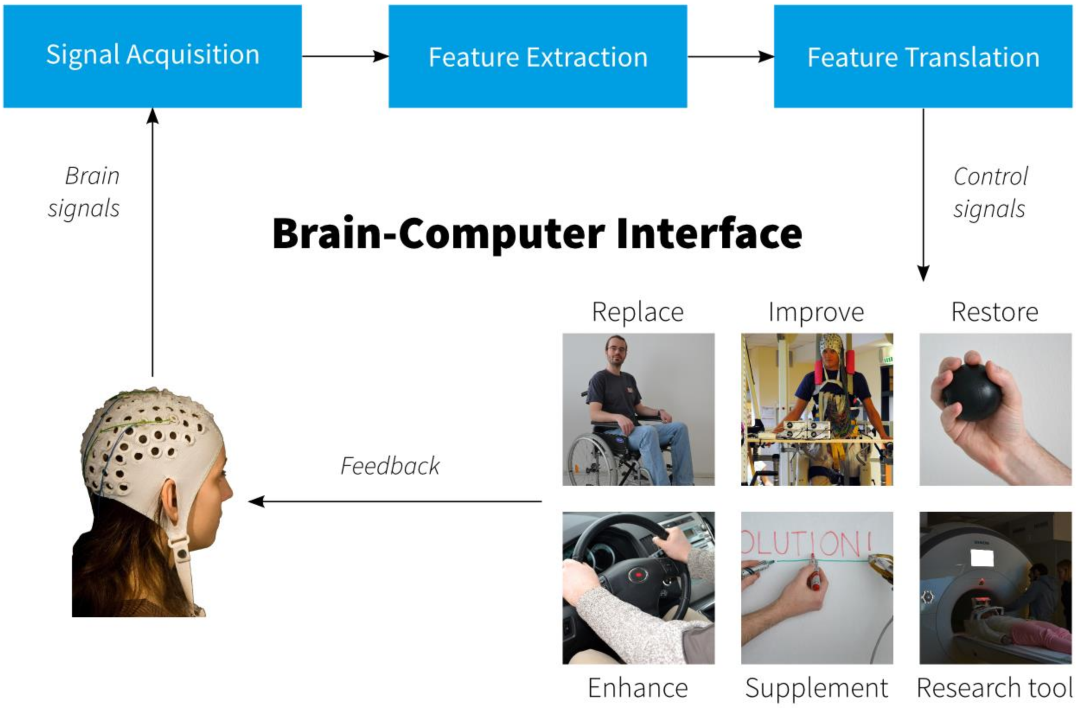


Figure 1: Brain-computer interface scheme.

In more detail, BCIs can be used in the following six scenarios:

1. BCIs can **replace** natural CNS output that has been lost as a result of injury or disease. Examples include communication (through a spelling system and voice synthesis) and motorized wheelchair control.
2. BCIs can **restore** lost natural CNS output. Examples include functional electrical stimulation of muscles in a paralyzed person and stimulation of peripheral nerves to restore bladder function.
3. BCIs can **enhance** natural CNS output. Examples include monitoring brain activity during prolonged demanding tasks such as driving a car and detecting lapses of attention, which alerts the person and restores attention.

4. BCIs can **supplement** natural CNS output. Examples include providing a third (robotic) arm to a person and providing a selection function for people using a joystick.
5. BCIs can **improve** natural CNS output. Examples include using a BCI in stroke rehabilitation that detects and enhances signals from a damaged cortical area and stimulate arm muscles or an orthosis to improve arm movements.
6. BCIs can be used as a **research tool** to investigate CNS functions in clinical and non-clinical research studies.

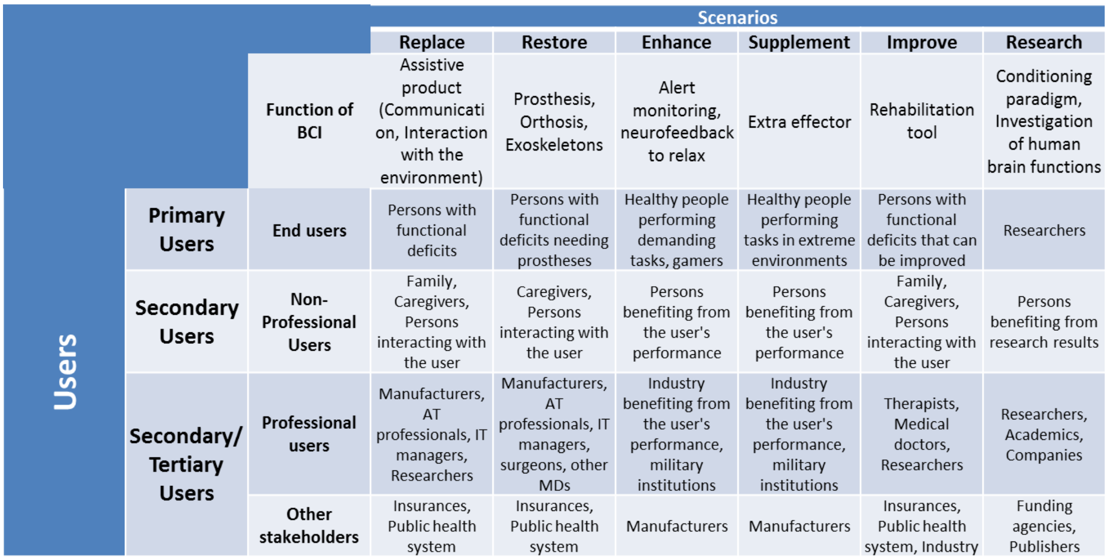
5 Who can use a BCI?

User-centered design (UCD) is a broad term to describe design processes in which end users influence how a product is designed. The UCD approach was standardized in ISO-DIS-9241-210. It is focused on the concept of usability, i.e. *the extent to which a product can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in a specified context of use*. It is based on the following principles: (1) early focus on users and tasks, (2) empirical measurements, and (3) iterative design (Gould & Lewis, 1985). Therefore, once the context of use has been identified, the iterative process consists of three main stages that are repeated until a product customized to the user is released: (1) Specify the user requirements, (2) develop design solutions to meet user requirements, and (3) evaluate the designs against the requirements.

The UCD defines the following users:

1. Primary users (or end users) actually use the product.
2. Secondary users occasionally use the product or use it through an intermediary.
3. Tertiary users are affected by the use of the product or make decisions about its purchase.

The UCD cycle usually applies to a specific product or task. However, the application scenarios (replace, restore, enhance, supplement, improve and research) comprise almost all conceivable BCI use cases, which could be developed into BCI products or applications of BCI technology. These scenarios are also helpful for defining current and future BCI users. For this purpose, we propose a classification matrix (Table 1) with applications in columns and users in rows.



			Scenarios					
			Replace	Restore	Enhance	Supplement	Improve	Research
		Function of BCI	Assistive product (Communication, Interaction with the environment)	Prosthesis, Orthosis, Exoskeletons	Alert monitoring, neurofeedback to relax	Extra effector	Rehabilitation tool	Conditioning paradigm, Investigation of human brain functions
Users	Primary Users	End users	Persons with functional deficits	Persons with functional deficits needing prostheses	Healthy people performing demanding tasks, gamers	Healthy people performing tasks in extreme environments	Persons with functional deficits that can be improved	Researchers
	Secondary Users	Non-Professional Users	Family, Caregivers, Persons interacting with the user	Caregivers, Persons interacting with the user	Persons benefiting from the user's performance	Persons benefiting from the user's performance	Family, Caregivers, Persons interacting with the user	Persons benefiting from research results
	Secondary/ Tertiary Users	Professional users	Manufacturers, AT professionals, IT managers, Researchers	Manufacturers, AT professionals, IT managers, surgeons, other MDs	Industry benefiting from the user's performance, military institutions	Industry benefiting from the user's performance, military institutions	Therapists, Medical doctors, Researchers	Researchers, Academics, Companies
		Other stakeholders	Insurances, Public health system	Insurances, Public health system	Manufacturers	Manufacturers	Insurances, Public health system, Industry	Funding agencies, Publishers

Table 1: BCI users and application scenarios.

In the BCI field, primary users (or end users) are people who directly benefit from a BCI solution in one of the identified BCI application scenarios. We can further differentiate between primary users with functional deficits and primary users without functional deficits (healthy users). Primary users with functional deficits will most likely benefit from applications in the ***replace***, ***restore*** and ***improve*** scenarios. Applications for healthy primary users are mostly found in the ***enhance***, ***supplement*** and ***research*** application scenarios. Secondary users are people who use the BCI product occasionally, or who use it through an intermediary. Tertiary users (professional users or stakeholders) are people who are affected by the use of the BCI product or make decisions about its purchase. Examples of tertiary users are insurance companies, public health systems or even manufacturers.

In our table, we made a few adaptations to the original user definitions. With the current technology and especially in some newer application scenarios, BCIs cannot be considered a proper market product. Thus, depending on the BCI application scenario, professional users may fall under the secondary or tertiary user category. That is, secondary users (non-professional or professional) in the aforementioned BCI application scenarios are mainly caregivers, relatives, researchers, therapists performing BCI tests, and other people, who by interacting with primary users can indirectly benefit from a BCI system (i.e. generally improving a service performance). Nevertheless, once BCIs become established market products, the professional figure now identified as "secondary user" (e.g. therapist) could as well be considered as a "tertiary user". This arbitrary interpretation of UCD-inspired user classification has the aim to simplify identification of user classes in the context of the BCI application scenarios.

6 Future opportunities and synergies

For decades, BCIs have been used for restoring communication and mobility of persons with functional deficits through applications such as spellers and web browsers (Gürkök & Nijholt, 2012). In parallel to advances in computational intelligence and the introduction of consumer BCI products, BCIs have recently started to be considered as alternative modalities in human-computer interaction (HCI). A popular topic in HCI is multimodal interaction (MMI), which deals with combining multiple modalities to provide powerful, flexible, adaptable, and natural interfaces. With the emergence of portable signal acquisition hardware as well as robust data processing and artifact removal techniques, BCIs have started to be considered as an HCI modality for healthy users as well. Some potential non-medical BCI applications include games, attention monitors, and interfaces to smart mobile devices. A typical use case would be the interaction between a user and smart glasses (e.g. Google Glass). Currently, the user can interact with the smart glasses using speech, gestures, or buttons. A drawback of these approaches is that the need to talk to the system might compromise privacy, whereas the use of a future BCI system is comparably unobtrusive. However, such a BCI would need to be robust against interference, non-visible or aesthetically pleasing. An example could be small in-ear sensors or sensors integrated in a baseball cap or hair extensions (Kidmose et al., 2013). Even piercing sensors might be appealing to a specific group of end users. Another interesting direction is the use of BCIs in (serious) games. One of the ideas behind BCIs in games is that the shortcomings of a BCI can be turned into challenges (Nijholt et al., 2009). Most BCI games of today are developed for research purposes as a proof-of-principle or are adaptations of existing games where traditional input mechanisms, e.g. a key press, is replaced by a BCI.

Lance et al. (2012)identified six high-level application areas for future BCI use. These areas include (1) direct control, (2) indirect control, (3) communication, (4) brain process modification, (5) mental state detection, and (6) opportunistic BCIs. According to Boff (2006), the current generation of ergonomics represents a shift away from designing machines to match human capabilities towards amplifying human capabilities to perform work. Thus, a natural way to search for potentially new opportunities of BCI technology is in environments where human capabilities to work, or, more generally, to perform any activity they would like to do, are constantly stretched. This view is closely mirrored in the five application scenarios (Wolpaw & Wolpaw, 2012), which either concentrate on users with limited functional abilities (*replace*, *restore*, *improve*) or users who would like to possess additional capabilities (*enhance*, *supplement*). For example, airline safety might profit from monitoring workload and attention of pilots, security sensitive areas might want to use BCI-based biometrics, and the entertainment industry might want to use BCI technology for optimal immersion.

In this sense, the EU-funded project Brainflight showed new opportunities within the **aerospace** sector by an ambitious project investigating the feasibility of flying a brain-controlled aircraft, which might reduce the workload of pilots and increase safety. Likewise, synergies between the **automotive** industry and BCI led to the development of cars that can be geared, steered or provide feedback by using brain-controlled systems like BrainDriver.

Examples of potential opportunities that could most benefit the **health care** or **medtech** industry are brain-controlled bionic legs and arms, or futuristic computerized bladders. BCIs may also be used in the treatment of neurodegenerative diseases in the recovery of lost cerebral functions. In 2009, the FDA approved a second clinical trial to implant the BrainGate technology into severely disabled patients. The Austrian company g.tec recently introduced mindBEAGLE, a package to assist medical doctors in diagnosing disorders of consciousness, which resulted from the EU-funded project DECODER.

Furthermore, BCI devices have a number of growing opportunities in the **entertainment** sector. The field of **education** is one of the major targets for open source (Puzzlebox Orbit) or commercial (MindWave Education) brain-controlled devices. These games claim to monitor attention levels of students performing a task. Other companies in the **entertainment** sector are developing BCI-based games, which let you manipulate targets just by concentrating on them (NeuroBoy, Mindflex, and the Star Wars Force Trainer). Games like Focus Pocus can be played on a PC simultaneously by multiple players. One of the ideas behind BCI in games is that the shortcomings of a BCI can be turned into challenges. The **music** industry is working on a device called Neuro Turntable (by Neurowear), which plays music only when the user is concentrated. Another related project explores a collaborative system to generate music supported by a hybrid BCI (b-Reactable). The **wellness** industry may benefit from BCI tools by devices like MUSE (InteraXon), which guides you to relax or focus before or after you perform a mentally challenging task, and which could be used for meditation.

Moreover, BCIs may allow the **marketing** sector to tailor **advertising** to an individual, based on mood, emotional state, and cognitive analysis. If successful, this could be incorporated in any device that allows for neurofeedback, including brain-controlled games and mobiles of companies such as Personal Neuro Devices, Neurosky, and Nielsen.

Large multinational companies in the **technology** sector are likely to form joint ventures with those BCI stakeholders offering the most promising BCI solutions. Apparel and accessory companies are releasing brain-controlled clothing and gadgets, such as Neurowear's Necomimi and Shippo, which are supposed to communicate individual moods. Other industry stakeholders in the BCI sector have produced systems (Epoc, IntendiX, Brainfingers, BrainGate) for brain control of laptops and PCs that may be beneficial for the **computer** industry. Potential synergies with the **telecommunication** industry are exemplified by Neurosky's MindWave mobile headset compatible with Apple iOS products and Android smartphones and tablets. Notably, despite the claims of the companies marketing these products, for some of these systems it is not clear if control is based on neural (EEG) or muscle (EMG) activity. Following the same line, synergies between BCIs and **assistive technologies (AT)** are progressing rapidly as shown by the brain-controlled DARPA prosthetic arm. We recently saw the success of the EU-funded projects TOBI, Mind Walker and WalkAgain. Similarly, other EU-funded projects such as BrainAble and BackHome relate AT and **domotics** with BCIs for smart home control aiming at improving autonomy in persons with functional deficits.

Additionally, the **defense** industry (e.g. Defense Advanced Research Projects Agency, DARPA) is interested in mind control of drones, weapons, aircrafts, and robotic devices. Other potential applications include the manipulation of the brain to enhance warfighting capabilities, maintenance of mental acuity, and reduction of effects of traumatic brain injury. Last but not least, BCIs can dramatically change **livestock farming** by providing access to the animals' mental states, such as stress or fear levels, thereby helping to optimize the industry, and generally to improve animal welfare. This could indirectly influence human nutrition and health in the long term.

Although promising as synergies of the BCI field, many of the above mentioned applications (especially those for entertainment and gaming) are based on basic scalp recording systems, the ability of which to actually record neural signals still has to be verified.

7 Executive summary

7.1 Opportunities/benefits

Will be available in the first public draft of the roadmap.

7.2 Recommendations

Will be available in the first public draft of the roadmap.

7.3 Highlight some use cases

Will be available in the first public draft of the roadmap.

8 State of the art

8.1 End users

Most current BCI systems target the ***replace*** scenario, i.e. a BCI is used to replace lost functions, e.g. motor functions or communication. Often, primary end users report that they would like a BCI which enables not “just” communication, but one which acts as a central hub for interacting with their environment. Thus, applications like emailing, web browsing, social networking, photo and music systems, gaming and even painting are much wished for (e.g. Sellers et al., 2010; Zickler et al., 2013; Holz et al., 2013). Over the past 20 years, BCI research has grown rapidly, but the majority of studies did not include end users. Thus, there exists a translational gap between the multiple facets of BCIs and their application in end users.

The User Centered Design (UCD) appears to be a valuable tool for transferring BCI technology towards the industry and end user, and there are already efforts introducing UCD into the BCI development process (e.g. Zickler et al., 2013; Holz et al, 2013; Schreuder et al., 2013). Use of UCD in BCIs is often located within the ***replace*** scenario, often with regard to communication applications in end users with functional deficits. Still, even among studies targeting disabled end users only about half of them actually involved such user groups. However, with BCIs rapidly maturing, efforts are underway to bring BCIs to the (home-based) end user (e.g. Bedlack et al., 2014), which often requires customizing the BCI (c.f. Huggins et al., 2014; Fried-Oken et al., 2013; McCane et al. 2014; Hill et al., 2011).

In the more recently developed ***improve*** scenario, which is currently dominated by the application of BCI to stroke rehabilitation, efforts have been made to bring BCI technology into clinical practice. This application brings together different classes of users (e.g. medical doctors, therapists) to fully assess the usability of BCI-based rehabilitation interventions (Morone et al., 2014). In this field, demonstration of efficacy (i.e. clinical improvement of the target medical condition) is crucial to allow acceptability on behalf of the medical staff and thus foster distribution among public and private health institutions.

Current BCIs for the ***restore*** scenarios concentrate on the control of limb prostheses. Experiences with end users (i.e. SCI patients) have highlighted the value of training and testing in real world environments, customizability of the proposed device to cope with the individual residual ability (Rohm et al., 2013).

Only some studies, mostly relating to the ***enhance*** scenario, refer to end users without functional deficits, primarily in areas such as gaming, human-computer interaction (HCI) design, or workload monitoring (Liao et al., 2012; Plass-Oude Bos et al. 2011).

Very few papers report users’ involvement, e.g. via interviews with focus groups or workshops, in the early phases of development of BCI paradigms and prototype (Blain-Moraes et al., 2012; Huggins et al., 2011; Zickler et al., 2009).

As for the evaluation phase, UCD usability metrics, e.g. effectiveness, efficiency, workload, and satisfaction have been increasingly applied in BCI studies (Riccio et al, 2011; Zickler et al., 2013). Effectiveness is represented by the accuracy and the completeness with which intended goals are achieved; efficiency refers to the amount of human, economic and temporal resources expended in obtaining the required level of product effectiveness; workload, which has been defined as the cost incurred by a human operator to achieve a particular level of performance, explores the efficiency domain; satisfaction is a measure of the immediate and the long-term comfort and acceptability of the overall system. Altogether, these parameters aim at establishing the acceptability of BCI paradigms and prototypes in real world applications (see Kübler et al., in revision, for an overview).

Given the traditional application of BCIs, most information on the use of BCIs is available for persons with functional deficits. Long-term BCI primary and secondary end users report the most difficult aspects of current BCI systems to be related to the hardware (the need for a cap, cables, and gel), speed and accuracy. Interestingly, aesthetic appearance seems to be a minor issue. Secondary end users emphasize reliability, easiness of use, and the possibility of independent use as most important, while price is deemed relatively unimportant (Kübler et al., 2013). These desires are partly matched by tertiary end users, who foresee the biggest market for small, light, and wireless systems suitable for home use.

8.2 Research

8.2.1 BCI concepts and paradigms

Possible control signals for BCIs derive from event-related potentials (ERPs) obtained during oddball paradigms (e.g. P300), modulation of spectral power (e.g. sensorimotor rhythms), brain signals obtained from the visual cortex (VEP, often steady-state evoked potentials, SSVEP), or from single or multiunit recordings.

BCI paradigms can be classified into exogenous and endogenous systems, depending on whether external stimulation is required (Nicolas-Alonso & Gomez-Gil, 2012). Exogenous BCIs (e.g. based on P300 or SSVEP) often use the visual modality to evoke brain responses, but auditory or somatosensory stimulation can be used as well. Endogenous BCIs do not need a stimulation device, typically offer continuous instead of discrete output such as the use of SMR during imagined movements for cursor control (McFarland, Sarnacki, & Wolpaw, 2010; Allison et al., 2012) and can be initiated at will. Finally, hybrid BCIs combine two or more CNS outputs or classifier results (Wolpaw & Wolpaw, 2012; Müller-Putz et al., 2011).

Increasing BCI performance is a field of active research. With exogenous P300 BCIs, the time required to integrate over several stimuli to reach a decision limits its effective throughput. However, increasing the signal-to-noise ratio (Kaufmann, Schulz, Grünzinger, & Kübler, 2011) and optimizing the number of stimuli (Schreuder et al., 2013a) promise to increase throughput. Performance of SSVEP BCIs depends on the number of discriminable frequencies, which is affected by hardware (e.g. LEDs vs. LCD screens) (Nicolas-Alonso & Gomez-Gil, 2012), setups (Lim, Hwang, Han, Jung, & Im, 2013), and coding schemes (Zhang et al., 2012). New approaches even allow continuous (e.g. smooth cursor control) instead of discrete control (e.g. choice selection) (Wilson & Palaniappan, 2011). Predictors of endogenous (SMR-)BCI performance include psychological, neurophysiological, and neuroanatomical variables. However, it still unclear whether these insights can actually improve performance (Grosse-Wentrup & Schölkopf, 2013). Hybrid BCIs rest on the idea that combining several input channels or BCIs, each optimized for a particular task, improves accuracy and reduces errors. However, not all combinations are effective. Complementary signals, acquisition devices, and software algorithms must be carefully selected (Müller-Putz et al., 2011; Amiri, Fazel-Rezai, & Asadpour, 2013)). Intelligent control systems reduce the dependence on (potentially) noisy signals by delegating as much work as possible towards software. For example, a wheelchair user might use a BCI to select waypoints instead of controlling individual movements, and leave the implementation of the task to the system (Allison et al., 2012a).

Despite strong efforts, current BCIs still face several challenges that limit their usefulness for most medical and societal applications. These challenges are related to increasing bit rates (Allison et al., 2012a), optimizing sensors, signal processing and classification techniques, but also to the type of control signal and overall systems design. Generally, exogenous BCIs can be used by a higher number of users, require less training, fewer sensors, and show a higher information throughput than endogenous systems. However, the need to permanently direct attention, and often, gaze, towards the stimuli, is tiring and the occupation of sensory capacity make it unavailable for other tasks. Further, the current plurality of performance metrics used to communicate about BCIs is critical. Although this issue is a matter of active research, generally, no single metric can capture a system’s performance adequately (Thompson, Blain-Moraes, & Huggins, 2013). Tests in healthy participants using typing tasks show very low bitrates (BR) for endogenous (SMR) BCIs (BR = 0.59 (Millán & Mouriño, 2003)), but higher rates for exogenous systems (e.g. BR = 61.7 for a P300 BCI, BR = 24.5 for a SSVEP BCI (Yuan et al., 2013)). However, bitrates show strong heterogeneity across implementations and settings (Nicolas-Alonso & Gomez-Gil, 2012), making reliable comparisons difficult. In addition, since a specific BCI may or may not use additional components within the BCI software ecosystem (e.g. automatic error correction, or predictive text entry), these simple measures may not accurately reflect the user’s perception of the system’s overall performance. In addition, reporting simple statistics such as accuracy ignore the need of many potential application areas to balance the tradeoff between accuracy and speed. In an attempt to address this problem, more global measures, such as the utility (Dal Seno, Matteucci, & Mainardi, 2010) metric (e.g. number of correctly spelled letters per unit of time) have emerged (Thompson, Blain-Moraes, & Huggins, 2013), but are not often used.

8.2.2 BCI data processing

Recorded neuroimaging data are a superposition of the signals of interest with a plethora of other signals - from the brain, from muscles, and from non-biological artifacts. Furthermore, the huge variability of brain activity between persons makes the real-time analysis of brain signals a challenge. Therefore, state-of-the-art BCI systems use adaptive signal processing and machine learning algorithms to extract specific information from brain signals. These techniques rely on a statistical analysis of calibration data to optimize classification models. Using these techniques, most BCI systems can be used without the need of lengthy training. There have been recent efforts to unify BCI data processing into unique software platforms (Brunner et al., 2013) with the goal to simplify the access to novel methods and to stimulate international collaborations. Research on BCI data processing focuses on the following topics.

As stated in the state of the art on BCI approaches, the development of BCI classification algorithms aims at providing the best performance (accuracy, speed, throughput etc). There are three kinds of components (i.e. spectral power changes, ERP, SVEP) that can be exploited by BCI systems based on EEG, MEG and ECoG signals. While the feature extraction has been optimized for each component individually, preprocessing and classification is very similar in most online BCI systems (Blankertz, Tomioka, Lemm, Kawanabe, & Müller, 2008; Krusienski, Sellers, McFarland, Vaughan, & Wolpaw, 2008; Blankertz, Lemm, Treder, Haufe, & Müller, 2011; Wang, Gao, Hong, Jia, & Gao, 2008; Liang & Bougrain, 2012). In order to improve performance of invasive BCIs based on multielectrode arrays (MEAs), optimized Kalman filter approaches (Malik, Truccolo, Brown, & Hochberg, 2011; Gilja et al., 2012; Dangi, Gowda, & Carmena, 2013) have been investigated as well as alternative approaches for feature extraction (Chestek et al., 2011; Homer, Nurmikko, Donoghue, & Hochberg, 2013).

One way of increasing BCI performance is to fuse different streams of information in a Hybrid BCI (Pfurtscheller et al., 2010). Several technical approaches have been proposed with the objective to either fuse multiple neuronal sources (e.g., EEG and NIRS, ERP and SSVEP or ERP and spectral power features) (Kaufmann, Herweg, & Kübler, 2014; Leeb, Sagha, Chavarriaga, & del R Millan, 2010; Fazli et al., 2012; Speier, Fried, & Pouratian, 2013; Zhang et al., 2013) or to integrate the BCI into existing technology (Kim, Kim, & Jo, 2014; Marshall, Coyle, Wilson, & Callaghan, 2013; Leeb, Lancelle, Kaiser, Fellner, & Pfurtscheller, 2013; Carlson, Tonin, Perdikis, Leeb, & Millan, 2013). As multimodal feature extraction and integration is highly relevant for neuroimaging in general, numerous methods have been adopted for other domains (Dähne et al., 2013; Leite, Leal, & Figueiredo, 2013) and some could potentially be used to improve BCI performance as well.

The applicability of both non-invasive and invasive BCI systems needs to be enhanced to make them ready for real world applications. Due to the non-stationary nature of neural data, maintaining performance over time typically requires a continuous adaptation of the BCI. Therefore, novel adaptive processing methods have recently been researched for both non-invasive and invasive settings (Vidaurre, Kawanabe, von Bünau, Blankertz, & Müller, 2011; Kindermans, Tangermann, Müller, & Schrauwen, 2014; Sanchez et al., 2014; McFarland, Sarnacki, & Wolpaw, 2011; Samek, Vidaurre, Müller, & Kawanabe, 2012; Lu, Patil, & Chestek, 2012; Moran, 2010). Some have shown performance improvements of up to 8 times (Orsborn, Dangi, Moorman, & Carmena, 2012) also across years (Gilja et al., 2012). For implanted multielectrode arrays (MEAs), short-term and long-term non-stationarities may also be addressed by using more channels, or by using multi-units or LFPs (Lu, Patil, & Chestek, 2012; Bansal, Truccolo, Vargas-Irwin, & Donoghue, 2012; Gilja et al., 2011). There are indications that ECoG recordings are relatively stable and may require less adaptation (Blakely, Miller, Zanos, Rao, & Ojemann, 2009; Chao, Nagasaka, & Fujii, 2010).

Non-invasive BCI systems need to be operated with novel sensors that are quickly applicable (e.g. dry electrodes for EEG). However, this hardware delivers highly variable signals which are commonly contaminated by numerous nonstationarities and artifacts. There is a need for novel processing tools that account for such technical artifacts.

Another practical aspect is the reduction of the calibration time. This can be achieved by transferring knowledge from existing data to new users (Kindermans et al., 2014; Lotte, Guan, & Ang, 2009), or by using self-calibrating classifiers (Bishop et al., 2014).

The use of powerful machine learning techniques brings about the necessity for a careful validation (Lemm, Blankertz, Dickhaus, & Müller, 2011). Moreover, purely data-driven feature extraction methods could be used to validate neurophysiological hypotheses (Orsborn & Carmena, 2013) and to interpret the neuronal sources on which the BCI is relying on. Haufe et al. (2014) argue that data processing tools need to be both highly discriminable and interpretable.

8.2.3 BCI hardware and recording techniques

EEG is the most popular signal type for non-invasive BCIs (Hwang et al., 2013). It records electrical activity of neural assemblies on a millisecond time scale. Besides this excellent time resolution, EEG is portable and relatively inexpensive. However, the spatial resolution of EEG is rather low, and it is susceptible to many types of artifacts (Fatourechi et al., 2007; Sabarigiri & Suganyadevi, 2014).

Traditional EEG sensors (so-called electrodes) require gel, which is a key issue that limits a more widespread adoption of EEG. An improved approach is based on water, which does not require people to wash their hair after EEG measurement. Another emerging alternative are dry electrodes (Fonseca et al., 2007), which ideally feature comparable signal quality, improved wearing comfort, and a drastically reduced setup time. Second, most EEG systems use leads to connect the electrodes to the amplifier, which places restrictions on the mobility of EEG recordings. Wireless systems establish a wireless connection between the amplifier and a computer, but their power consumption and physical size must be minimized. Last, many current EEG systems ship with active electrodes, which include small preamplifiers directly on each electrode and thus minimize artifacts induced by cable sway. Alternatively, shielded cables are also used in some systems.

MEG measures the weak magnetic fields caused by currents within the brain (Hansen et al., 2010). Like EEG, it is a direct measurement of neural activity with high time resolution (Baillet, 2011). MEG is only sensitive to tangential sources on the cortical surface. The magnetic fields are less influenced by volume conduction, and therefore MEG has a slightly better spatial resolution than EEG.

A limited number of studies has demonstrated successful implementation of MEG-based BCIs (Mellinger et al., 2007; Buch et al., 2008), but this field is still in a very early stage and the relative advantages and disadvantages compared to other signal acquisition techniques are currently unclear (Nicolas-Alonso & Gomez-Gil, 2012). However, it is unlikely that these BCIs will see adoption outside the research field due to the high cost and physical constraints of the measurement device (i.e. size, requirement for magnetic shielding) (Nicolas-Alonso & Gomez-Gil, 2012; Shih et al., 2012).

Functional magnetic resonance imaging (fMRI) measures the hemodynamic response to neural activation in the brain. It reveals locations with changes in oxygenated and deoxygenated blood flow and volume (Hillman, 2014) by using blood-oxygen-level dependent (BOLD) contrast imaging methods. The main advantage of fMRI is its high spatial resolution.

There are several approaches to improve image quality. First, signal to noise ratio increases with increasing field strength. Currently, clinical routine and research apply 1.5-3T, and 3T-7T, respectively (Van der Zwaag et al., 2009). Another way to improve image quality in defined regions is to apply multi-channel coils (Parikh et al., 2011; Salomon et al., 2014). Third, new image acquisition sequences are constantly being developed, which further improve image quality (Budde et al., 2014; Mugler, 2014; Wang et al., 2014). Although physical (size, strong magnetic field), methodological (e.g. low temporal resolution, delayed haemodynamic response) and financial aspects constrain fMRI for most BCI applications (Nicolas-Alonso & Gomez-Gil, 2012), there is an increasing interest to use fMRI for detecting consciousness (Owen, 2013), neurofeedback training (Weiskopf, 2012) or to prelocalize regions for subsequent electrode implantation (Vansteensel et al., 2010; Shih et al., 2012). In this respect, the exact relationship between the BOLD response and electrical neuronal activity is currently unclear and requires investigation. Besides these applications, this technique will remain an excellent scientific tool to complement BCI research (Nicolas-Alonso & Gomez-Gil, 2012).

Functional near infrared spectroscopy (fNIRS) is an emerging non-invasive optical technique for the assessment of cerebral oxygenation (Ferrari & Quaresima, 2012; Boas et al., 2014). Similar to fMRI, fNIRS measures hemodynamic changes in the brain, but fNIRS is less expensive and more portable than fMRI (Nicolas-Alonso & Gomez-Gil, 2012). The technique is relatively new, but BCI applications seem feasible, either as an alternative to (Sitaram et al., 2007) or in combination with (Pfurtscheller et al., 2010; Fazli et al., 2011) EEG. Due to the complementary nature of fNIRS and EEG, such a combination may be used for BCIs if shown beneficial.

Similar to fMRI, fNIRS measures BOLD responses, which are typically slow and have a strong delay relative to the underlying neuronal events. Compared to fMRI, fNIRS has a worse spatial resolution and a lower signal to noise ratio (Cui et al., 2011). A practical issue is the optimal fixation of the optical probes to the head, finding a balance between patient comfort and stability of the recordings. Another important aspect is the large number of models that describe changes in oxygenation. For clinical application of fNIRS, analysis should be standardized (Obrig & Steinbrink, 2011).

Multi-electrode arrays (MEAs) for BCI are arrays of tens to hundreds needles of 1-10 mm, introduced into the cortical surface. MEAs allow recording of local field potentials (LFPs), multi- and single-unit activity. The Blackrock (Utah) array is approved for long term human use (Lu et al., 2012) and has been used in the BrainGate(2) trials (Hochberg et al., 2006; Hochberg et al., 2012). Electrocorticography (ECoG) measures fields generated by large groups of neurons, using cortical surface electrodes. Typical implants are grids and strips of electrodes with 1 cm interelectrode distance (approved for subdural use for 28 days), but higher resolution grids are also becoming available. ECoG-BCI control is mostly based on spectral power changes in isolated brain areas (Shih et al., 2012), but ERPs are also used (Brunner et al., 2011; Song et al., 2012). Currently, these methods are mainly considered for severe medical applications, for which they are regarded highly promising because of the high quality signals in terms of spatial resolution and spectral width (Nicolas-Alonso & Gomez-Gil, 2012; Shih et al., 2012; Lee et al., 2013).

MEA BCI research has focused on combining single unit information of many electrodes, thereby maximizing the number of degrees of freedom (Georgopoulos et al., 1982; Hochberg et al., 2006). Research is mainly performed with non-human primates, and has demonstrated the use of MEA signals to control a prosthetic arm in several directions for self-feeding (Velliste et al., 2007). The BrainGate(2) trials have so far enrolled 11 tetraplegic patients, and have demonstrated multidimensional control over computer cursors and artificial limbs using imagined movement, months to years after implantation (Hochberg et al., 2006; Hochberg et al., 2012).

ECoG-BCI research is mainly aimed at replacing lost motor function and is mostly performed with epilepsy patients with subdural, subchronic implants (Ritaccio et al., 2011). Quick and accurate control over a cursor (1-3 dimensions), prosthetic hand and speller have been demonstrated using e.g. motor execution, motor or sensory imagery, working memory, visual attention and overt or imagined articulation (Vansteensel et al., 2010; Andersson et al., 2011; Shih et al., 2012; Zhang et al., 2013). Time resolution is at least comparable to that of EEG-based systems and signal quality in terms of spatial resolution and spectral width is better (Nicolas-Alonso & Gomez-Gil, 2012). One study has reported ECoG-based BCI for cursor control in a tetraplegic patient during 28 days before explantation (Wang et al., 2013). A more longterm study using a completely implantable device (Rouse et al., 2011) is currently recruiting patients.

There are many efforts to optimize performance of invasive BCIs, among others by optimizing decoding algorithms, combining multiple types of signals (e.g. single unit and LFP data), studying effects of learning and plasticity on brain signals, providing additional sensory feedback besides the often used visuals, and considering alternative brain functions and regions (Vansteensel et al., 2010; Gilja et al., 2011; Lee et al., 2013; Speier et al., 2013).

Despite promising reports on longterm, usable, recordings with MEAs (Lee et al., 2013), tissue reaction, tissue damage and the associated signal loss remain an issue of concern (Shih et al., 2012; Nicolas-Alonso & Gomez-Gil, 2012; Lee et al., 2013). Approaches currently being investigated to address this issue are biocompatible coatings and optimized algorithms (Gilja et al., 2011; Lu et al., 2012; Lee et al., 2013). Longterm stability of human ECoG recordings is not yet assessed, but recordings over multiple days in humans and multiple months in animal studies are promising (Blakeley et al., 2009; Chao et al., 2010; Moran, 2010; Henle et al., 2011).

Current invasive recording systems suffer from substantial infection risk due to percutaneous wires (Lu et al., 2012; Lee et al., 2013). Several groups are working on wireless solutions for MEA (Chestek et al.,. 2009; Sharma et al., 2012; Schwarz et al., 2013; Yin et al., 2013) and ECoG (Charvet et al., 2013; Matsushita et al., 2013) to solve this issue. For ECoG, epidural recordings are being investigated. In primates, stable impedance and signal to noise ratio was obtained for 15 months without any visually detectable effects on the dura mater or the underlying brain. Signals from 3 mm apart could be modulated independently. Signal loss compared to subdural recordings is substantial, but does not hamper classification (Moran, 2010; Torres Valderrama et al., 2010; Ritaccio et al., 2011).

New ECoG grids, ranging from closely spaced electrodes to actual high-density micro-electrodes have been developed recently. Using these grids, more information can be extracted from a small patch of cortex, allowing more degrees of freedom (Wang et al., 2013). To make optimal use of the detailed organization of the cortex, even denser grids are necessary. These could be based on new, flexible materials with unique properties, allowing a wide range of electrode configurations (Ritaccio et al., 2011). It will take considerable financial and time investments to obtain regulatory approval for longterm implantation of these grids in humans. Other attempts to maximize the number of degrees of freedom extracted from ECoG recordings are based on optimizing decoding algorithms (Liang & Bougrain, 2012; Do et al., 2013) and spatiotemporal features for decoding and control (Kubanek et al., 2009; Onaran et al., 2011; Mugler et al., 2014a).

Recent non-human primate studies demonstrate the possibility to restore grasping with a temporarily paralyzed limb using muscle stimulation (Shih et al., 2012; Lu et al., 2012). In addition, efforts are ongoing to induce somatosensory perception by electrical stimulation of the cortex (S1) (Schultz & Kuiken, 2011; Lee et al., 2013).

8.3 Industry

For a general picture of the BCI sector and related domains, we identified, classified, and analyzed current BCI and potential BCI-related industry stakeholders from all over the world. The majority of these companies are based in Europe and North America. Market research methodology was used to identify, collect, validate, and further analyze the most relevant input data. The gathered industry input data has been qualitatively evaluated in order to assess the market impact, and to develop guidelines and recommendations towards a technology transfer plan for the current BNCI Horizon 2020 roadmap.

8.3.1 BCI-related industry stakeholders

The final BNCI industry ecosystem database is composed by a sample size of 148 BCI-related industry stakeholders. Following homogeneity criteria in terms of target users and market segments, we grouped these 148 BCI-related industry stakeholders into the following sectors:

1. the ***BCI sector*** with 65 companies;
2. the ***automotive and aerospace sectors*** altogether composing 7 BCI-related industry stakeholders;
3. the ***medtech, rehabilitation and robotics sectors*** altogether composing 46 BCI-related stakeholders;

4. the ***entertainment and marketing sectors*** altogether composing 10 BCI-related industry stakeholders; and
5. the ***technology sector*** comprising 20 BCI-related industry stakeholders.

Figure 2 elucidates the percentage distribution of company size (i.e. company type) per group sector, depending whether the industry stakeholder is a large enterprise, an SME, a public entity (non-profit) or a startup. We used the corresponding EC company definitions for our classification, that is, an SME is an independent company with less than 250 employees, an annual turnover less or equal to 50 million €, and balance sheet less or equal to 43 million €. Further, we considered a company as being a startup if it was founded less than 4 years ago (i.e. 2010). Generally, a public entity is a non-profit institution, and large enterprises are mostly multinational companies.

For each BCI-related industry group sector, Figure 2 shows the proportion (%) of companies classified by company size. The results obtained from analysing the company size from our BCI industry ecosystem show that the BCI sector, the entertainment and marketing sectors, and the medtech, rehabilitation and robotics sectors are mainly comprised by SMEs. The largest proportion of startups (14%) can be found in the BCI sector, whereas the largest percentage of large enterprises can be found in the automotive and aerospace sectors, followed by the technology sector. Public or non-profit industry institutions are mainly found in the aerospace sector, the technology sector, and the BCI sector.

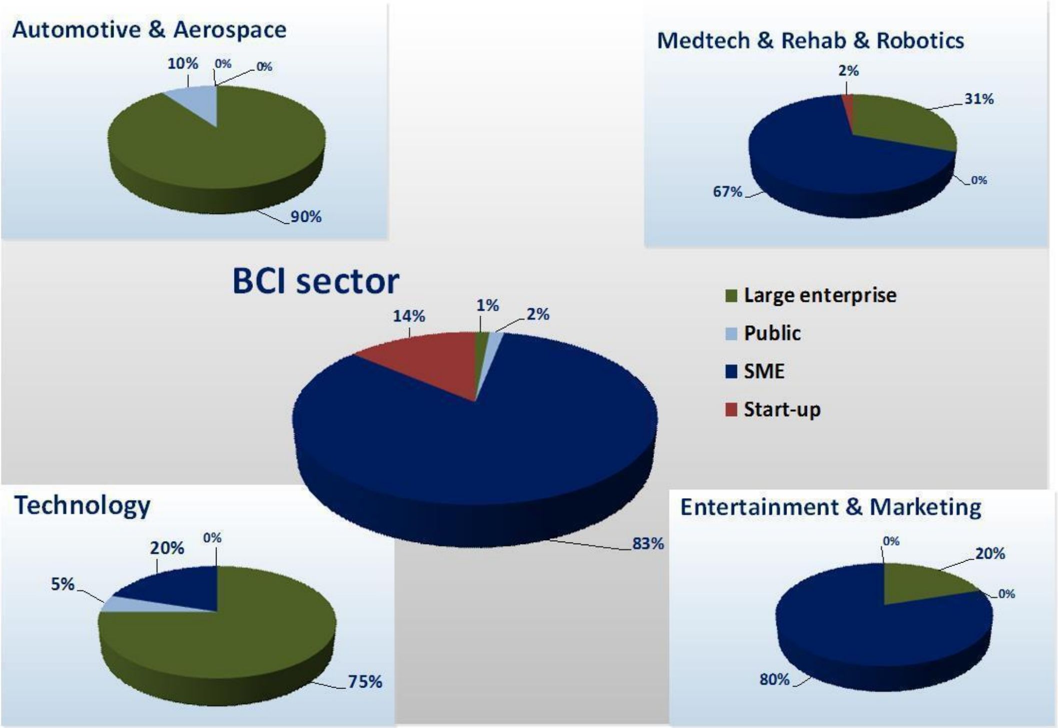


Figure 2: Company size of the BCI and BCI-related industry stakeholders arranged by group sectors. Percentage of companies classified by company size: large enterprise; public (non-profit); small to medium companies (SME); and startups.

8.3.2 The BCI sector

From our analysis, 65 industry stakeholders were directly associated to the BCI sector. Most of these BCI companies (~83%, Figure 2) are Small to Medium Enterprises (SMEs) (see Annex for details). Many stakeholders offer or use more than one signal type, but EEG is the most preferred one. EMG and ECG are robust, cheap and non-invasive, which could be the reason why they are found on second and third place. Invasive electrical signal acquisition of the brain comprises electrocorticogram (ECoG), local field potentials, multi-unit recordings and, single-unit recordings. The invasiveness, and thus the practical problems if used, might be one reason why only 6% of the stakeholders use invasive signals. Other potential BCI-related signals, such as near infrared spectroscopy (NIRS) and respiration rate (for hybrid BCIs) have about the same share as invasive electrocorticography. The remaining analyzed BCI-related signals sum up all other signals that are used, like fMRI or galvanic skin response. Some examples of existing BCI market applications are the following: g.tec intendiX is a P3-based device that enables the user to sequentially select characters from a keyboard-like matrix on the screen just by paying attention to the target for several seconds. The g.tec mindBEAGLE system is a tool for consciousness assessment and communication for patients with disorders of consciousness. Brainfingers (a trademark of Brain Actuated Technologies) uses a headband to detect facial EMG, EOG, and brainwaves. Based on these signals, a user is able to control a computer mouse. Mindflex is a toy by Mattel that is controlled by BCI technology. The aim is to control a ball by changing the level of concentration. Neurowear’s Necomimi may be described as a gaming, but also communicating tool: the cat’s ears reflect the current feelings of the user, e.g. interest, shame, or happiness.

9 Application scenarios

Based on the BCI definition from Wolpaw & Wolpaw (2012) and the related application scenarios, we aim at introducing a tentative match among these application scenarios and new emerging opportunities in synergy fields. Potential key BCI market applications in relation to these identified synergy fields and industry sectors are illustrated in Table 2. In this sense, the ***replace*** application scenario includes communication & control, and also AT & smart home control market applications. For this aim, a BCI device ***replaces*** the natural output that has been lost as a result of injury or disease (e.g. communication, motorized wheelchair control, in-house light control, and bed position control). Health & neurofeedback applications overlap also the ***replace*** scenario, i.e. BCI applications specifically addressed to in-hospital patients with disorders of consciousness. Nevertheless, health & neurofeedback market applications most directly relate to both the ***restore*** and ***improve*** application scenarios. In the former, a BCI ***restores*** lost natural output (e.g. a person using a BCI to stimulate a paralyzed muscle via electrodes to move the limbs). In the latter, a BCI device aims at ***improving*** natural CNS output. (e.g. a person using a BCI to detect and enhance signals from a damaged cortical area in order to improve functions that have been impaired).

The widest scope within the identified key BCI market applications can be found in the ***enhance*** application scenario, where a BCI device ***enhances*** natural CNS output (e.g. a person using a BCI to monitor attention level during a demanding task). Here, nearly all identified application groups in Table 2 could be considered. Similarly, though more futuristic, the ***supplement*** application scenario, where a BCI device ***supplements*** natural CNS output (e.g. a person who is using a BCI to control a third robotic arm and hand) would mostly be suitable for AT & smart home control, safety & security and entertainment & gaming market applications. Finally, the fact of using a BCI as a ***research*** tool can give rise to more novel market applications not identified so far.

Table 2: Key BCI market applications in relation to application scenarios, synergy fields and industry sectors.

Application scenario	**Market application groups**	**Key BCI-related market applications**
replace *enhance*	communication & control	affective computing, interface to smartphones, multimodal PC interaction, apparel and accessories (**technology sector**)*
restore *improve* *replace* *enhance*	health & neurofeedback	prevention, diagnosis, therapy, monitoring, cognitive and motor rehabilitation , addiction disorders, wellness, nutrition (**medtech & rehab & robotic sector)***)
replace *supplement*	AT & smart home control	ambience intelligence, domotics, elderly care, geriatric hospices (**technology sector**)*
enhance *supplement*	safety & security	public transport (**automotive and aerospace sectors**)*, fire brigade, police, process controls, banking security, agriculture
enhance *supplement*	entertainment & gaming	educational games, serious games, cinema, art, sports, meditation techniques (e.g. yoga, tai chi) (**entertainment sector**)*

enhance supplement	neuromarketing & finance	market research, decision-making studies and support (**marketing sector**)*, neuroeconomics, stockbrokers
research	R & D	real-time analysis, signal acquisition, signal processing, output devices, BCI-hybrid interfaces, artificial intelligence & machine learning

*Relates to identified synergy fields and industry stakeholders in potential BCI-related sectors

9.1 Replace

9.1.1 Mobility with a brain-controlled wheelchair

End users who show no contraindications to using a powered wheelchair and who are able to master the use of the multimodal BCI will be able to enjoy a degree of mobility independence through the use of a brain-controlled wheelchair. Typical scenarios may include: (1) performing a range of basic wheelchair skills (such as turning left and right, driving forward, etc.), which forms a basic repertoire from which most typical wheelchair maneuvers are composed. This scenario will draw inspiration from the Wheelchair Skills Test, which is used to both teach and assess potential wheelchair users' abilities; (2) Navigating from one room to another, passing through narrow doorways and corridors. This could be done in a hospital scenario or in the user's home; (3) Navigating to specific places to perform typical activities of daily living, such as docking to the kitchen table or to a computer desk, or driving in/out of an elevator or up/down a ramp.

9.1.2 Bionic arm with sensory feedback

Andy is a 39-year old tattoo artist who considers many rock stars as his faithful clients. Due to a motorcycle crash about two years ago, he has lost his right hand. In the first months after the crash, Andy was quite depressed because he was afraid he could never perform his job again. After having recovered from the other injuries, his surgeon mentioned the possibility to obtain a brain-controlled bionic arm that also provides sensory feedback to the brain. Although Andy was quite scared of brain surgery in general, he chose to have the implant. He received two multi-electrode Utah arrays: one in the primary motor area of the hand, and one in the primary sensory area of the hand. Small subcutaneous wires connect the electrodes to an amplifier/stimulation device that was implanted subcutaneously in the chest area. Andy has also received a very fancy bionic arm that communicates wirelessly with the subcutaneous device. It took him quite a few months to learn how to control the bionic arm correctly, but he is very proficient now. He has learned that just by attempting to make the same movements that he would make with an intact hand he can produce the same movements with the bionic arm. On top of that, the bionic arm contains sensors that send information to the device in his chest, and from there to the electrodes on his sensory cortex. Each time the sensors of the bionic arm are activated, small currents are fed back into the sensory cortex, providing Andy with a sense of touch and grip strength. Last week, Andy has placed the first tattoo using his bionic arm. It was a simple picture, but he is confident that after even more practice, he will be able to get back to his old skill level.

9.1.3 BCI-controlled leg orthosis

Jacob is a 64-year old construction worker. Although he enjoys his work, during the last years he was looking forward to his retirement and the long walks in the forest he wanted to make when he would have more free time. Unfortunately, he was hit by a subcortical stroke last year. Jacob is happy to be still alive, but is very sad that he permanently lost the function of his left leg due to the stroke. Despite physical therapy, he still is unable to walk and uses a wheelchair to get around. He has tried to take the wheelchair to the forest, but the bumpy paths made a nice tour impossible. His therapist mentions the possibility of a BCI-controlled leg orthosis. Jacob immediately likes the idea, consults a neurosurgeon, and a few weeks later, he is scheduled for surgery. During surgery, a small high-density ECoG grid is implanted over the primary motor area controlling the left leg. Thin wires connect the electrodes to a subcutaneous amplifier and transmitter. This device wirelessly sends the relevant signals to the orthosis, which looks like a thin cast, and which is strapped around his waist, hip, and left leg. A few weeks of rehabilitation therapy are needed to teach Jacob how to use the BCI-controlled leg orthosis. Every time he correctly imagines taking a step with his left leg, neuronal signals of the left leg area are decoded and translated into signals that make the orthosis take a step. After a few more weeks of practice at home, Jacob decides it is time for the first forest hike since his stroke. He enjoys every minute of it.

9.2 Restore

9.2.1 BCI-controlled neuroprosthesis

Steve is a 39 year old construction engineer. His favorite pastime is painting, and he spends a lot of his money on painting classes and painting equipment. Two years ago, he was working at a construction site and a wooden beam hit him directly on his neck. A helicopter quickly brought him to a trauma center, where they diagnosed a complete spinal cord injury at the fourth vertebra. One year later, Harry is discharged from the rehabilitation center and returns back home. He is unable to move his legs, and he cannot fully move his elbow and his fingers to grasp objects.

During one of his periodic rehab stays, Steve meets Katie, a rehabilitation therapist. She works in the rehab center to apply neuroprostheses. After filling out a form about his medical status, Steve schedules an appointment with her again. At this meeting, Katie runs a test battery to assess Steve’s muscle activity, arm movement, and brain patterns, among other parameters. “The brain patterns will be used to initiate grasp patterns”, Katie explains. She shows Steve a stylish and very unobtrusive EEG cap, which he will wear while operating his neuroprosthesis. At the end of the day, Katie collected all necessary data to start preparing a neuroprosthesis to restore hand grasp function for Steve.

A couple of weeks later, Steve receives his new neuroprosthesis. Katie instructs him how to use it in an individual training program. First, Steve starts with very crude movements, and he gets feedback about the process directly on his iPad. He has to think of moving has hand to produce unique brain patterns that can be detected by the neuroprosthesis. The training program will adapt itself to Steve’s progress, and will include finer movements as he gets better in controlling his device.

Half a year later, Steve uses his neuroprosthesis every day. He is able to grasp and hold simple objects, and he even started to paint again. He is also back in his old job as a construction engineer, where he now focuses on work he can perform solely on a computer. Occasionally, he even visits construction sites, and that’s when he misses the time before his accident the most. Otherwise, he is very happy with his new situation in general and his neuroprosthesis, which made all of this possible, in particular.

9.2.2 Cochlear implant adjustment

Alfred was born with a severe sensorineural hearing loss in the year 1991. He was quite lucky, because his parents and the doctors detected his hearing loss very early. The doctors suggested a new technology to them: a cochlear implant. A cochlear implant is a surgically implanted electronic device that restores the ability to hear. With 9 months, he got his first cochlear implant. Due to the fact that the technology is very well tested and robust, 25 years later his implant still works. However, one problem has always existed: it is very hard to find the correct settings for the implant. For example, sometimes he hears just low frequency tones, sometimes just high, or a special frequency band is louder than another. However, after the latest update of the implant, it has a novel feature. The settings of the implant are automatically adjusted to the user's needs by a brain-computer interface (BCI). An electrode on the external part of the implant continuously measures the activity of his brain and detects errors of the implant.

Two weeks after the upgrade, Alfred went to the opera. Suddenly, when the main actress was singing the aria of the Queen of the Night, Alfred heard a crackling noise, and one moment later he heard just the low tones, and a few seconds later his normal hear ability was restored again. What happened? The novel BCI adjusting system had detected that Alfred had a problem with his implant. Then the system tried different predefined settings and detected via BCI whether the settings worked for Alfred or not. When no distraction of Alfred in the brain signal was detectable, the correct setting was found.

9.2.3 Spinal cord stimulation for reach and grasp

Paul is a 24-year old man who suffered from a spinal cord injury due to a diving accident. At the moment, he is paralyzed from the neck. He is perfectly able to speak and controls a joystick with his mouth to steer his wheelchair and control his computer. He is very unhappy with this level of functioning, and with the fact that he needs to do everything with his mouth. He feels very dependent on others and has a strong desire of regaining some level of arm and hand function, so that he can control his wheel chair and computer with his hand, and for example also eat by himself, without someone feeding him. His neurosurgeon tells him about an implantable BCI system that would allow him to control his own arm and hand muscles. Paul is immediately very interested in this option and decides to go for it. During surgery, a 96-channel Utah multi-electrode array is implanted in the primary cortex of the hand and arm. The array is connected to an implantable amplifier/stimulator, which is implanted subcutaneously in the chest area, from which fine wires continue to the spinal cord and are connected to the relevant nerves controlling hand and arm function. After recovery from surgery, Paul follows a tailored training program that allows him to control his own arm for reach and grasp functions. He only has to attempt making the movement he desires, and then the brain activity patterns are translated into a stimulation sequence for the spinal cord nerves, producing movement of his arm and hand. A few weeks later, Paul returns home and is very happy with his increased level of independence. Especially the ability to eat by himself makes a large difference.

9.3 Enhance

9.3.1 A hybrid BCI for the use in an adaptive learning environment (neurotutor)

Adaptive learning environments enable us to provide optimal learning conditions for each single student. Current systems are already able to detect different cognitive and emotional user states. Unfortunately, such systems usually use behavior that can be directly observed, like speech and facial movements. This kind of indicators are not always present and can also be manipulated quite easily. A hybrid BCI could add functionality and reliability to the existing systems with an implementation following a passive BCI approach.

9.3.2 User experience in computer games

Sarah is quite excited today, because she bought the new X-Thought device for her next-gen game console. The device is able to interpret her thoughts and feelings during her daily gaming session of Dark Souls III. Sarah opens the wrapping and a spider-like device unfolds. She puts the device on her head and plugs it to her console.

She is thrilled by the enclosed demo game, which introduces her to the features and the functionality of the X-Thought device. Sarah quickly plays through the demo game (as a gaming veteran, the tasks are no match for her experience).

Finally, she starts playing her favorite game: Dark Souls III! As she slashes her way through hordes of evil monsters trying to block her way, she barely notices the subtle changes in volume of the effects and the changing gloom of the in-game graphics. At last, she comes under increasing pressure as some unexpected enemies try to get to her from the side. "This wasn't expected", she thought and tries to focus intensely on these opponents. Suddenly, her in-game avatar does a new unexpected move she has never seen before, and a fireball blasts her foes away. In the right corner off the screen a small translucent X-Thought logo blinks and an in-game voice yells "X-Thought Fireball".

"Wow, I didn't expect that! What a cool device!", says Sarah to herself and continues her in-game tour.

9.3.3 Automatic emergency calls

Elsa is an elderly woman who uses an EEG-based BCI in her daily life. One day, she was rushing to the kitchen to stop her food from burning and tripped over the carpet. When she fell, she bumped her head on the kitchen table and lost her consciousness.

The loss of consciousness and a sudden change in Elsa’s heart rate triggered an emergency call to the ambulance, fire brigade, and police.

Seven minutes later, several trucks are in front of her door and after nobody answered it, the police gave the firefighters permission to forcefully open the door. After the ambulance took emergency measures, Elsa is transported to the nearest hospital as soon as possible.

With the use of this technology it was possible to keep the time between the accident and emergency medical procedures below 30 minutes, which possibly saved Elsa from a brain hemorrhage.

9.4 Supplement

9.4.1 BCI-controlled robot assistant (telepresence)

With a cracking noise the little tin can (at least that’s how Laurie calls him) runs against the door frame of her room. “Well, that will leave a dent”, Laurie sighs. Among all the changes in the last couple of months since the accident, the little robot is at least one of the more enjoying ones. Since her accident, Laurie can't move her limbs anymore, even turning her head seems rather difficult. Her parents organized this little robot assistant in order to give her a little degree of freedom. The "tin can" on wheels is able to perform rudimentary tasks, like pushing switches or driving around the house. For controlling the tin can, Laurie does not need her limbs - she is able to control it only by thought.

At the beginning, it was hard for her to learn the mental tasks for controlling the little helper, and the spider-like device on her head was uncomfortable. But after a few weeks she got the hang of it - and it became common for her. Most of her room is equipped with high-tech features: a voice-controlled TV set and phone, even the bed can be adjusted with her voice. But all these things are just assistive devices - the little tin can however did give her something else: fun!

The robot is equipped like a little multimedia center: camera, microphone, and screen. She can drive it outside her room and can see what's going on around the family. Finally, she manages to get past the door frame and finds her mum in the kitchen. "Hey Laurie, everything fine?", her mum asks, always a little on the worrying side. "Yep", she answers through the microphone, "just checking." She directs her little tin can to the french window which leads outside in the family garden. “The new offroad wheels for the robot will arrive on Thursday", she remembers. "Finally, we can have a look outside, little tin can."

9.4.2 Multi-brain computing

A few rescue workers are working in a collapsed building. Scattered through the building, they individually notice signs of an imminent collapse, but due to ambiguous observations and their occupied attention, they find it difficult to integrate their knowledge and identify the threat. They die. In this example, the collective minds of the rescue workers contain the knowledge to identify the thread. Theoretically, the uncertain observations and knowledge of the soldiers can be integrated using contextual (e.g. spatial) information with a multi-brain BCI, to identify threads that the workers could not identify individually.

In general, multi-brain computing would be useful when communication between users is limited, for example because communication is already in use for other tasks, it is too slow (split-second decisions), communication is between a human and a computer, or when non-experts are not familiar with the necessary jargon or communication procedures (e.g. civilians can identify threats for professionals without extra training).

Other examples might include:

1. Making decision in a group when voting is not adequate (too many options to choose from).
2. Finding knowledge and experts in an organisation.
3. Integrating witness reports in crime investigation accounting for uncertainty.
4. Implicit feedback for tiny details that would otherwise not be reported (e.g. every sentence in a meeting).
5. use humans as semantic sensors, the rescue workers example is an instance of human sensors identifying threads.

9.5 Improve

9.5.1 Hybrid BCI-driven FES system for upper limb rehab after stroke

Francesco is a 41-year-old engineer from Rome. He had a hemorrhagic stroke in the right hemisphere involving the fronto-temporo-parietal lobes. One year after the event, he is able to walk with a cane, but he has severe deficits in the left upper limb (proximal movements only are spared, with moderate flexion spasticity). He is undergoing a BCI-based rehabilitation therapy in addition to standard rehabilitation (as outpatient). During the BCI session, he is seated in a chair with an EEG electrode cap on his head. On his left arm he has electrodes recording muscular activity from four muscles (extensors and flexors in the forearm, biceps and triceps in the arm). Also, he has a muscular stimulation device (Functional Electric Stimulation, FES) which provides contraction of extensor muscles in the forearm to open his hand. During the training session, he is asked to attempt opening his hand (auditory cues and a therapist nearby guiding him in the exercise); the EEG electrode cap records his brain activity and recognizes the intention to move (desynchronization on motor related electrodes on the affected hemisphere); the electrodes on his arm record muscular activity and detect whether his attempt to extend is generating unwanted contraction in flexor muscles (biceps and finger and wrist flexors); if both the EEG and the muscular activity are correct (both are under the therapist's supervision on a computer screen), the FES system activates to extend his fingers and open his hand.

9.5.2 Epilepsy

Susan is a 30 year old woman with severe frontal cortical epilepsy. Her seizures come without warning signs, and when she gets a seizure, she falls on the ground, often injuring her head and face, sometimes severely. She has tried multiple types of anti-epileptic drugs, but none of them has the desired effect. Using non-invasive methods, such as EEG, MEG and fMRI, it has been demonstrated that the source of her epilepsy extends into eloquent cortex, which means that surgical resection will not be possible. Her neurologist explains a third option to her: a small, implantable device that detects when a seizure is coming, and which is then able to provide a warning signal and at the same time produces a specific electrical stimulation sequence in an attempt to stop the epileptic discharges before they are full-blown seizures. Susan chooses to go for this option. During surgery, she receives two strips of four electrodes covering the lateral part of the left middle frontal cortex. Small wires connect the electrodes to a miniature sensing/stimulation device that is firmly fixed to the skull. Each time the neuronal activity in the area covered by the electrodes has the characteristics of a seizure onset, the sensing/stimulation device will produce a very small electrical pulse that Susan can feel as a clear tickle on her scalp at the device, warning her to sit down quickly. At the same time, the device will produce electrical pulses at the site of the electrodes in order to stop the seizure from developing further. A year after the implantation, Susan considers her quality of life greatly improved. Although she sometimes still has a seizure without a warning sign and without the neurostimulator stopping it, the number of seizures has decreased dramatically, and most of the time, she is able to sit down in time and thereby prevent injury.

9.5.3 Cognitive stimulator

“Why can’t I remember again in which hotel are we staying?” Jürgen’s colleague realised that his partner (63 years old) may need help for attention, day-to-day memory and remembering, after he got lost in a business trip to Paris, a well-known city for both of them. Mild cognitive impairment (MCI) is the term used for this condition. For some people diagnosed with MCI, memory loss will be the first sign of Alzheimer's disease. Currently, there is no cure for Alzheimer's. But drug and non-drug treatments may help with both cognitive and behavioral symptoms.

There is some evidence that exercising the mind as well as the body can also help reduce the risk of MCI and dementia. Intellectually stimulating leisure activities such as card games or crossword puzzles in mid-life may allow the brain to build up a 'reserve capacity' that can help prevent or delay the onset of dementia. Keeping socially active may also help to reduce risk. To keep Jürgen's motivation & attention alive, his GP lend him the new BCI cognitive stimulator, with specific and enhanced EEG methods that capture Jürgen's attention and re-address him again to his card-game, crossword puzzle or cognitive rehabilitation task. Jürgen uses the BCI stimulator at home. The device wirelessly sends gathered input data to his smartphone, and presents real-time visual stimuli based on self-learning and fuzzy-logic algorithms that often help him to remember things and tricks for his games. Now, thanks to an ergonomic and fashionable outlook of the BCI stimulator headband, Jürgen wears it quite easily while playing computer games, or even, table-games with his former colleagues. Though now in retirement, he will visit Paris once again for a week. Of course, all by himself.

9.6 Research

9.6.1 Research Tool for Cognitive Neurosciences

Silvia is the head of the Institute of Cognitive Neuroscience at her university. One of their research areas is the investigation of "decision making and free will". An aspect of their research is to question "when is a decision done". Silvia knows that Brain Computer Interface technology could offer completely new possibilities to drive their work: using BCI tools one could decode intentions and decision making in real-time and hence also interact with the subject.

Recently she got new national grant on topic "when is a decision done". None of her staff is expert in BCI technology, and it would take some months to hire new staff and to let them develop new BCI tools. On a Neuroscience conference in the US, she met the CEO of a startup company (called X-BCI) offering complete BCI ecosystems. Their software platform is interfaced to the hardware of some of the worldwide leading BCI hardware maintainer. Thus, X-BCI offers a complete BCI bundle, that comes with the soft- and hardware that fits the customer's demands. If a BCI paradigm could not be implemented with the standard toolkit, X-BCI would do the additional software adaptations and implementations. Their team of experienced programmers and their expertise in BCIs would guarantee fast solutions and full support, such that the Research team in Silvia's institute doesn't need any programming expertise.

In her grant proposal Silvia explained the necessity of a complete BCI toolkit. The BCI system can be purchased in a bundle with additional IT service by X-BCI, with X-BCI doing the programming work which is necessary to setup the experiments. The reviewers of the proposal agreed to that proposal and the project was approved.

9.6.2 Medical exams

Many medical examinations focus on the relation between stimulus presentation and perception, e.g. visual field test, auditory perception, and often the examined person is required to indicate whether (and how, where, etc.) a stimulus was perceived. A BCI could automate this process by modulation stimulus presentation depending on recorded brain-signal activity. The result would be a fully automated determination of the user's perceptual abilities.

9.6.3 Adaptive neurofeedback BCI training application

A number of nervous system disorders might demonstrate themselves with simultaneous cognitive and motor impairments (e.g., Cerebral Palsy, Amyotrophic Lateral Sclerosis). Besides preventing the use of conventional AT, this symptom combination also renders common BCI paradigms for communication and control ineffective, as end-users are incapable of following the paradigm-dependent training instructions compatible with the supervised machine learning principles conventionally employed. On the other hand, the possibility of learning to modulate a variety of brain signals through operant conditioning, neurofeedback-based approaches, where explicit instructions can be spared, has been demonstrated in both animal models and human individuals. Operant conditioning BCI training is, however, associated with extremely long training periods, while there currently also exists large uncertainty regarding the responsiveness of different brain correlates (i.e., EEG brain-rhythm spatio-spectral characteristics) to this type of training, and the extent to which optimal correlates are subject-specific. Enhancing BCI neurofeedback training with adaptivity along with suitable feedback representations could allow the gradual identification by the BCI of the most responsive brain activity, thus considerably reducing the required training time and boosting the training success rates despite the cognitive impairments. Successful training of the sorts described hereby (e.g., down- or up-regulation of different brain-rhythms) could provide a general unary, binary or even multi-functional control channel. The latter can be subsequently employed for the control of a variety of interfaces and brain-actuated devices (spellers, wheelchairs, smart-home environments).

9.7 Recommendations

9.7.1 End users

Will be available in the first public draft of the roadmap.

9.7.2 Research

When asked about the bottlenecks of BCIs, respondents of our Researchers' Questionnaire agreed that (long-term) system durability and (long-term) system performance are still sub-optimal for both invasive and non-invasive systems, although for invasive systems, system durability seems to be a more important issue (63% vs. 51% agreed or strongly agreed), whereas system performance was more often selected as a bottleneck for non-invasive than for invasive systems (73% vs. 53%). This could be related to insufficient evidence about (long-term) durability (invasive 53% & non-invasive 38%) and performance (invasive 63% & non-invasive 48%).

Non-invasive BCI systems are considered safe by a large majority (78%) of respondents, but also invasive applications are considered safe by 50% of the respondents (34% considered the risks of invasive systems to be too high). Especially for invasive BCI systems, more evidence should be gathered about the risk/benefit ratio for the users (63%) and the (long-term) system safety for the users (47% agreed or strongly agreed, versus 28% disagreed/strongly disagreed).

Interestingly, only a minority of researchers considers the target populations as being too small for commercialization of both BCI systems (invasive 0% & non-invasive 31%) and many respondents reported they see clear advantages of invasive (63%) and non-invasive (43%) BCI solutions over non-BCI solutions. In that sense, a remarkable bottleneck for both techniques is that potential users do not actually seem to know about the existence of both invasive (72%) and non-invasive (66%) BCI tools. The price of both BCI systems was considered by many as being too high (invasive 53% & non-invasive 45% agree or strongly agree) and the equipment still too complicated for home use (invasive 56% & non-invasive 70%). Invasive and non-invasive BCI systems were considered too large (44% & 42%), cosmetically unappealing (53% & 51%), and to not meet the wishes and needs of end users (56% & 61%).

Respondents suggested that both invasive and non-invasive BCI research should focus on the development of better hardware (84% & 90%) and software (78% & 83%) to improve system performance. In particular for invasive BCIs, implantable multi-channel amplifiers with a long battery life are considered essential for the future (84%).

Respondents expressed a wish for clinical trials that should shed light on system performance (87% & 78%) and durability (87% & 67%). Clinical trials to establish safety seem more important for invasive (81%) than for non-invasive BCIs (46%). Clinical trials should also demonstrate the efficacy of the devices (75%) and the risk/benefit ratio for end users (78%) of invasive in comparison to non-invasive BCI systems. More research is needed according to respondents in order to identify the wishes and needs of end users (87% & 60%) that use both invasive and non-invasive BCI systems.

9.7.3 Industry

In line with future opportunities in the above identified synergy fields and the key BCI market applications specified in Table 2, BCIs applied for communication & control aim to *replace* or *enhance* natural CNS output. This matches the **technology** sector where apparel and accessories industry stakeholders joining the computer and telecommunication industry may play a fundamental role. BCIs applied for health & neurofeedback aim to *replace, restore, enhance* or *improve* natural CNS output by replacing lost function, modifying brain activity, guiding neural plasticity, increasing the efficacy of rehabilitation, or as a diagnostic tool. In this sense, future key BCI market applications may influence the **medtech**, **rehabilitation**, and **robotics** sectors. BCIs applied for AT and smart home control aim to *replace* or *supplement* natural CNS output. Most BCI synergies will be in the assistive technology and domotics industry, here also part of the **technology** sector. BCIs applied for safety & security aim to *enhance* or *supplement* natural CNS output. Here, the **automotive** and **aerospace** sector will benefit from the BCI synergies. BCIs applied for entertainment & gaming and also neuromarketing & finance aim to *enhance* or *supplement* natural CNS output, clearly influencing **entertainment** and **marketing sectors.**

As ongoing research looks promising, the impact of BCIs on our society is expected to increase in the near future thanks to new, emerging opportunities in identified synergy fields. Expanding into new markets offers even more growth opportunities than expanding into related markets. The further a company departs from its current markets, the greater the number of opportunities. But it is also true that the further a company travels from what it knows, the greater the risk. The difference between a related and an unrelated new market can be a matter of perspective, though. Based on the identified key BCI market applications (see Table 2), we intend to provide a qualitative market analysis estimating their relative market growth and relative market value by 2020 (see Figure 3). This is also an approach to qualitatively assess potential future market opportunities for SMEs and other type of industry stakeholders in the BCI and related emerging markets. The estimated relative market growth and relative market value analysis portrayed in Figure 3 is based on our evaluations, interpretations, and experience.

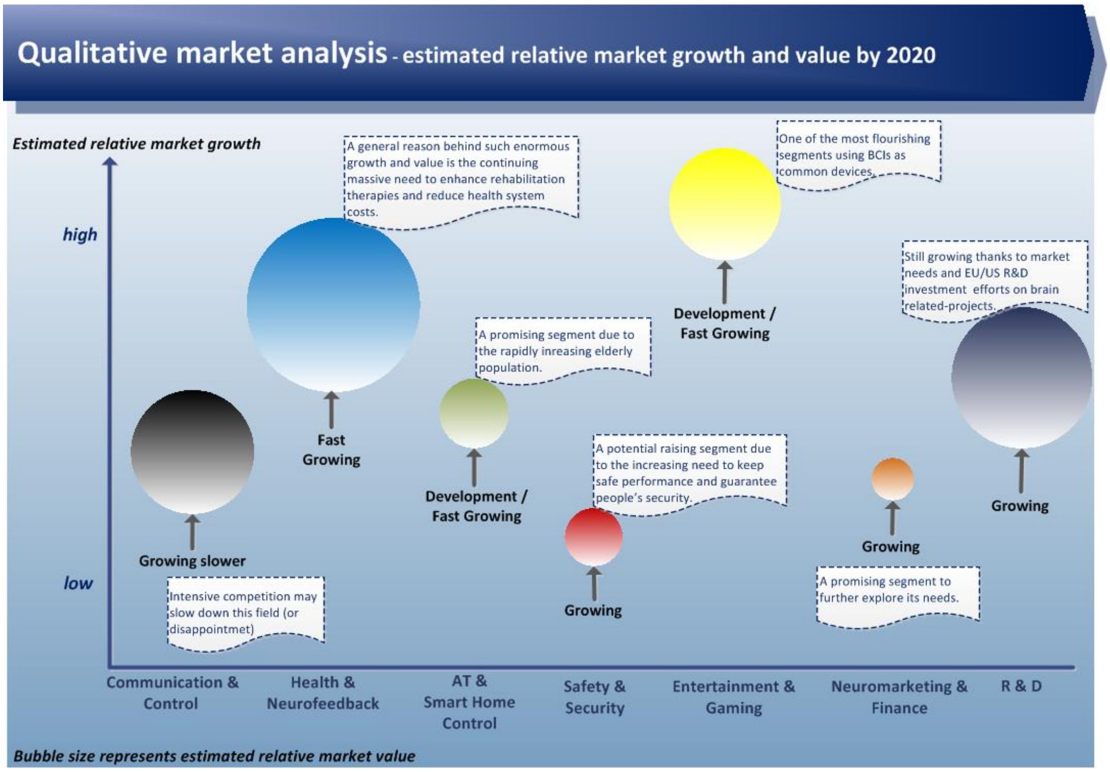


Figure 3: Qualitative market analysis on estimated relative market growth and relative market value by 2020 from the identified key BCI market applications groups.

The intensive competition in communication & control technologies, such as eye-tracking and enabling software, may slow down the growth of this conventional and most specific BCI field - but just relative to other new emerging applications groups.

In health & neurofeedback related market applications, a general reason behind such enormous growth is the continuing massive need to enhance rehabilitation therapies and preventive practices (for example to delay cognitive impairment) in an effort to reduce overall healthcare costs. The increase in life expectancy in developing countries, and the rapidly growing elderly population (especially in Western Europe and the US) will give rise to larger market opportunities in related fields in the upcoming years. Age is directly associated with stroke and dementia incidence, with age being an uncontrollable risk factor. This demographic change in the 21st century demands new strategies in health care addressed to the elderly. This framework makes health systems policies having to face several challenges concerning care for the elderly and comorbidities associated with old age. In the same line, new BCI solutions can emerge as AT & smart home control applications, thus growing faster and in parallel with health & neurofeedback related applications by the year 2020. This assumption is based on the idea that rehabilitation does not need to be restricted to the hospital, but could also take place at the patient's home. Of course, BCIs for rehabilitation and BCIs for AT are two different approaches. However, if end users get used to BCI devices "for rehab at home", this can open a window to use the same BCI device as a new way to generally access the environment. Given the right measures, BCIs can therefore be easily extrapolated to different purposes and applications in manifold settings.

On the other hand, safety & security market applications are now a real emerging segment due to the increasing need to guarantee people's security and safety in diverse environments (see Table 2). Entertainment & gaming applications are among the most flourishing segments using BCIs as common devices. Essential for its success are the availability and reduced costs of BCI gaming products. That is the reason why its estimated relative market value might be smaller in comparison to other BCI market applications. Further, entertainment & gaming applications may turn BCI shortcomings into challenges finding potential new end users. This fact may become an incentive for future industry investments that may lead to the highest estimated relative market growth (see Figure 3) for this application group. Likewise, but not yet with such a growth, neuromarketing and finance applications may be quite promising. BCIs may help to further explore consumer needs and even influence (IT)-finance, as a whole. Finally, R & D investment efforts are still required to try to answer basic science questions aiming to improve real-time processing methods and self-learning algorithms, to increase throughput rates, and to achieve higher accuracy and reliability.

10 Ethical issues

With BCI technology rapidly growing and attempting to move closer to users' in real world scenarios, ethical issues related to both medical and non medical applications emerge. Some of those issues are shared with other technologies, while others are specific to the BCI itself. To approach the ethical debate, we first analyzed previous experiences and then contextualized them in the current BCI scenarios, highlighting relevant issues emerging from the use cases (UCs).

The **Future BNCI** roadmap identified several potential ethical issues (Table 3) and drew the following recommendations: (1) foster cooperation between BNCI and ELSI (ethical, legal, and societal issues) projects, (2) new BNCI projects should be required to address ethical, legal, and societal issues, (3) communicate results to the public, (4) encourage citizen participation in BNCI projects, (5) educating PhD students on neuroethics, (6) research on BNCI use as an assistive technology with special attention to ELSI issues.

Such recommendations address the principal ethical issues covered by the recent scientific literature such as unrealistic expectations in study participants, the selection of study participants, benefits and strains of participation, BCI illiteracy, the possibility of detrimental brain modifications induced by BCI use (Grübler et al., 2014), research on BCIs as assistive technology (Carmichael & Carmichael, 2014), and communication with social media (Purcell-Davis, 2013).

Table 3: Ethical issues in BNCI use

Research & Development	**Daily life of users**	**Society as whole**
● Informed consent in people having difficulties communicating ● Risk/benefit analysis ● Shared responsibility in BCI teams	● Consequences of BCI technology for end users and caregivers ● Personal responsibility ● Personhood ● Risk of excessive use	Mind reading and privacy Mind control Selective enhancement and social stratification Mental integrity Bodily integrity

- Side-effects - Ethics in translational research from animal models to humans - Human dignity - Regulating safety - Communication to the media	therapeutic applications	

The EU BCI project **TOBI** (www.tobi-project.org) devoted a work package to ethical issues mainly focusing on benefits and risks for subjects involved in a trial (therapeutic and non-therapeutic research). The aspect of the informed consent in BCI research was in-deep addressed and other issues emerging from the use of BCI technology for rehabilitation goals were discussed.

The **NERRI** project (in progress, www.nerri.eu) addresses the issues of responsible research and innovation in the field of neuro-enhancement in order to bring the ethical debate to the different stakeholders.

The report of the **Nuffiled Council on Bioethics** (www.nuffieldbioethics.org) highlights two main risks with respect to BCIs: surgery complications for invasive BCIs and changing brain structure and functioning in non-invasive BCIs since these employ a highly repetitive use of certain pathways. The latter document proposes an Ethical Framework articulating all the ethical and social concerns with regard to neurotechnologies.

The analysis of UCs will allow identification of the main ethical issues concerning short and long term applications of BCI technology and to draw practical recommendations both for researchers and industries taking into account ethical, legal and societal aspects.

11 Recommendations

From the industry perspective, we estimated the relative market growth and relative market value of a set of identified key BCI market applications by 2020, which are likely to guide future opportunities for interfacing with industry stakeholders, target end users, potential competitors, collaborators, and some of their interrelations. For the final roadmap, we intend to develop practical guidelines and actionable recommendations plans in relation to the selected use cases, as a tool mainly to SMEs and policy makers, in order to support and promote industry innovation.

Will be completed in the first public draft of the roadmap.

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Appendix

The following pages illustrate a first design draft for our roadmap. It is intended to provide a first peak into how the roadmap could look like in its final version (the first public draft in M12 will be based on this layout). However, please completely disregard the content of this layout draft on the following pages.

THE FUTURE IN BRAIN/NEURAL-COMPUTER INTERACTION:

HORIZON 2020

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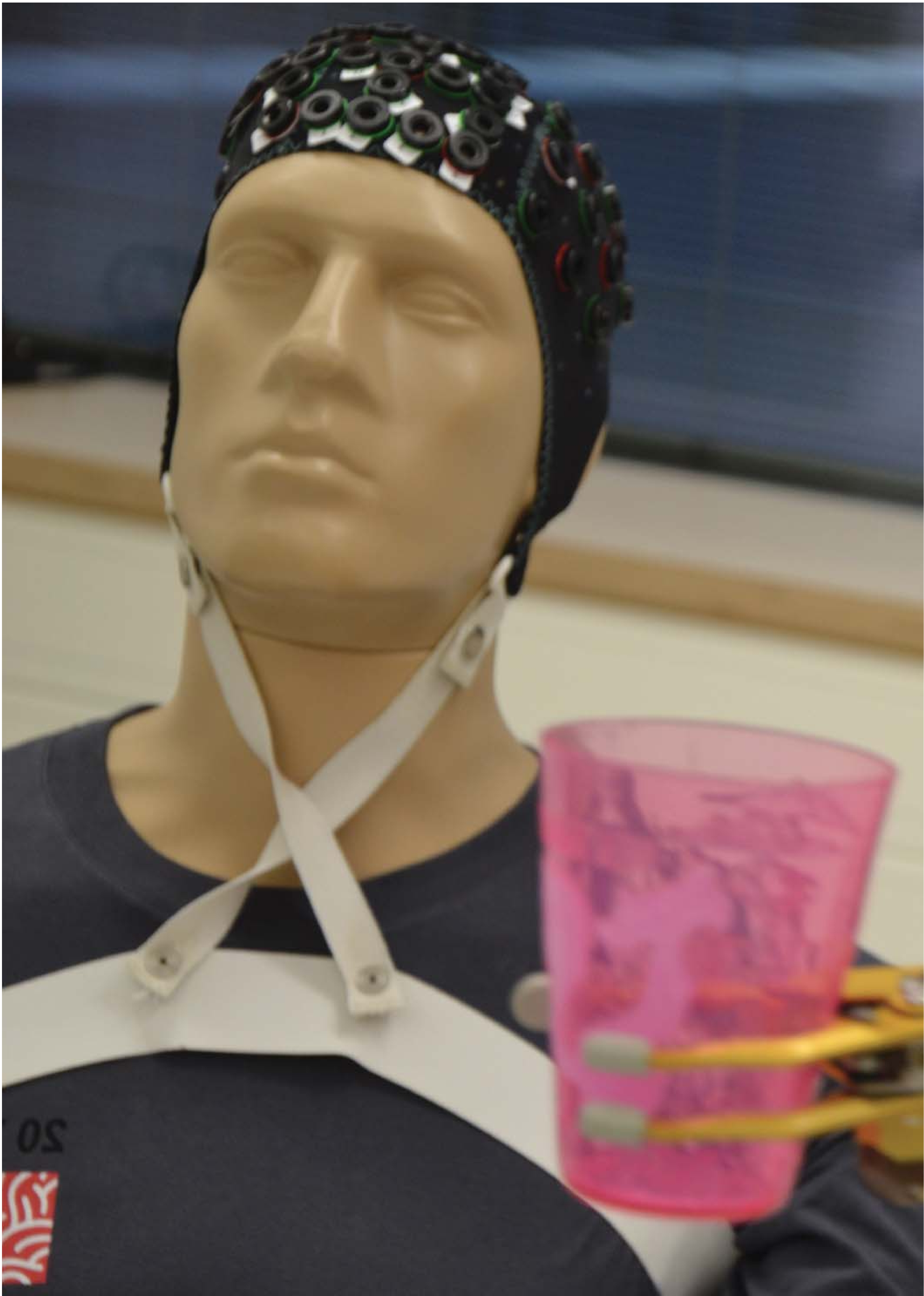

The Project

Brain-computer interfaces (BCIs) have become a popular topic for research in recent years. A BCI is a communication device which allows people to control applications through direct measures of their brain activity. A BNCI (brain/neuronal computer interaction) system extends a BCI by including other physiological measures such as muscle or eye movement signals. The number of BCI research groups around the world, peer-reviewed journal articles, conference abstracts, and attendance at relevant conferences are indicators of the rapid growth of this field. With dozens of companies and research groups actively participating in the development of BCIs and related technologies, collaboration, a common terminology, and a clear roadmap have become important topics.

To provide a solution to these issues, the European Commission funded the coordination action Future BNCI in 2010/2011. This project was the first effort to foster collaboration and communication among key stakeholders. BNCI Horizon 2020 aims to continue and improve upon the efforts initiated by Future BNCI.

A main result of BNCI Horizon 2020 will be a roadmap for the BCI field. This roadmap can support the European Commission in their funding decisions for the new framework program Horizon 2020. More specifically, we will focus on consolidating recent results in BNCI research and on investigating new BNCI activities and synergies with relevant fields. We will discuss potential new applications leading to the enhancement of functions for healthy people as well as people with motor, sensory, cognitive and mental disabilities. Furthermore, we will elaborate on key technological advancements necessary to achieve future goals, and we will touch upon other key topics including ethics, societal needs for and acceptance of BNCI systems, user-centered approaches, evaluation metrics, and the transfer of technology from research labs to the market.

BNCI Horizon 2020 will foster communication, collaboration, and dissemination of information; create public awareness of BNCIs by organizing a retreat-style conference specifically for companies and end users; actively support the foundation of an official BCI Society; create and maintain a website for researchers, reviewers, the industry, end users, and the general public; and involve both academic and industrial key stakeholders as well as end users and end user associations.

All these areas are important to further advance this still young and growing research field into a full-fledged major research discipline. A clear and comprehensive roadmap produced by BNCI Horizon 2020 will lay the foundations for, and impact on, a (continued) dominance and clear visibility of European research groups in the future. In addition, the roadmap will display opportunities, but also limitations and constraints, for the industrialization and commercialization of BNCIs.

DOI: 555-555-BNCI-H2020-WP1

The consortium

Our consortium includes eight major European BCI research institutions, three industrial partners, and two end user organizations (one of which is also a research partner).
Technische Universität Graz, Graz, Austria

École Polytechnique Fédérale de Lausanne,
Lausanne, Switzerland

Julius-Maximilians-Universität Würzburg,
Würzburg, Germany

Fondazione Santa Lucia,
Rome, Italy

Universitair Medisch Centrum Utrecht,
Utrecht, The Netherlands

Technische Universität Berlin,
Berlin, Germany

Barcelona Digital Centre Tecnològic,
Barcelona, Spain

Guger Technologies OG,
Schiedelberg, Austria

Universiteit Twente,
Twente, The Netherlands

Eberhard-Karls-Universität Tübingen,
Tübingen, Germany

Institut de Neurorehabilitació Guttmann,
Barcelona, Spain

enablingMNT GmbH,
Berlin, Germany

Objectives

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Findings

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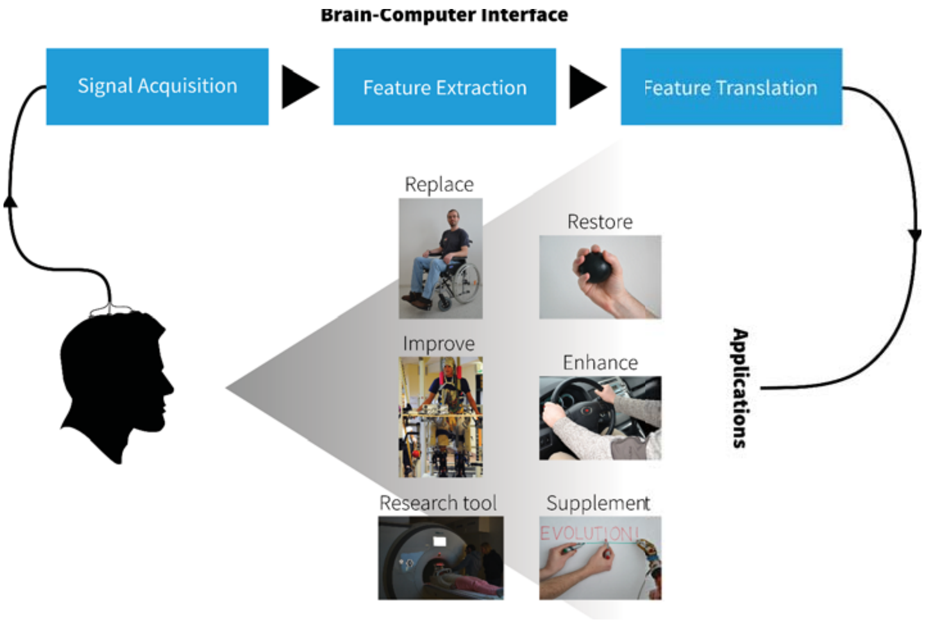

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Recommendation:

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Policy Brief

DOI: 555-555-BNCI-H2020-WP2

Research

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Objectives

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Findings

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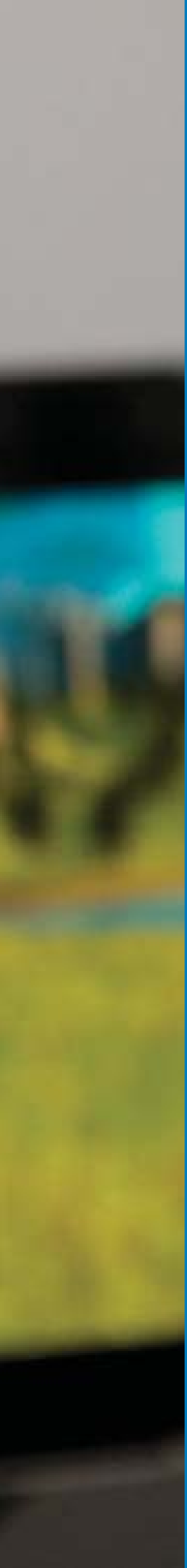
DOI: 555-555-BNCI-H2020-WP3



industry

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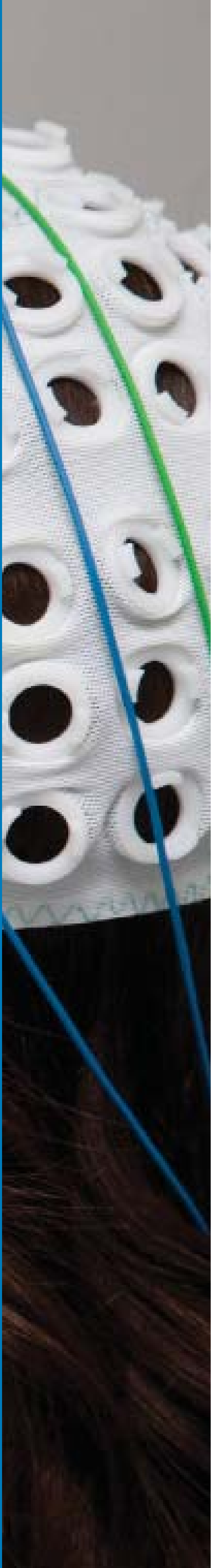

Introduction to the BNCI industry sector

introductory chapter on BNCI industry

Identification of other main industry related sectors

a brief taxonomy on other related industry stakeholders (aiming at the 6 application scenarios - tbd)
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Critical survey of the BNCI industry ecosystem

Methodology - Selection of sources
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Main industry stakeholders and their relation to the BNCI industry sector
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Analysis & Discussion
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Evolution of the BCNI industry towards 2020

R&D emerging tools & technologies [must be done with WP2]
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Identified new future groups [must be done with WP4]
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New scenarios & applications [must be done with WP2-WP4]
Potential market impact & industry adoption [must be done with WP2-WP4]
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Recommendations: what would help BNCI transfer of technology

Success stories & business cases
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Feedback mechanisms between industry & knowledge centers [must be done with WP2-WP3]
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Guidelines - to industry & policy makers
- *to industry: plans for exploitation & transfer of technology*
- *to policy makers: recommendations based on this industry roadmap*

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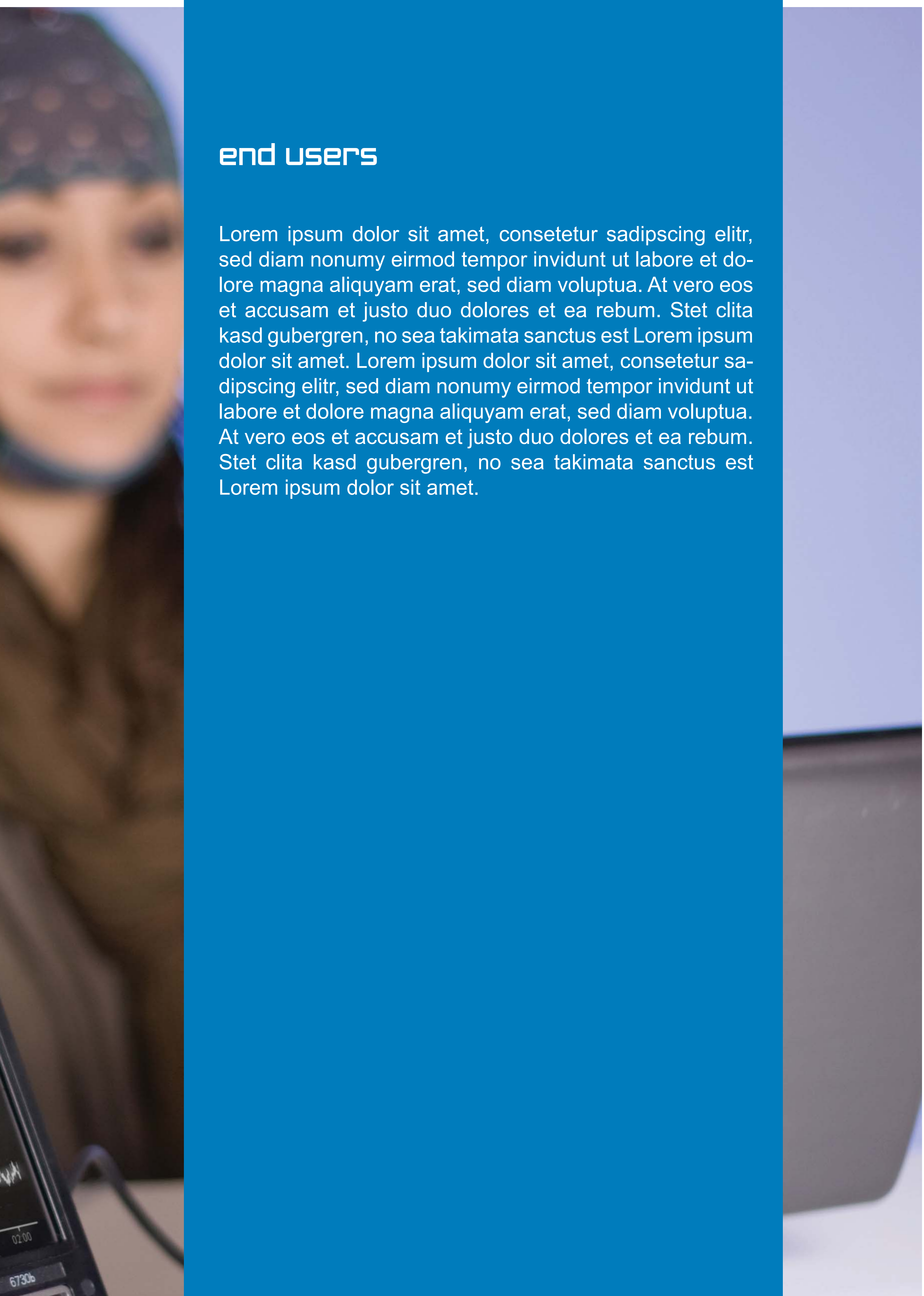

end users

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User-Centered Design

introductory chapter on UCD, other wps could have brief introductory chapters on other topics
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BCI Applications and Users

a brief taxonomy of BCI applications/users could be applied to all WPs (based on the 6 scenarios). Brain Painting At vero eos et accusam et justo duo dolores et ea rebum. Stet clita kasd gubergren, no sea takimata sanctus est Lorem ipsum dolor sit amet. At veroLorem ipsum dolor sit m et justo duo dolores et ea rebum. Stet clita kasd gubergren, no sea takimata sanctus est Lorem ipsum dolor sit amet. At vero eos et accusam et Lorem ipsum dolor sit m et justo duo dolores et ea rebum. Stet clita kasd gubergren, no sea takimata sanctus est Lorem ipsum dolor sit amet. At vero eos et accusam et

Critical survey of the State of the Art

Selection of sources

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SoA of BCI design processes and usability evaluation

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Discussion on the survey

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What users want vs. what science can offer

In a similar way, other wps could state “what is there” and “what is needed” referring to different topics (what is needed from the BCI world to reach industries, what is needed from BCI to reach neuroscience research in general)

Elicitation of stakeholders’ comments and recommendations.

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Summary of technological roadmap [must be done with WP2-WP3]

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Users of next generation BCIs

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Recommendations: what would help fulfilling the users' needs

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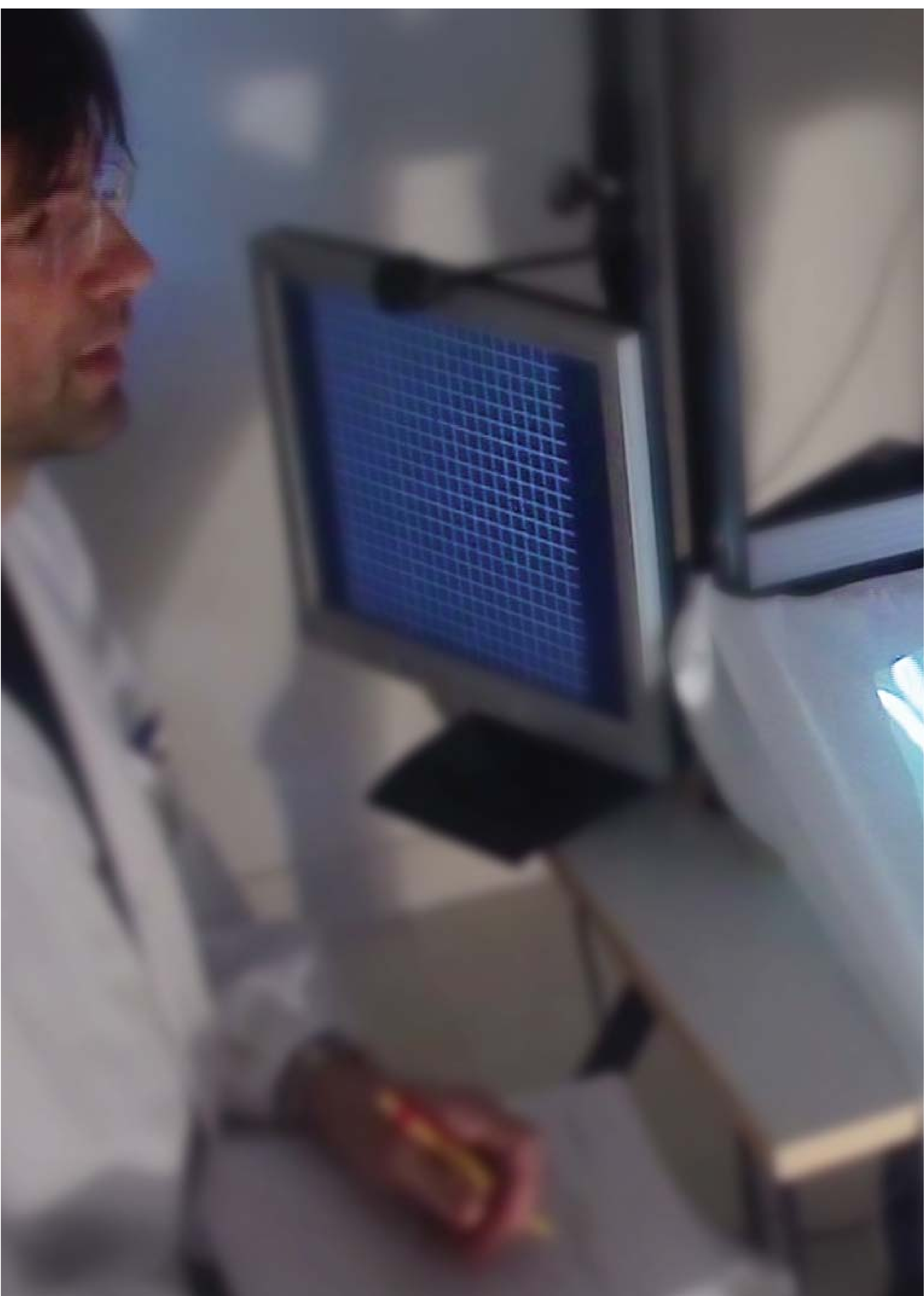

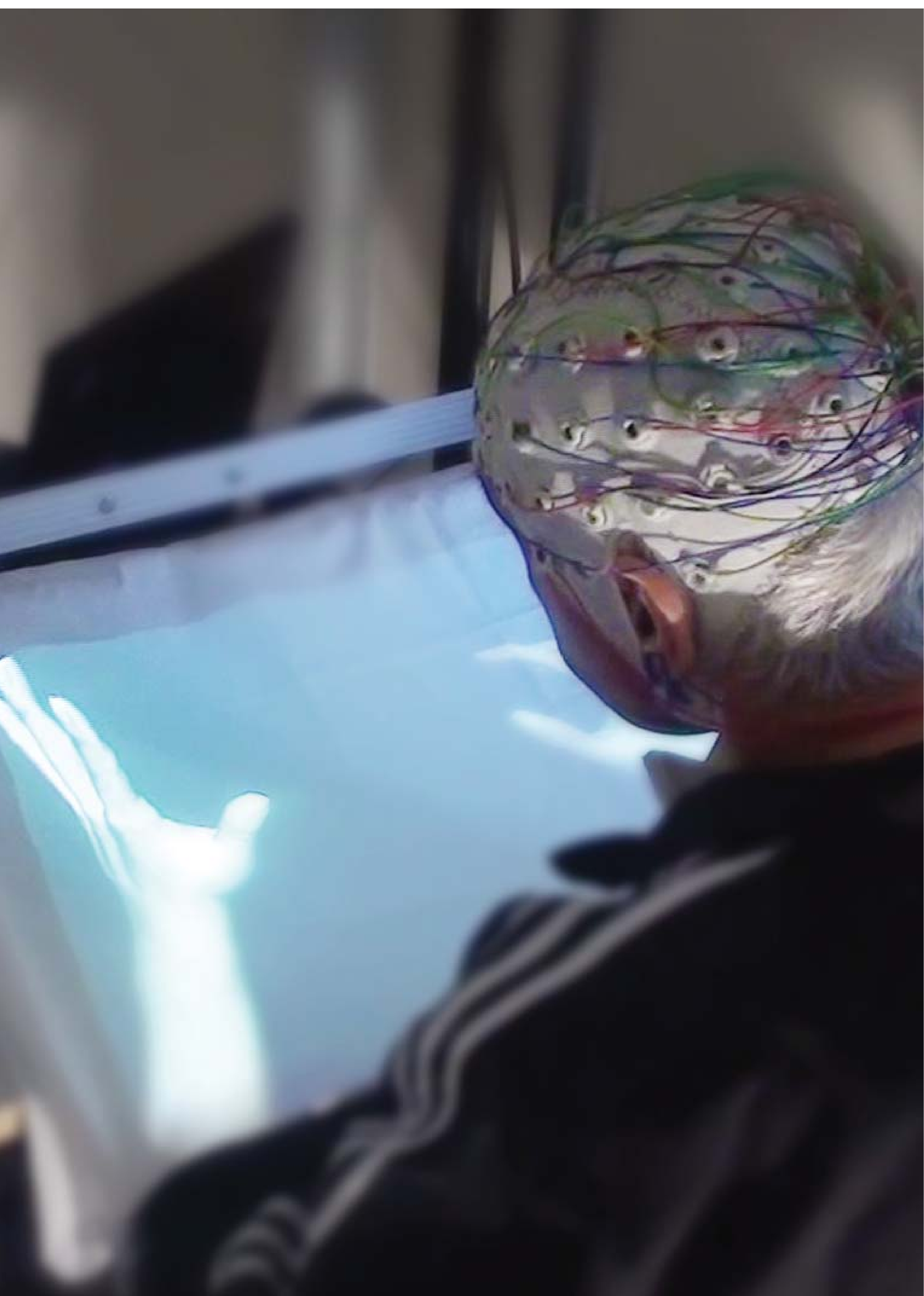

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