Why User-Centered Design Is Relevant for Brain–Computer Interfacing and How It Can Be Implemented in Study Protocols

Sonja C. Kleih and Andrea Kübler

Abstract

User-centered design (UCD) focuses on the needs and requirements of targeted users while developing assistive technology. Early inclusion of end-users may help to overcome the translational gap between BCI development and actual deployment by end-users. Despite its potential, the UCD is hardly followed in applied BCI research. In our book chapter, we describe how to implement the UCD in BCI studies, define usability, and how to incorporate evaluation as one component of the UCD. Different metrics to measure usability, that is, effectiveness, efficiency, and satisfaction, are readily available and should be regularly applied. To address specific BCI-controlled applications, new usability metrics can be easily integrated. We emphasize the importance to deliberately choose and define a BCI end-user group and to realize long-term field studies. Some exemplary studies with diverse clientele are presented as examples of successful UCD implementation in a BCI context.
30.1 FOR WHO IS THIS CHAPTER MOST RELEVANT?

Anyone who is aiming at bringing BCI to end-users of any kind, that is, the chapter is relevant for those who

- Are involved in applied BCI research
- Work with BCI end-users
- Are involved in the development or improvement of BCI-based applications
- Investigate the usability of BCI-based applications

In this chapter, we introduce user-centered design (UCD), which was standardized in ISO 9241–210 (ISO 2008) and present how to implement it in BCI research. We delineate why we consider UCD to play a major role in reaching the goal of BCI technology transfer to the end-user population for use in daily life. We focus on clinical end-users, mostly with motor impairments (for a definition of end-users, see EU project BNCI Horizon 2020 roadmap, http://bnci-horizon-2020.eu/roadmap).

30.2 THE RELEVANCE OF UCD

Even though an exponential increase in BCI research papers between 1988 (Farwell & Donchin 1988) and today is clearly observable (Kübler et al. 2015), BCI technology was only implemented in the daily lives of BCI end-users in very specific cases (Botrel et al. 2015; Holz et al. 2015b; Neumann & Kübler 2003; Sellers et al. 2010). Nevertheless, improvements in several aspects, such as accuracy and ease of use, have been achieved (e.g., Acqualagna et al. 2016; Allison et al. 2014; Faller et al. 2014; Kaufmann et al. 2013; Pfurtscheller et al. 2010; Townsend et al. 2010; Vidaurre et al. 2011). BCI applications are mostly developed and tested in healthy subjects, often students who volunteer for credits. The results of such research are relevant and valuable in the field of BCI, but they are rarely transferable to BCI end-users, who are mostly considered the target population for BCI (EU project BNCI Horizon: http://bnci-horizon-2020.eu/roadmap). BCI end-users may be diagnosed with (sometimes terminal) progressive muscular or neurological disease or traumatic brain injury (Grootenhuis et al. 2007; Mitchell & Borasio 2007), and some of them must be artificially ventilated, or fed, or both. Perceptual difficulties—for example in seeing—might occur (Palmowski et al. 1995) as well as cognitive impairment or fluctuation of consciousness (Bruno et al. 2011; Kübler & Kotchoubey 2007; Lulé et al. 2013). Therefore, BCI applications, which were developed in collaboration with healthy students, require changes, or improvement, or both to fulfill end-users’ needs. The UCD approach directly addresses this problem: It describes the process of how end-users can be included in the design process of assistive technology from the beginning and thereby secure the creation of an application that is needed, accepted by, and adjusted to the end-user. UCD might therefore, after 30 years of BCI research, enable technology transfer that, and thereby, support overcoming the translational gap (Kübler et al. 2013; Nijboer 2015; Vaughan et al. 2012).

In non–BCI-based human–machine interaction, UCD is the standard procedure to be followed (ISO 2008). Therefore, it seems somehow surprising that in the BCI field, implementation of UCD has not yet been established and more intensively propagated, albeit the respective procedure is recommended and requested by others (e.g., Taherian et al. 2017). This is even more surprising as UCD has been adapted to BCI-controlled applications (Kübler et al. 2014). In the following sections, we will outline the UCD concept, address how to include UCD in BCI research, and hypothesize why it has not yet been broadly taken up by the community despite many declarations about BCIs being developed for end-users in need.

30.3 WHAT IS UCD?

The major goal of UCD is to focus on the needs and requirements of a specific target user while in the design process of an assistive technology or tool. Following the UCD, interfaces should be adaptable.
to individual needs and allow for high usability not only for skilled users but also for novices (Laux et al. 1996). UCD was defined by the International Organization for Standardization (ISO) as an

Approach to systems design and development that aims to make interactive systems more usable by focusing on the use of the system and applying human factors/ergonomics and usability knowledge and techniques. (https://www.iso.org/obp/ui/#iso:std:iso:9241:-210:ed-1:v1:en)

The ISO norm 9241-210:2010 released six principles concerning UCD for interactive systems: (1) understanding users, tasks, and environments; (2) users’ involvement throughout the development process; (3) design being based on and adapted to the results of user-centered evaluation; (4) the adjustment process is iterative; (5) the user experience as a whole is taken into account; and (6) multidisciplinary skills and perspectives are included.

To follow the UCD, one needs to explicitly consider from the beginning the research goal or the purpose of an application and its implications for end-users. A research plan should be deduced in accordance with the UCD, such that the BCI application under investigation is presented to end-users early in the design process. Refinements are then based on end-users’ feedback as assessed by evaluation metrics. Evaluation allows for comparison of the achieved solution with the requirements it is supposed to address. Actual use is possible and likely only if user requirements are met (for a recommendation on how to realize UCD for BCI-based application, please see Figure 30.1).

![UCD adapted to BCI applications](image)

Fortunately, examples in which BCI applications were developed based on the UCD process do exist and users’ requirements were directly addressed (Holz et al. 2013; Rohm et al. 2013; Schreuder et al. 2013; Zickler et al. 2013). In other studies, user requirements were taken into account in the design of the BCI application or the choice of the protocol without explicitly emphasizing UCD (e.g., Morone et al. 2015; Riccio et al. 2015; Saeedi et al. 2016; Schettini et al. 2015; Vansteensel et al. 2016). In the Section 30.4, we present a nonconclusive review on examples for both approaches.

30.4 UCD REALIZED IN BCI APPLICATIONS

The importance of implementing UCD in BCI development and protocol elaboration was acknowledged not only in the clinical field but also in the BCI application areas of gaming and entertainment (e.g., Plass-Oude Bos et al. 2011). Plass-Oude Bos et al. (2011) interviewed BCI users about the strategies they would like to use (such as inner speech) to change brain states to control a character in the gaming environment. They implemented these requested changes in their BCI application. However, the authors do not report the success with which the BCI gamer controlled the application.

Scherer et al. (2015) investigated usability of a newly developed row–column scanning communication board for individuals with cerebral palsy. By iterating evaluation loops with persons with cerebral palsy, relatives, and caregivers, they adapted the regular spelling paradigm in several aspects according to the received information. The authors created a $3 \times 3$ matrix comprising symbols such as a soccer ball or a banana instead of the usually displayed letters to decrease paradigm complexity. Rows and columns were consecutively highlighted instead of randomly. This highlighting mode facilitated BCI use as the target population was already used to the scanning mode for operation of other assistive technologies. Motor imagery (MI) was chosen as an input signal because previous trials with evoked potentials were not as successful as MI BCI use, mostly due to strong muscle artifacts (Daly et al. 2013). Also in line with UCD, the authors report iterative BCI design development steps, which included testing a maximum-likelihood selection adaptable to the user. However, the adaptive BCI version that would provide an estimate of the symbol intended to be spelled was too confusing for end-users and therefore was abandoned during further trials. With the final BCI system, 6 of 11 participants performed above chance level.

In a report of two patients with ALS, the UCD approach was implemented to modify and adjust the artistic BCI application Brain Painting (BP) (Botrel et al. 2015; Holz et al. 2015a). The patients used the P300-based BP application at home with caregivers and relatives learning to provide the necessary assistance for home use that is independent from a local research support team. Data storage and BCI system control were adjusted to a remote connection such that the research team at the University of Würzburg could support the end-users from the laboratory. At the same time, relatives and caregivers were taught how to set up the BCI application as recommended in UCD. The paradigm itself was designed following UCD as the stimulation mode was changed from a regular flashing to the so-called face speller mode (Kaufmann et al. 2013). In this stimulation mode, letters are overlaid with faces instead of flashes, leading to ERPs related to face recognition in addition to increased P300 amplitudes (Chen et al. 2016). Less time was then needed by the end-users to paint, which increased usability and satisfaction. Visual analog scales were answered by the users after every use of the BCI application and questionnaires regularly after a defined amount of sessions, such that the system could be adapted continuously over time to the user’s wishes. Evaluation revealed that the end-users would prefer more functions available in the application. Additional functions should allow for a higher level of artistic expression. Therefore, the software was changed according to the end-user wishes (Botrel et al. 2015). This new, more complex BP version was enthusiastically used by one end-user, while for the other, it was too complicated. Adjustments should therefore be realizable based on individual needs. Thus, a UCD-based BCI application ideally fulfills the criteria of generalizability and at the same time of adaptability (one prototype application that can be individually specified, e.g., Kleih et al. 2016).
30.5 USER-ORIENTED BCI APPLICATIONS

Some studies take into account end-user requirements but were not explicitly designed following the UCD. We will review two examples for such applications. In a BCI application that was developed for rehabilitation of motor function in the upper extremity, stroke patients imagined movements with their affected hand to trigger movement of a virtual hand representation that was projected on a white cloth placed on the affected hand (Morone et al. 2015; Picchiori et al. 2015). In this application, the BCI system detects MI and the virtual hand moves according to the imagined movement (opening or closing the hand as discrete feedback). The projection on the cloth was chosen as a feedback because patients had reported previously that the observation of a moving hand (instead of e.g., a cursor) would probably help them to imagine movements with their paralyzed hand. Moreover, different hand models (e.g., male and female) were developed. Participant feedback on the prototype hand model revealed that it was judged to represent a female hand. This perception would possibly hinder a male participant to accept the provided hand model as a representation of its own hand. Furthermore, patients reported being used to therapeutic support and to benefit from the interaction. Thus, a therapist was included in the BCI protocol to guide the BCI user through the training. The therapist supported the patients by giving continuous feedback on their performance in addition to the discrete feedback provided by the moving hand.

In a case study presented by Saeedi et al. (2016), the authors report BCI control by a tetraplegic, artificially ventilated end-user who used the BCI for 11 months. The participant’s oculomotor muscles were completely paralyzed; thus, MI was chosen as an input signal. The participants’ task was a two-class gaming task, which in later studies could be changed to a communication or navigation task. The authors tested an adaptive assistance approach and argued that such an approach could reliably take into account the cognitive state and brain signal—the so-called internal context. The adaptation consisted of a variable trial duration, and the adaptation level was determined by a performance estimator. Therefore, the BCI could directly use the information provided by the user (brain signal stability) and react to it.

30.6 THE ROLE OF EVALUATION

As often recommended (e.g., Laar et al. 2011; Schlögl et al. 2007; Vaughan et al. 2012), Kübler et al. (2014) suggested evaluation metrics for BCI applications based on the concept of usability. Usability is defined as the extent to which a product can be used by a specified target population to reach specific goals with effectiveness, efficiency, and satisfaction (ISO 2008). While effectiveness relates to the accuracy that can be achieved, efficiency refers to the cost and time invested in relation to effectiveness. Satisfaction assesses perceived accessibility, comfort of use, and product–user match (ISO 2008; Kübler et al. 2014; Laar et al. 2011). Transferring this concept to BCI use, Kübler and colleagues assessed effectiveness (accuracy = correct responses in relation to the number of total responses), efficiency (amount of information transferred per time unit and invested mental workload), and satisfaction in 19 end-users who operated BCI systems for spelling, painting, or gaming. They concluded that specific metrics yield informative results and that these metrics are applicable in end-users who are diagnosed with major motor impairment or even with the locked-in state. The framework proposed by Kübler et al. (2014) allows for integrating additional metrics depending on the application under investigation. As evaluation is the basis of the iterative UCD process, it should become a standard procedure in applied BCI research.

30.7 USER INVOLVEMENT

Even though involvement of end-users in the design process of assistive technologies was strongly recommended and supported by some authors (e.g., Eisma et al. 2004; Huggins et al. 2011; Kübler et al. 2014; Laar et al. 2011; Lightbody et al. 2010; Plass-Oude Bos et al. 2011; Vaughan et al. 2012),
others argue that research should be independent of and not dictated by end-users’ ideas (Newell & Gregor 2000). Newell and Gregor state that

in User Centred Design although the needs and wants of users are the focus of the research, the user cannot be in control of the research, as is sometimes suggested by the proponents of PAR (Participatory Action Research). (Newell & Gregor, p. 40)

A potential conflict of interest is evident: On the one hand, the ultimate goal of the UCD is the development of a technological application for end-users reaching the best possible person–technology fit; on the other hand, potential dead ends that are not realizable or too complicated or not individually adjustable should be avoided. This implies that not every possible wish for technological changes or further investigation in the development process of an assistive device can be followed by the researchers; a modular hardware and software design may alleviate these issues. In this respect, applied clinical research must be distinguished from basic research, which, in our opinion, helps to resolve the conflict. Applied clinical research in the field of BCI aims at the development of solutions that can be used outside the laboratory, thereby overcoming the translational gap. This also comes with a potential loss of research possibilities as one route determines future paths to be investigated. Without a doubt, UCD should be followed in applied BCI research. Thus, we do not argue for applying the UCD in any BCI study, but for an unambiguous definition of the research goal—and if it is to provide BCI for end-users in the field, following the UCD is mandatory. This also includes a thorough definition of the end-user who can be manifold, such as doctors, paramedical staff, neurofeedback trainers, caregivers, or the patients themselves (for a thorough elaboration of end-users, see http://bnci-horizon-2020.eu/roadmap). Importantly, following the UCD in applied research does not exclude a realistic estimation and communication of possibilities to the end-user that can be realized at any point in time. However, if a BCI-controlled application was neither developed in cooperation with end-users nor took into account end-users’ needs, it will not be used by the targeted population as is the case with almost all BCI-controlled applications, despite publications in high-impact journals (e.g., Hochberg et al. 2006). Therefore, applications as well as end-users should be carefully selected. To support such selection, Vaughan et al. (2012) provided some guidelines on end-user selection that were adopted and further developed by Kübler et al. (2015), who suggested an exemplary algorithm to select candidates for independent use of a BCI at home. Potential BCI candidates should be interested in BCI use, be in need of an assistive technology, be able to give informed consent, live in a supportive environment, and be cognitively able to operate a BCI system. If all these apply, the best-fitting stimulation modality (e.g., visual) and signal type (e.g., P300) can be identified. By following clearly defined selection criteria, generalizability of achieved results from the study sample to the entire population is more likely and lessons learnt might be transferrable to future translational studies in end-users’ homes.

Basic research, on the other hand, generates research hypotheses and investigates fundamental principles. BCI prototypes that may not fulfill end-user criteria are tested and might provide meaningful input for later solutions applicable in end-users.

30.8 WHY THE UCD IS NOT IMPLEMENTED IN APPLIED BCI RESEARCH—SOME HYPOTHESES

While we consider UCD mandatory if applied BCI research seriously aims at bringing BCIs to end-users in the field, we are well aware of the problems that come along with it (Chavarriaga et al. 2017). Research with end-users, specifically those with disease, is effortful and requires appropriate financial and human resources, and studies need to adopt longitudinal designs—all requirements that are not easy to implement in a research environment that often appreciates most, a long publication list. The lack of funding for longitudinal studies adds to the problem.
Another possible reason why the UCD is only reluctantly taken up by the community is that researchers rather follow their own ideas of what may be valuable for an end-user. Garud and Ahlstrom (1994) suggested a Socio-Cognitive Model of Technology, pointing out the potential problem that researchers usually tend to create their research questions based on their own beliefs and experiences, leading to a technology that matches the researchers’ rather than the end-users’ needs. In comparison to the real needs of end-users, those of the researchers are often easier to achieve and evaluated accordingly because only convenient measures are used. Evaluation will, thus, most naturally, positively reinforce the created idea. Thereby, researchers might be limited by their own vision of end-users’ needs instead of choosing potential new ways of improving and adjusting technology.

Furthermore, the end-user population is a vulnerable one, as BCI end-users who are really in need of assistive technologies are most likely also medically in a challenging state, some being artificially ventilated or fed, or both. Even with a perfectly planned data acquisition schedule, personal and health issues, family conflicts or interference with other therapies might occur and prevent fast and smooth data acquisition at the end-user’s home. One is involved in the BCI end-user’s personal history, is confronted with sometimes desperate relatives, and must try to create an atmosphere of mutual trust and collaboration in another person’s home. This is challenging for researchers and end-users alike.

### 30.9 DO-IT-YOURSELF UCD AND EVALUATION—GETTING PREPARED

The first step always is and under all circumstances must be: Reading. Our experience is that results older than a few years or from different research groups or from fields not directly linked to the research question at hand are often neglected. This prevents integration of results and fosters reinventing the wheel albeit with a different tire.

Also, it is mandatory to get familiar with the end-user population you wish to work with. Ideally, one would spend some time with the (patient) end-users and attend focus groups or meetings of support groups. This will help to realize a BCI application that the targeted end-users’ need indeed. Furthermore, in case your end-users have an idiosyncratic communication style (e.g., due to motor impairment), you must be ready to learn individual ways or codes of communication. We recommend following the advice given in the section “user involvement”: cooperate with the family and staff and use their expertise as a resource for your research. Before starting BCI measurements, be very clear about the purpose of your work: Which goals would you like to achieve?

You also should plan extra time for data assessment with a clinical population. Because of sickness or hospital stays (Saeedi et al. 2016), measurements might be cancelled. You must, and even more in UCD-based studies, continuously check the assessed data to make sure that there are neither mistakes in the protocols nor major problems with the signal (e.g., artifacts caused by inflation of the anti-decubitus mattress). Finally, evaluate the BCI application you worked with and its usability, and use questionnaires to ensure systematic evaluation (Kübler et al. 2014).

### 30.10 FINAL REMARKS

We believe that overcoming the translational gap between BCI development and transfer to real-world use can be fostered by UCD implementation. This would support development of BCI devices that are (1) really needed, desired, and, thus, accepted by end-users; and (2) individually adjusted to the end-users’ requirements. You as a scientist involved in applied BCI research can substantially contribute to bringing BCI technology to end-users. Become familiar with the UCD and the respective evaluation metrics. Ask for the needs and requirements of the target population and include from the beginning this information in your design of an application. Be ready to spend some time on readjustments and be convinced that the process is worth it, for the benefit of end-users in need.
REFERENCES


