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User-centered design in brain–computer interfaces—A case study[☆]

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ABSTRACT

Objective: The array of available brain–computer interface (BCI) paradigms has continued to grow, and so has the corresponding set of machine learning methods which are at the core of BCI systems. The latter have evolved to provide more robust data analysis solutions, and as a consequence the proportion of healthy BCI users who can use a BCI successfully is growing. With this development the chances have increased that the needs and abilities of specific patients, the end-users, can be covered by an existing BCI approach. However, most end-users who have experienced the use of a BCI system at all have encountered a single paradigm only. This paradigm is typically the one that is being tested in the study that the end-user happens to be enrolled in, along with other end-users. Though this corresponds to the preferred study arrangement for basic research, it does not ensure that the end-user experiences a working BCI. In this study, a different approach was taken; that of a user-centered design. It is the prevailing process in traditional assistive technology. Given an individual user with a particular clinical profile, several available BCI approaches are tested and – if necessary – adapted to him/her until a suitable BCI system is found.

Methods: Described is the case of a 48-year-old woman who suffered from an ischemic brain stem stroke, leading to a severe motor- and communication deficit. She was enrolled in studies with two different BCI systems before a suitable system was found. The first was an auditory event-related potential (ERP) paradigm and the second a visual ERP paradigm, both of which are established in literature.

Results: The auditory paradigm did not work successfully, despite favorable preconditions. The visual paradigm worked flawlessly, as found over several sessions. This discrepancy in performance can possibly be explained by the user's clinical deficit in several key neuropsychological indicators, such as attention and working memory. While the auditory paradigm relies on both categories, the visual paradigm could be used with lower cognitive workload. Besides attention and working memory, several other neurophysiological and -psychological indicators – and the role they play in the BCIs at hand – are discussed.

Conclusion: The user's performance on the first BCI paradigm would typically have excluded her from further ERP-based BCI studies. However, this study clearly shows that, with the numerous paradigms now at our disposal, the pursuit for a functioning BCI system should not be stopped after an initial failed attempt.

1. Introduction

Brain–computer interfaces (BCI) hold the promise of allowing those with (near-)complete paralysis another chance at communication or environmental control. Such paralysis is called locked-in syndrome (LIS) if all but ocular-motor functions are compromised. If this last voluntary control is also lost, the condition is called total- or completely locked-in syndrome [CLIS, 1]. For both conditions, a BCI may be the only form of independent expression. But even for patients suffering from incomplete locked-in syndrome, those

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remaining residual motor functions may fatigue quickly, and they may thus be augmented by BCI.

So far, BCIs have mainly been targeted at end-users suffering from late stage amyotrophic lateral sclerosis (ALS) [2–5], a neuro-degenerative disease with short life-time expectancy after diagnosis. The median survival time after tracheostomy, the time were a BCI becomes relevant, has been reported at 21 months [6]. For ALS, the course of progression varies widely between patients, but the symptoms are rather similar. In the final state, the patient loses all reliable, voluntary muscle control [7]. It was long assumed that cognitive functions remain largely untouched, however, several recent findings have challenged this concept [8–10]. They state that a range of cognitive changes are associated with ALS, although this is difficult to assess systematically for patients in the locked-in state. Nevertheless, the symptoms in ALS largely overlap.

Interestingly, the largest cause of LIS is brainstem damage, such as a brainstem stroke or physical injury as in traumatic brain injury (TBI, [11]). There is a large population of people suffering from the consequences of such strokes or TBIs for which a BCI may be desirable [12]. The yearly mortality rate for TBI patients that survive the first six post-trauma months is estimated to be only 1.33 times higher than that of the general population [13]. For first-time stroke patients that survive the first 30 post-incident days the mortality rate is estimated at about 2.3 times that of the general population [14]. It is highest for immobile patients, due to an increase in secondary causes of death such as circulatory problems; still the life expectancy is on the order of decades once the chronic phase has been entered. In the light of this it seems odd that end-users with locked-in syndrome due to stroke or TBI have thus far played only a minor role in BCI research.

TBIs and strokes manifest themselves in very diverse ways; the level of functional and cognitive impairment depends on the locus of the trauma and the extend of the damage. Symptoms can be completely different between (1) an isolated brain-stem stroke, which mostly impairs motor-functions and can lead to vigilance and awareness deficits, and (2) a diffuse stroke, where a wide area of cognitive functions are compromised. With such a heterogeneous target group, it can be expected that a BCI may be of highest practical use for the subset that has intact cognitive abilities. The applied complexity of the BCI control and the chosen interaction paradigm should largely be determined by the extent of the loss of cognitive abilities. For example, a simple binary BCI like in [15] may – at first glance – be slower than multi-class approaches such as described in [16], but the added complexity of the second approach may require a greater mental effort. The same consideration should be made for the modality used, be it visual, tactile or auditory. For most TBI and stroke patients, a certain set of neurophysiological and -psychological tests is part of their routine post-trauma assessment. They typically test for attention-, memory- and other cognitive abilities. The results of such tests could be a viable starting-point for finding a BCI system that matches the user's abilities.

Practically, this pursuit of an appropriate BCI can be realized in a user-centered design process, which is formally described in the ISO 9241-210. In short, it states that the software should be designed with deep understanding of the end-user, that end-users should be involved in every step of the design and that the design process should have several iterations where end-user feedback is incorporated. Furthermore, any testing should be done with the potential end-user. Taking the prior knowledge of neurophysiological and -psychological tests of an end-user into consideration, such deep understanding can be gained and quantified. Using this, one or more BCI paradigms and modalities are then screened for their applicability with the particular end-user. During the screening of each such paradigm, an iterative process is followed to adapt the settings of the BCI system to the end-user's needs and abilities.

The present case-study reports on a single female end-user (FD) with severe motor- and communication deficits after a brain stem stroke. She participated in two different BCI studies. Even though both were based on event-related potentials (ERP) measured by electroencephalography (EEG), the BCI performances were substantially different. To investigate potential reasons for this difference, FD's existing history of repeated neurophysiological and -psychological test results was re-examined.

2. End-user profile

2.1. Case report

The end-user (FD) is a 48-year old Italian woman. At age 44 she suffered from an ischemic stroke in the area of the basilar artery, after which she showed a clinical picture characterized by tetraplegia and severe dysarthria. Her impairment lead to a severe lack of communication. A magnetic resonance imaging (MRI) scan, acquired 10 days after the ischemic event, showed an altered signal intensity in the infero-posterior area of the left cerebellar hemisphere, in the upper area of the right cerebellar hemisphere, in the cerebellar vermis, and in the midbrain with greater extension on the left. It also showed a small hemorrhagic rift within the left cerebellar hemisphere lesion and in the central pontine area. Twenty days after the ischemic stroke, FD was alert and able to localize sound stimuli by turning her eyes towards the sound source and reasonable changes in facial expression were present. Her motor disability was characterized by motor tetraplegia with hypotonia and symmetrical generalized hyperreflexia. She was thus diagnosed with the locked-in syndrome. Immediately after the diagnosis, a binary model of communication exploiting eye gaze was set up. FD was trained to communicate by focusing her gaze on an alphanumeric communication board, which she still uses to date. Before the event, FD worked in the field of graphic arts and played drums in a band; she was confident with using computers and other technology. At the time of testing, FD had the ability to perform inaccurate movements with the right arm and the head, had preserved facial expressions and precise eye movements. The communication of primary needs was only possible with the support of her communication board on which she pointed to letters. In addition, she could acknowledge requests by a button press.

FD was curious and motivated to test BCI. She initially joined for testing the auditory BCI prototype AMUSE (**a**uditory **mu**lti-class **s**patial **E**RP, see Section 3.2.1) when she was 46 years old and, one year later, she joined the testing of a vision-based BCI prototype (Photobrowser see Section 3.2.2). Her motor deficit did not change between the studies. Around the time of the testing of each prototype, FD underwent assessment of her cognitive functions. The results of both evaluations are described in Section 4.3.

2.2. Neuropsychological assessment

In the context of a standard clinical diagnosis process, FD was subjected to a neuropsychological assessment of general cognitive impairment, attention, memory, working memory and executive functions twice (see Fig. 1). The first assessment took place about 4 months before the first AMUSE trial, the second assessment around 6 months after the last Photobrowser trials. The test battery was administered in a quiet room and over several sessions to prevent fatigue. During both assessments, FD was motivated and cooperative. Her general cognitive level was tested by means of the mini mental state examination (MMSE; [17]). The two subtests of the scale that were not applicable due to FD's physical condition (spontaneous writing subtest and constructive praxis ability