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Original article

Thought-based row-column scanning communication board for individuals with cerebral palsy

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ABSTRACT

Impairment of an individual's ability to communicate is a major hurdle for active participation in education and social life. A lot of individuals with cerebral palsy (CP) have normal intelligence, however, due to their inability to communicate, they fall behind. Non-invasive electroencephalogram (EEG) based brain-computer interfaces (BCIs) have been proposed as potential assistive devices for individuals with CP. BCIs translate brain signals directly into action. Motor activity is no longer required. However, translation of EEG signals may be unreliable and requires months of training. Moreover, individuals with CP may exhibit high levels of spontaneous and uncontrolled movement, which has a large impact on EEG signal quality and results in incorrect translations. We introduce a novel thought-based row-column scanning communication board that was developed following user-centered design principles. Key features include an automatic online artifact reduction method and an evidence accumulation procedure for decision making. The latter allows robust decision making with unreliable BCI input. Fourteen users with CP participated in a supporting online study and helped to evaluate the performance of the developed system. Users were asked to select target items with the row-column scanning communication board. The results suggest that seven among eleven remaining users performed better than chance and were consequently able to communicate by using the developed system. Three users were excluded because of insufficient EEG signal quality. These results are very encouraging and represent a good foundation for the development of real-world BCI-based communication devices for users with CP.

1. Introduction

Cerebral palsy (CP) is a non-progressive condition caused by damage to the brain during early developmental stages [1,2]. Individuals with CP may have a range of problems related to motor control, speech, comprehension, or other cognitive impairments. Around one quarter of individuals with CP have normal intelligence, but nevertheless are often classified as cognitively challenged as a result of their inability to communicate [3]. Communication solutions are available; however, they strongly depend on motor activity and on the assistance of others. Brain-Computer Interfaces (BCIs) represent a possible alternative communication channel [4].

BCIs translate brain activity directly into action [5–11]. Non-invasive BCIs are typically based on electroencephalographic (EEG) signals. To send messages, BCI users either focus on sensory stimuli (visual [12], auditory [13] or somatosensory [14]) and generate evoked potentials (EPs) or perform, independently of any stimulus, specific mental imagery and induce transient changes in spontaneous EEG rhythms (Event-Related Desynchronization [15]). Such mental imagery includes, amongst others, motor imagery (the

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kinesthetic imagination of movement [16]), mental arithmetic, and the mental generation of words [17–20].

Within the framework of the FP7 Framework EU Research Project ABC, we recently started developing BCI technology for individuals with CP. The aim of the project is to develop assistive technology that improves independent interaction, enhances non-verbal communication and allows expression and management of emotions for users with CP. Several challenges have to be faced: Firstly, EEG sensor placement can be difficult due to body posture or head and neck support systems and will benefit from novel materials and sensor processes that are user-friendlier. Secondly, involuntary movements and spasms generate bioelectrical activity that lead to artifacts, which can produce misleading EEG signals or destroy them altogether [21]. Ensuring high signal quality is essential [22–24]. Thirdly, time-consuming BCI calibration processes need to be optimized. While EP-based BCIs typically achieve higher detection rates and require substantially less training time than imagery-based BCIs, which type will be most useful depends on residual motor and cognitive capabilities of the user. Major issues that impact the detection performance are the non-stationarity and inherent variability of EEG signals. Novel methods and user-group related protocols have to be developed that allow predicting robust control signals from EEG data. Fourthly, BCI training paradigms and instructions have to be adapted to the CP user's individual capabilities and skills. Depending on situation and availability, individuals with CP are able to attend school or special training programs. Therefore, each user is different and information must be presented in a user-specific manner.

To ensure usability and functionality of our developments, we follow user-centered design principles [10,25]. In this paper, we present our first prototype BCI and a corresponding communication application, and report results of a supporting online study in 14 end-users with CP.

2. Methods

2.1. User-centered system design adaptations

The BCI was designed and remodeled in several iteration steps according to the feedback received from adult CP users, relatives, caregivers and healthy test users. Firstly, we tested EP-based and imagery-based BCIs in CP users. We found that CP users could not utilize EP methods for a number of reasons, however, imagery-based methods were viable [17,26]. Secondly, for communication we aimed at developing a communication application. Some individuals had previous experience operating row-column scanning communication boards such as The Grid Augmentative and Alternative Communication software (Sensory Software international, Malvern, UK). The Grid uses one-switch row-column scanning to select items that are arranged in a grid. Row-column scanning means that each row within the grid is sequentially highlighted until the user selects the row containing the desired item (for example, letters or icons, Fig. 1) by activating the switch. The columns within the selected row are then scanned until the target item is highlighted and can be selected by activating the switch a second time. Consequently, we aimed at developing a BCI that robustly generates a binary control signal for replacing the switch. To optimize communication speed, we first implemented a maximum-likelihood selection, i.e., letters that are most likely to be selected appear as the next available item. Using a dynamically adapted scanning protocol, however, was confusing for most users. Thus, we switched back to the slower but familiar row-column scanning mode. Thirdly, to concentrate on continuous feedback, which is typically used in BCI, was very demanding for the users. Therefore, we changed to discrete feedback (Fig. 1). Users were only notified on whether imagery (equals switch activated) was detected while the current row (item) was highlighted or not. Fourthly, spelling words by selecting individual letters was very difficult for CP users. To facilitate selection, we used symbols and images representing the action to be performed. Fifthly, BCI training paradigms and BCI-based control are usually different, in that training does not provide feedback on detected imagery activity. This distinction was not transparent for users. Conventional training paradigms were moreover too abstract and boring for the user. Consequently, training and control paradigms were combined. Reducing graphical user interface (GUI) complexity makes instructions for the user simpler and less ambiguous.

Based on these specifications, and with the aim to overcome some of the challenges mentioned initially, we developed the current BCI system (Fig. 1).

2.2. System architecture

The BCI has a distributed, modular architecture and was implemented by using open standards when possible. In the current implementation a Windows operating system (OS) based laptop computer was used for EEG acquisition and signal processing. Feedback and the application were presented on an Android OS tablet computer (Fig. 1). BCI modules were implemented following the TOBI interface specifications [27,28]. Communication between the BCI and the Android application was based on a specially developed ABC protocol. This allows users to interact with the application by means of other input signals and modalities developed within the ABC project (for example, standard human-computer interaction or inertial measurement devices). Operator computers can be used for monitoring and controlling experimental procedures.

2.3. The row-column scanning communication board

Fig. 1 shows a picture of the GUI. The screen was split into two parts. The left side contains the grid. On the right side feedback on the selected item was presented. Each row (item) was highlighted with a red colored box for a predefined time. The marker disappeared and after a short break the next row (item) was highlighted. When the last row (item) was reached, the marker jumped again to the first element and the sequence started again. The selection of a row (item) was reported back to the user visually by showing an animation sequence of the row (item) dissolving. Additionally, an auditory beep was presented. When an item was selected, the scan cycle started again from the first row. In this study a grid with three rows and three columns was used. Rows (items) were highlighted for 4 s with a 2-s break between the markers. Timing can be adapted to fit the user needs, when required. Items included a strawberry, soccer ball, banana, lemon, watermelon, heart, grapes, flower and pineapple (Fig. 1).

2.4. The BCI switch

The switch for selecting row (item) was implemented by training the BCI to classify between imagery and non-imagery EEG patterns. Signal processing was performed with Matlab/Simulink (MathWorks, Natick, MA, USA). The standard method of common spatial patterns (CSP) was used to design class specific spatial filters in user-specific frequency bands, and Fisher's linear discriminant analysis (LDA) classifier to classify the log-transformed normalized variance from 4 CSP projections ($m = 2$, [29]). The CSP method projects multi-channel EEG data segments from two classes into a low-dimensional spatial subspace in such a way that the variances of the time series are optimal for discrimination