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The auditory P300-based single-switch brain–computer interface: Paradigm transition from healthy subjects to minimally conscious patients

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ABSTRACT

Objective: Within this work an auditory P300 brain–computer interface based on tone stream segregation, which allows for binary decisions, was developed and evaluated.
Methods and materials: Two tone streams consisting of short beep tones with infrequently appearing deviant tones at random positions were used as stimuli. This paradigm was evaluated in 10 healthy subjects and applied to 12 patients in a minimally conscious state (MCS) at clinics in Graz, Würzburg, Rome, and Liège. A stepwise linear discriminant analysis classifier with 10×10 cross-validation was used to detect the presence of any P300 and to investigate attentional modulation of the P300 amplitude.
Results: The results for healthy subjects were promising and most classification results were better than random. In 8 of the 10 subjects, focused attention on at least one of the tone streams could be detected on a single-trial basis. By averaging 10 data segments, classification accuracies up to 90.6% could be reached. However, for MCS patients only a small number of classification results were above chance level and none of the results were sufficient for communication purposes. Nevertheless, signs of consciousness were detected in 9 of the 12 patients, not on a single-trial basis, but after averaging of all corresponding data segments and computing significant differences. These significant results, however, strongly varied across sessions and conditions.
Conclusion: This work shows the transition of a paradigm from healthy subjects to MCS patients. Promising results with healthy subjects are, however, no guarantee of good results with patients. Therefore, more investigations are required before any definite conclusions about the usability of this paradigm for MCS patients can be drawn. Nevertheless, this paradigm might offer an opportunity to support bedside clinical assessment of MCS patients and eventually, to provide them with a means of communication.

1. Introduction

Traditional means of assistive technologies (AT), such as joystick or button-based systems rely on residual muscular output from the user. In contrast, a brain–computer interface (BCI) is a technology that utilizes neurophysiological signals directly from the brain to control external devices, bypassing the natural muscular output [1]. Currently, BCI systems based on electroencephalography (EEG) can provide severely motor-disabled people with a new output channel to voluntarily control applications for communication and environmental control [2–8].

In addition, different neuroimaging and electrophysiological techniques have revealed signs of intact cortical processing and awareness in unresponsive patients diagnosed with vegetative state (VS) and minimally conscious state (MCS) [9,10]. MCS is a disorder of consciousness (DOC) that is clinically identified on the basis of behavioral assessment that shows the presence of non-reflexive responses to visual and auditory stimulation [11,12]. Severe motor impairment might, however, prevent the disclosure of awareness even during a careful repeated examination, leading to a rate of misdiagnosis of approximately 40% [10]. To overcome this problem, EEG-based BCI systems might offer a unique

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opportunity in supporting the bedside clinical assessment of unresponsive patients and eventually, in providing them with a means of communication. When considering BCI-based communication for unresponsive patients, the main goals of development should be to implement simple and robust devices. Both requirements can be fulfilled by using a single-switch BCI (ssBCI) which reliably detects one specific brain pattern of the patient [13,14]. Consequently, any kind of assistive technology (AT) can be controlled by simple binary yes/no commands provided by the ssBCI [15].

When designing an ssBCI for unresponsive patients, the specific needs and capabilities of the target patient group need to be taken into account. One promising way to realize a BCI in unresponsive patients is to use an auditory paradigm [16–18]. While vision might be considerably impaired, the auditory system is usually preserved in unresponsive patients [19–21] or might even be the only remaining channel usable for BCI-based communication [22]. One brain signal often used to realize a BCI is the P300 component of the event-related potential (ERP). The P300 component is a positive deflection in the EEG that can be elicited by a so-called oddball paradigm and occurs about 300 ms after a rare stimulus event in a stream of standard stimuli [23–26]. Previous studies have shown the applicability of auditory P300-based paradigms, allowing a user to make a binary decision by focusing attention on one of two concurrent tone streams [27–29]. Hill et al. [27,28] presented the tone streams separately to the left and the right ear. In contrast, Kanoh et al. [29] showed that focusing attention on one of the tone streams is even possible when both streams are presented to the right ear only. These studies showed promising results, but only in healthy subjects.

Based on these considerations, the aim of our current work was to develop an auditory P300 paradigm similar to [29] which just allows for binary decisions and which does not rely on binaural hearing. Such a paradigm is considered to be simpler than other P300 paradigms (e.g., auditory matrix speller [4]) since only two classes (i.e., two tone streams) exist. It is, therefore, assumed to be suitable for unresponsive patients. This paradigm was evaluated in healthy subjects and then applied to MCS patients. Our work, therefore, shows the transition of a paradigm from healthy subjects to MCS patients. Our main question was, whether a paradigm that is promising in healthy subjects can also successfully be applied to MCS patients. Some preliminary results of this work have already been presented in [30].

2. Materials and methods

2.1. Auditory stimulation

In order to create an oddball paradigm similar to [29], two tone streams with infrequently appearing deviant tones at random positions were used as stimuli. Both tone streams were composed of short beep tones with a length of 60 ms and a rise and fall time of 7.5 ms each. The beep tones were arranged according to the tone stream pattern LHL_LHL_... ('L' = low tone, 'H' = high tone, '_' = silent gap). In this way, the low tone stream (LTS) was twice as fast as the high tone stream (HTS). This was an attempt to make the streams more distinguishable. Based on our own experience when listening to the tone streams we considered the tone streams to be better distinguishable if the tones would not only differ in frequency (low/high) but also in the presentation rate (fast/slow). In the LTS, the inter-stimulus interval (ISI) was 300 ms and the standard low tones had a frequency of 396 Hz, whereas the low deviants had a frequency of 297 Hz. In the HTS, the ISI was 600 ms and the standard high tones had a frequency of 1900 Hz, whereas the high deviants had a frequency of 2640 Hz. Both tone streams were intermixed

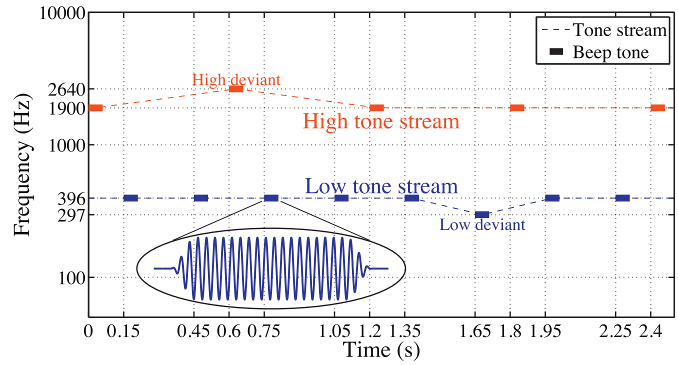

Fig. 1. Schematic representation of the two intermixed tone streams used as stimuli. Both the high and the low tone stream (dashed lines) consisted of short beep tones (short bars) with randomly placed deviants. In the high tone stream, every other tone is omitted corresponding to silent gaps in the tone stream pattern. The waveform of one standard low tone is also shown in magnified view.

with an offset of 150 ms. In Fig. 1, a schematic representation of the tone streams can be seen.

Since the frequency separation between both tone streams was large enough and the presentation rate was sufficiently high, the beep tones could be perceived as two segregated tone streams [31]. Therefore, it was possible to intentionally shift attention from one stream to the other and thus to modulate the P300 response elicited by the deviant tones in the attended tone stream [27–29,32]. The modulated P300 amplitude could then be used to infer which tone stream the participants paid attention to. Both tone streams were presented binaurally using in-ear headphones, making the paradigm usable for patients with only monaural hearing capabilities.

The percentage of deviant tones was 20 % in the HTS (slow) and 10 % in the LTS (fast) respectively, resulting in the same absolute number of deviants in both streams. The deviants were randomly distributed with some restrictions. In the LTS, between 5 and 13 standard low tones (uniform distribution; 9 tones on average) always appeared between two deviants. In the HTS, between 2 and 6 standard high tones (uniform distribution; 4 tones on average) always appeared between two deviants. Additionally, across streams, high and low deviants could not appear consecutively.

A regular computer with Matlab/Simulink together with a custom-made C++function to ensure high-speed and low-delay audio output was used to play the beep tones. The beep tones were generated with a sampling rate of 44,100 Hz. To ensure that all four types of beep tones (low/high standard tones, low/high deviant tones) were perceived equally loud, the loudness of the tones was adjusted according to the normal equal-loudness-level contours defined in the ISO standard ISO 226:2003 [33] (see Fig. 2). In this way, bias effects toward one of the streams were reduced.

2.2. Participants

This multi-centered study was conducted in two parts, one part with healthy subjects and another with MCS patients which was conducted approximately one year later. In the first part, 10 healthy subjects (3 female, 7 male) aged between 24 and 33 years (mean age 27.6 ± 3.0 (SD) years) participated in this study. They were informed in detail about the aims of the study, gave informed consent and were paid for participation. One participant reported a slight tinnitus in both ears, but had no problems hearing the beep tones or perceiving the two tone streams separately. All other participants did not report any hearing problems. All EEG measurements with healthy subjects were conducted at Graz University of Technology.

The second part of this study was conducted with 12 MCS patients (4 female, 8 male) aged between 14 and 66 years (mean