Improving Auditory Paradigms for Consciousness Detection by Brain-Computer Interfaces Technique

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***Abstract*—Recognition of consciousness using auditory oddball paradigms has become an important research topic in the brain-computer interface (BCI) field. Minimizing the time needed to acquire sufficient data for an assessment could be crucial for patients who have limited concentration. This study aims to reduce the assessment time for auditory oddball paradigms by testing different settings and stimulation approaches. One paradigm uses the subject's own name as deviant sound. The other paradigms use standard sine waves for stimulation. EEG activity was recorded during four different auditory oddball paradigms in a group of nine healthy persons. For comparison, the area under the curve of the P300 of each paradigm was calculated. First, we demonstrate that the name of the subject produced a larger P300 area than the sine tones. More importantly, we found that the name paradigm requires fewer trials to achieve similar results as in a standard auditory paradigm. This means the execution time of the auditory paradigm can be reduced compared to using sine waves.**

Keywords—Disorders of Consciousness, BCI, evoked potentials, P300

I. Introduction

Patients who survive a brain injury sometimes remain in states where they show no signs of consciousness. There are different disorders of consciousness (DOC) corresponding with different levels of function: coma, vegetative state (VS), minimal consciousness state (MCS), and locked-in syndrome (LIS). In VS, people show complete unawareness of themselves and the environment, but show sleep-wake cycles with some preservation of autonomic brain-stem functions. Patients in MCS show limited but clearly discernible evidence of consciousness of themselves or the environment, but are unable to communicate. LIS is a rare neurological disorder in which there is complete paralysis of all voluntary muscles except for the ones that control the movements of the eyes. Individuals with LIS are conscious and awake, but have no ability to produce movements (outside of eye movement) or to speak (aphonia). Cognitive functions are usually unaffected [1].

The diagnosis of patients with DOC is difficult and patients are often misclassified. Up to 43% of patients with DOC are erroneously assigned a diagnosis of VS [2]. This is due to the limitations of the behavioral rating scales used for the classification. New technologies that can add brain activity data could be a useful tool in overcoming these limitations. Medical imaging with functional magnetic resonance imaging (fMRI) or positron emission tomography (PET) have proven to be useful tools for awareness detection [3-5]. Electroencephalography (EEG)-based brain-computer interfaces (BCI) can also detect brain activity and show awareness by following a predefined task. Measurement of event-related potentials (ERPs) is an easy technique for evaluating residual cognitive functions in patients with consciousness disorders [6]. Late and cognitive evoked potential P300 are the most appropriate cognition-related waves which are related to the end of cognitive processing, to memory updating after information evaluation, and to information transfer to consciousness [7].

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Auditory paradigms using sinusoidal tones to elicit the P300 response have already been designed and evaluated successfully (e.g. [8]). Additionally, paradigms using the subject's own name for stimulation have been used in prior studies [9].

This study seeks to reduce the session time of the auditory oddball paradigm as used in a study before [8], by using the subject's own name as deviant sound and reducing the number of standard and deviant sounds. Four different auditory oddball paradigms are used for the study. These paradigms are tested in a control group (CG) of nine naïve healthy people to see which elicits a larger peak of the P300 wave, as a predictor of awareness.

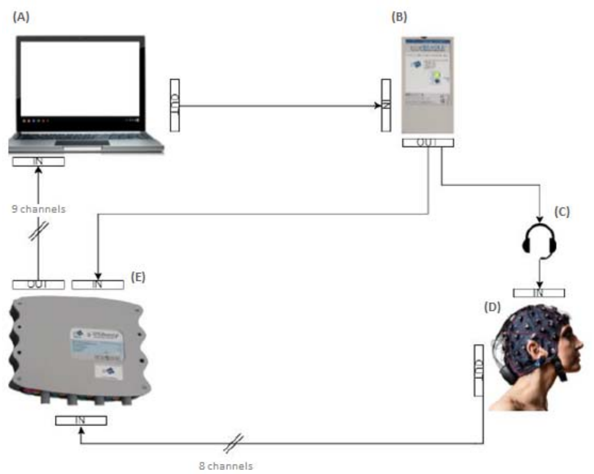

Figure 1. Schematic of the experimental setup. (A) Represents the computer, running the paradigms. (B) The audio trigger adapter box ensures precise triggering of audio stimuli. (C) The headphones provide the stimuli for the users. (D) EEG cap. (E) The g.USBamp records the EEG data and trigger events from (B) in synchrony and forwards data to the laptop.

II. Methods

A. Materials

To perform the study, we used a g.USBamp bio-signal amplifier, an audio trigger adapter box, an 8 channel EEG cap (all of which produced by g.tec medical engineering GmbH), MATLAB/SIMULINK and a pair of headphones.

Figure 1 shows a schematic of the setup. The PC produced the auditory paradigms coded in a MATLAB script and sent them to the audio trigger adapter box, which produced the sounds to the headphones and elicited a trigger signal that went to the amplifier. This hardware generated trigger prevents jitter on the EEG signal related to the onset of auditory stimulus.

Electrode locations included the FCZ, C3, CZ, C4, CP1, CPZ, CP2, and PZ positions. Reference electrode was placed in the right earlobe. The amplifier was set with a high pass filter at 0.5 Hz, a low pass filter at 30 Hz and a notch filter at 50 Hz. The 8 channels of EEG signals and the trigger signal were stored as a .mat file. The sampling frequency was 256 Hz.

B. Stimuli

For this study, 4 auditory paradigms were used, where the total number of stimuli and the ratio between deviant and standard stimuli varied: 1) a 7-1 ratio sine tone paradigm with a total of 60 deviant and 420 standard stimuli; 2) a 5-1 ratio sine tone paradigm with a total of 60 deviant and 300 standard stimuli; 3) a 4-1 ratio sine tone paradigm with a total of 60 deviant and 240 standard stimuli; and 4) a 4-1 ratio name paradigm with the subject's name as the deviant sound and a total of 20 deviant and 80 standard stimuli. Sine tones were used for paradigms 1 to 3, while a voice audio with the subject's name was used as deviant sound for paradigm 4 (name paradigm). For each paradigm 5 additional standard stimuli were presented in the beginning, to accustom the user to the stimuli and generate a stable P300 for the first deviant stimulus.

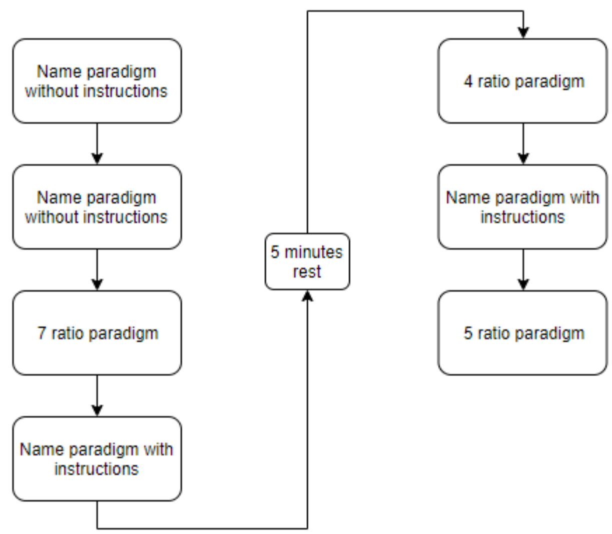

Figure 2. Example of an experiment workflow.

The sine tones had a frequency of 1000 Hz for deviant stimuli and 500 Hz for standard stimuli. All sounds had the same volume. For the first 3 auditory paradigms there was a 700ms delay between sounds, while for the name paradigms the delay was about 1500ms.

C. Protocol

Each participant (seven males and two females between 22 and 26 years old) was subjected to an experiment session consisting of seven runs of the different paradigms (Table 1). The name paradigm was performed in total four times. The first two runs of each session consisted of the name paradigm without any instruction to test the influence of passive P300 waves. The order of the remaining five runs was pseudo randomized for each session in order to reduce the effect of fatigue/training. After four runs the subjects were asked to take a five minute break. Figure 2 shows an example of the experiment workflow.

D. Signal Processing

Data were triggered for 100ms before, and 600ms after each stimulus.

First, artifacted trials were detected using a threshold value set to 100 µV. This meant if the EEG in one of the channels exceeded 100 µV or was below -100 µV, this trial was marked as an artifact trial and rejected from further calculations.

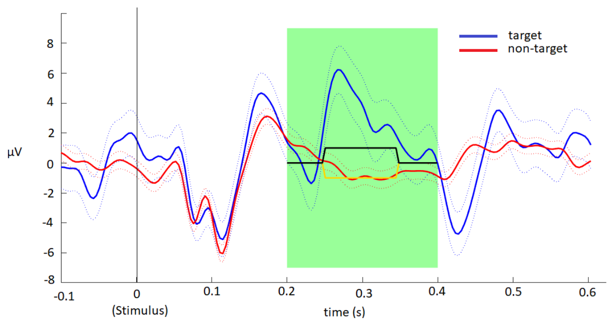

Figure 3. Deviant signal (blue), standard signal (red) of a channel for a specific run. The dotted line shows the SE of each signal, the orange line shows the areas where the SE of the deviant signal is greater than the SE of standard signals and the black line shows if these differences are statistically significant. The green marked area visualizes the time of 200ms to 400ms where the significant area is counted for analysis.

Next, we assume each trial contains an ERP (deterministic component) and noise (indeterministic, zero-based component). Therefore, every trial was base-line corrected, subtracting the mean of the first 100ms of EEG (prior to the stimulus) from the whole trial. Finally, all trials of the same type (deviant or standard) were averaged. This led to an averaged representation of the EEG response to deviant and standard stimuli for each channel of the EEG cap in every run, with minimal noise. Additionally, the standard error (SE) was calculated for the averaged deviant and standard responses. An example of those response can be seen in Figure 3.

TABLE I.

Run	Properties			Duration
	Paradigm	***Number of deviant stimuli***	***Number of standard stimuli***	***Minutes***
1	Name without instructions	20	80	3
2	Name without instructions	20	80	3
3	7 ratio	60	420	5.6
4	5 ratio	60	300	4.3
5	4 ratio	60	240	3.6
6	Name with instructions	20	80	3
7	Name with instructions	20	80	3

Properties of each run of the experiment.

E. Data Analysis

To detect how large the P300 was in each channel, we computed the difference between the deviant and standard signal areas from 200ms to 400ms (green area in Figure 3) after the stimulus as this is the time window where the P300 most commonly occurs [7]. First, the time windows where the lower SE of the deviant signal was greater than the upper SE of the standard signal was detected (if any). This is marked in Figure 3 with the orange line. Then, a Mann-Whitney U test was performed between those SE, to check if there are statistical differences between them. Significant differences are marked with the black line in Figure 3.

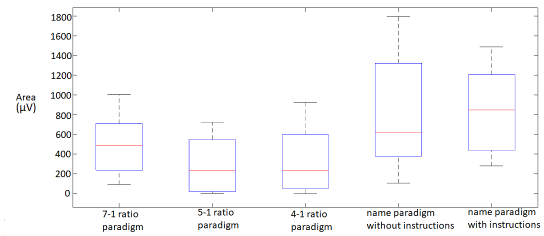

Figure 4. Mean, 25th and 75th percentile of the area for each paradigm.

We call the significant difference between the SE of deviant and standard trials between 200ms and 400ms "area." In the example of Figure 3, they are marked with a black line. Thus, each run led to 8 areas (one per channel) that are added together to get one single value representing the quality of the ERPs in the run. Then the area representing each paradigm in each subject are averaged obtaining one area representing the averaged ERP quality for a given paradigm.

III. Results

A Friedman test was performed to see if the differences between each paradigm's areas was bigger than the differences within the paradigm's areas. An $\alpha=0.05$ was set as the significance threshold.

To analyze the areas in an individual way, the mean, 25th, and 75th percentile of each paradigm was calculated (Figure 4). To analyze the paradigm's areas in an individual way, a Wilcoxon test was performed comparing pairs of 2 paradigms.

The Friedman test resulted in a p value < 0.005, meaning that there are statistical differences between the paradigm's areas.

The Wilcoxon test showed that there were no statistical differences (p=0.135, p=0.19, p=0.29, p=0.06) in areas between the 7-1 ratio paradigm and the 5-1 ratio, 4-1 ratio, name paradigm without instructions, and name paradigm with instructions, respectively (Figure 5).

The name paradigm with instructions was compared with the other paradigms, and no significant differences (p=0.06, p=0.86) were found with the 7-1 ratio and name without instruction paradigm. However, there were differences (p=0.01) between the name paradigm with instructions and the 5-1 ratio and 4-1 ratio paradigms. For the name paradigm without instruction, there are no statistical differences compared with the 7-1 ratio paradigm (p=0.29) or the name

(A)

7 ratio	
Paradigm	p-value
5 ratio	0,135
4 ratio	0,19
name without instructions	0,29
name with instructions	0,06

(B)

name with instructions	
Paradigm	p-value
7 ratio	0,06
5 ratio	0,01
4 ratio	0,01
name without instructions	0,86

(C)

name without instructions	
Paradigm	p-value
7 ratio	0,29
5 ratio	0,03
4 ratio	0,03
name with instructions	0,86

Figure 5. (A) *p*-values of the Wilcoxon test of the 7-ratio paradigm against the rest of the paradigms. (B) *p*-values of the Wilcoxon test of the name paradigm with instructions against the rest of paradigms. (C) *p*-values of the Wilcoxon test of the name paradigm without instructions against the rest of paradigms.

paradigm with instruction (p=0.86), but there are statistical differences (p=0.03) with the 5-1 ratio and 4-1 ratio paradigms. Figure 5 illustrates such results.

The P300 area of the 7-1 ratio paradigm is 491 µV, while they are 281 µV, 310 µV, 818 µV and 856 µV for the 5-1 ratio paradigm, 4-1 ratio paradigm, name paradigm without instructions, and the name paradigm with instructions, respectively. The statistical analysis showed that there are no differences (p=0.135, p=0.19, p=0.29, and p=0.06) in terms of P300 area between the 7-1 ratio and the other paradigm proposed in this paper. All paradigms produced the same areas regardless of the paradigm duration, which was 5.6, 4.3, 3.6, and 3 minutes for the 7-1 ratio, 5-1 ratio, 4-1 ratio, and name paradigm, respectively. Nevertheless, the use of the subject's own name as deviant sound produced the maximum P300 area with the least execution time.

IV. Discussion

As can be seen in the Results section, there is no statistical difference in the P300 area between the 7-1 ratio paradigm and the name paradigm with/without instructions. This means that these two name paradigms, with a shorter time execution than the 7-1 ratio paradigm, get the same results. This is an improvement in P300 detection because the experiment time can be reduced by almost 50%. What this means for DOC patients still needs to be evaluated. Risetti and colleagues found significant amplitude changes for a passive name paradigm in patients in a sample of VS and MCS patients, but a significant increase in amplitude for active counting only in MCS and not in VS patients [10]. Although their paradigm was slightly different from ours, the name paradigms could possibly be used to assess the status of DOC patients.

The 5-1 and 4-1 ratio paradigms were demonstrated to be as effective as the 7-1 ratio paradigm in terms of eliciting the P300, indicating a possible option for reducing the time requirement of a consciousness detection BCI experiment. The Wilcoxon test shows that there are statistical differences (p=0.01) between the name paradigm and the 5-1 and 4-1 ratio paradigms. The mean values of each paradigm show that the name paradigms produced a better P300 than the 5-1 and 4-1 ratio paradigms, indicating better BCI performance. The reduction of the ratio is a good solution but not as good as the use of the subject's name as the deviant sound.

One limitation of this study worth considering is that results from healthy controls could differ highly from results in DOC patients. The time needed for an experiment could be crucial for patients with a limited attention span, while not being as relevant for healthy controls. Additionally, the meaning of a passive P300 response in DOC patients needs further investigation.

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