Bone–conduction–based Brain Computer Interface Paradigm - EEG Signal Processing, Feature Extraction and Classification -

Daiki Aminaka[1], Koichi Mori[2], Toshie Matsui[1], Shoji Makino[1], and Tomasz M. Rutkowski[1,3,*]
[1]*Life Science Center of TARA, University of Tsukuba, Tsukuba, Japan*
[2]*Research Institute of National Rehabilitation Center for Persons with Disabilities, Tokorozawa, Japan*
[3]*RIKEN Brain Science Institute, Wako-shi, Japan*
[*]*Email: tomek@tara.tsukuba.ac.jp*
http://bci-lab.info/

***Abstract*—The paper presents a novel bone–conduction based brain–computer interface paradigm. Four sub–threshold acoustic frequency stimulus patterns are presented to the subjects in an oddball paradigm allowing for "aha–responses" generation to the attended targets. This allows for successful implementation of the bone–conduction based brain–computer interface (BCI) paradigm. The concept is confirmed with seven subjects in online bone–conducted auditory *Morse–code* patterns spelling BCI paradigm. We report also brain electrophysiological signal processing and classification steps taken to achieve the successful BCI paradigm. We also present a finding of the response latency variability in a function of stimulus difficulty.**

***Keywords*-Auditory BCI, P300, EEG, brain signal processing.**

I. Introduction

A brain computer interface (BCI) is a technology that utilizes human neurophysiological signals to communicate with an external environment, without depending on any muscle activity [1]. Particularly, in the case of patients suffering from locked–in-syndrome (LIS) [2], such technology could help them to communicate or to complete various daily tasks (type messages on a virtual keyboard or control their environment using a computer, etc). This would create a very good option for amyotrophic lateral sclerosis (ALS) or coma patients to communicate with their families, friends or caretakers by using only their brain waves. Recently, many approaches have focused on visual modality BCI applications, which results with the most reliable evoked response potentials (ERP) [3]. However, a visual modality BCI has limited application in case of ALS patients who, in the advanced stages of the disease, often suffer from limited or lost sight. In this paper, we present the concept and report results obtained with an auditory bone–conduction stimuli based BCI, which we refer to in brief as bcBCI (bone–conduction BCI). The stumuli are four *Morse–code* auditory patterns as in a classical BCI–speller included in the original BCI2000 package. The bcBCI concept is based on a feature of the human skull which allows for a transmission of acoustic frequency vibrations directly into inner ear [4], [5]. This will allow to create a less intrusive and using a higher frequency, close to upper band hearing threshold, acoustic stimuli. The bone–conduction effect for audio, which could help ALS–LIS or coma patients with additionally compromised hearing due to middle ear effusion/negative pressure (a so–called "ear stacking syndrome" [6]). The acoustic stimuli near upper band frequency hearing threshold for subject could be easy to ignore the *non–targets* stimuli. To confirm these two advantages of bcBCI, we conducted a phychophysical experiment and an EEG measurement using high frequency sound patterns which were similar to *Morse–code*. The experiments were carried out with seven healthy subjects as a pilot study of clinical application for ALS patients.

In this paper, we report also on the new finding that the different ERP latency of the $P300$ response (a so–called "aha–response" starting at around 300 ms after expected target stimulus onset - see Figures 5 and 6) supports the discrimination between auditory stimulus targets attended to or not.

The remainder of the paper is organized as follows. In the next section, the experimental set up and the bone–conduction auditory paradigm are described, together with EEG signal pre–processing steps. Next, analysis and optimization procedures of the ERP $P300$ response latencies for all experimental subjects are described. Finally, the paper is concluded by classification and discussion of the bcBCI paradigm's information transfer rate (ITR) [7] results, together with future research directions.

II. Materials and Methods

The experiments in this paper were performed in the Life Science Center of TARA, University of Tsukuba, Japan. All the details of the experimental procedure and the research targets of this approach were explained to the seven healthy human subjects, who agreed voluntarily to take a part. The psychophysical and online EEG BCI experiments were conducted in accordance with *The World Medical Association Declaration of Helsinki - Ethical Principles for Medical Research Involving Human Subjects*. The experimental procedures were approved and designed in agreement with the ethical committee guidelines of the Faculty of Engineering, Information and Systems at University of Tsukuba, Tsukuba, Japan. The experimental protocol was designed to compare results with the previously developed auditory BCI experiments as first proposed by Rutkowski et al. [8] and further expanded to audiovisual paradigm by Chang et al. [3]. In

[*]Corresponding author.

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the presented study we extended the previously proposed approach by creating the novel auditory BCI by including the bone–conduction–based stimulus reproduction [5].

Seven right–handed volunteer subjects participated in the experiments. The average age of the subjects was 24.71 years old (standard deviation 7.50 years old; one female and six male participants).

In the following sections we explain details of the bone–conduction stimulus creation, together with the psychophysical and EEG experiments protocols respectively.

A. Bone–conduction Stimulus Generation

The bone–conducted auditory stimuli were delivered to the subject scalp via transducers as sinusoidal waves generated by a portable computer with MAX 6 software [9].

The subject mastoids were stimulated using safely attached two BCT-1 22 x 14 mm bone–conducting transducers, attached at each side of a scalp, with a frequency response in a range of $300 \sim 19,000$ Hz. The bone–conducting transducer was placed under an EEG cap in order to keep it slightly pushed toward the mastoid (with a pressure below 5 N), as depicted in Figure 1. The high acoustic frequency guaranteed no electromagnetic interference with the active EEG recording electrodes.

Each transducer was set to emit a sinusoidal wave at 1500 Hz (roughly a single frequency decade) below each subject's upper band frequency hearing threshold. In order not to emit uncomfortable loudness for each subject in both psychophysical and EEG experiment the sound level was set to not exceed 60 dB (as measured in close distance with integrated sound level meter LA-1440 by OnoSokki, Japan). For all the subjects in the presented experiments the hearing thresholds did not exceed upper frequency limits of the bone–conduction transducer used in the study (see Table I). The subject upper band frequency hearing thresholds were evaluated individually before experiments using a freeware software application MaMiMiChk version 1.010 [10].

Four patterns combining short and long sound signals resembling *the Morse–code* letters were chosen as bone–conducted stimuli (see Table II for details). In the psychophysical experiment the subject was instructed to recognize only a target pattern while ignoring the other sounds. Behavioral responses were collected in form of computer keyboard button–presses. Later, in the online EEG BCI experiments only the mental response (the so–called "aha" or P300) after each target stimulus was captured and classified. In the both above experimental paradigms the training instructions were presented visually by means of the MAX 6 program designed by our team as depicted in form of an user interface display in Figure 2.

B. Psychophysical Experiment Protocol

The psychophysical experiment was conducted to investigate subjects' response time and recognition accuracy of auditory bone–conducted stimulus patterns used later in the online BCI sessions. The behavioral responses were collected using numeric keypad and the developed by our team MAX 6 program as shown in Figure 2. Each subject was instructed to press the response button with a dominant hand when *the target* stimulus was heard in a random series presentation. The correctly identified *targets* were counted by the program together with behavioral response time delays. The stimuli lengths and patterns has been summarized in Table II. Before each random presentation series the subject was instructed auditory and visually (in form of an arrow pointing the *Morse–code* pattern as in Figure 2) which $target$ pattern to attend. In the psychophysical experiment each subject was presented with 80 *target* and 240 *non–target* patterns in order to collect enough samples for the subsequent statistical analysis. Each trial was composed of a randomized series

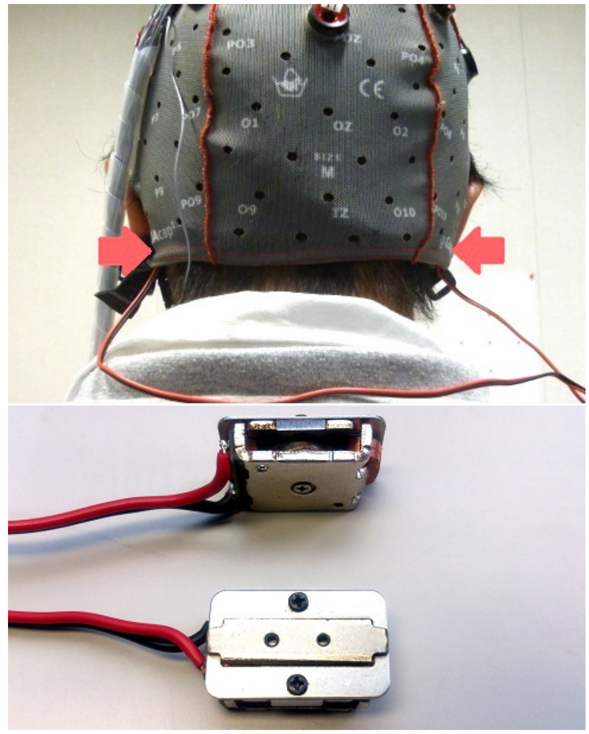

Figure 1. The experimental bone–conduction stimulus delivery set up. Each bone–conducting transducer (as shown in the lower panel) was set between each mastoids and the EEG cap surface. The top panel in the above figure depicts the transducer locations with red arrows. The bottom panel shows two BCT–1 22 x 14 mm bone–conducting transducers in top and side views. The same set up was used for the psychophysical and the EEG experiments.

Table I
EXPERIMENTAL SUBJECT SEX, AGE, AND HEARING THRESHOLD SUMMARY

Subject number	Sex	Age [years old]	Frequency upper bound hearing threshold [kHz]
#1	male	21	17.5
#2	male	43	14.0
#3	male	23	16.5
#4	female	22	14.0
#5	male	21	18.0
#6	male	22	18.0
#7	male	21	17.0

Table II
FOUR ACOUSTIC BONE–CONDUCTION STIMULUS PATTERN TYPE DETAILS

Stimulus type	Stimulus duration	Morse code pattern
pattern #1	75 ms	·
pattern #2	200 ms	· ·
pattern #3	350 ms	· –
pattern #4	350 ms	—

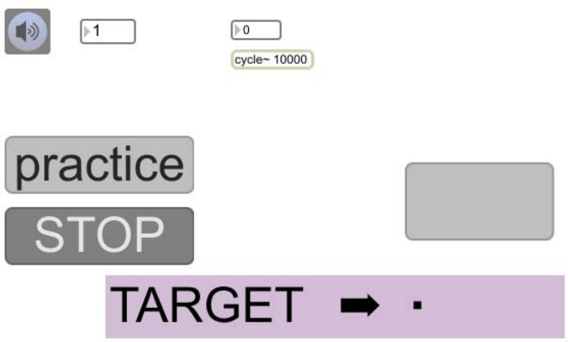

Figure 2. The user interface display with instructions presented to the subject during the experiments. Each stimulus in form of the *Morse–code* letter and its visual representation was displayed located in the bottom purple square. The top and left side controls were used by the experimenter to set up acoustic frequency and to start practice or experimental sessions respectively. Practice session was used for the subject to familiarize with the sound patters and the associated *Morse–code* instruction pictograms.

of four pattern stimuli of which inter-stimulus-interval (ISI) was set to 1500 ms. The ISI was decided to provide sufficient time to press button based on a preliminary experiment. The single random series was generated to contain one *target* and three *non–targets*. Each of the four bone–conducted sound patterns was 20 times presented as the *target*.

The response time were recorded with the same MAX 6 program, which also used for the stimulus generation and instruction presentation. The results of the psychophysical experiments are discussed in the Section III-A.

C. EEG Experiment Protocol

In the EEG BCI online experiment the bone conducting transducers were attached to the mastoids in the same manner as in the previously explained psychophysical session (see Figure 1). This time the EEG electrodes were also used in order to collect electrical brain waves online. The EEG signals were captured with a portable EEG amplifier system g.USBamp by g.tec Medical Engineering GmbH, Austria. The 16 active wet EEG electrodes were connected attached to the extended $10/10$ international system [11] head locations as follows: Cz, Pz, P3, P4, C3, C4, CP5, CP6, P1, P2, POz, C1, C2, FC1, FC2, and FCz. The ground electrode was attached to head location FPz and the reference electrode was attached to left earlobe. Details of EEG experiment set up are summarized in Table III. The sampling frequency was set to 512 Hz and a notch filter in a rejection band of $48 \sim 52$ Hz was applied to remove power line interference of 50 Hz.

Table III
EEG EXPERIMENT CONDITION DETAILS

Number of subjects	7
Stimuli length	$\{75, 200, 350\}$ ms (see Table II)
Stimuli frequency	1500 Hz under each subject's threshold (see Table I)
Inter-stimulus-interval	500 ms
EEG recording system	g.USBamp with active wet EEG electrodes system
Number of EEG channels	16
Electrode locations	Cz Pz P3 P4 C3 C4 CP5 CP6 P1 P2 POz C1 C2 FC1 FC2 FCz
Reference electrode	Left earlobe
Ground electrode	FPz
Stimulus generator	2 BCT-1 22 x 14 mm Bone Conducting Transducer
Number of sequences	5

The recorded EEG signals were captured and preprocessed by the BCI2000–based application [12]. The 16–channels EEG signals were next bandpass filtered with 8^{th}–order Butterworth IIR high– and low–pass filters set at 0.1 Hz and 60 Hz cutoff frequencies respectively in order to avoid possible phase distortion caused by a single filter.

The EEG responses classification in online BCI mode was conducted using a stepwise linear discriminant analysis (SWLDA) [13] method with features drawn from the $0 - 800$ ms of the ERP interval. The inter–stimulus–interval (ISI) was set to 500 ms and each bone–conducted sound utterance duration was ranged from 75 ms to 350 ms as shown in Table II. The ISI was decided to provide sufficient time to distinguish each stimulus and reduce test duration.

In the online BCI experiment each *target* was presented ten times in a single series and the averages of the ten ERPs were later used for the classification in order to filter out random noise activity very common in the EEG signals [1], [12]. The subjects were requested to limit eye–blinks and movements to avoid responses rejections or time consuming muscular artifact filtering [14].

Each subject performed five sessions of spelling the four *Morse–code* symbols (all together randomized 40 *targets* and 120 *non–targets* for each pattern in a signal session).

III. RESULTS

This section presents and discusses results that we obtained in the psychophysical and in the online bcBCI experiments. The very encouraging results obtained in the bcBCI paradigm support the proposed concept.

A. Psychophysical Experiment Results

The psychophysical experiment results are summarized in Figures 3 and 4 in form of response time distributions and accuracy confusion matrix, respectively. The median response times and the probability distributions are depicted for each stimuli pattern as *violin–plots* in Figure 3. One-way ANOVA was performed on the response time (at the 0.05 level). The effect of stimulus type was significant ($F(3, 539) = 7.3418$, $p < 0.0001$). Tukey-Kramer HSD test resulted in significant pattern differences $\#3$ $vs.$ $\#4$ and $\#3$ $vs.$ $\#1$ ($p < 0.0001$ and $p = 0.0485$, respectively). This result showed that response time might depend on stimuli duration. The above observation was not confirmed in response accuracy presented in form of confusion matrix presented in Figure 4, since the subjects did not make mistakes between patterns #3 and #4, but mostly between #2 and #3 as visualized on form of larger percentages in off–diagonals. Overall the psychophysical experiments accuracies were satisfactory and allowed us to conduct the bcBCI EEG experiments of which results are presented in the next section.

Table IV
PSYCHOPHYSICAL EXPERIMENT RESULTS (NOTE, THIS IS NOT A BINARY ACCURACY CASE YET THE ONE WITH A THEORETICAL CHANCE LEVEL OF 25%) IN AUDITORY BUTTON-PRESS TASK.

Subject number	The best psychophysical accuracy
#1	100%
#2	100%
#3	100%
#4	100%
#5	100%
#6	100%
#7	95%
Average:	**99.3%**

B. *bcBCI EEG Experiment Results*

The results of the online bcBCI EEG experiment are summarized in Tables V and VI in form of interfacing accuracies and ITR scores respectively. Additionally we present the brain responses in Figures 5, 6, and 7. The six subjects, except for subject #3, could score well above the chance level of 25% in the proposed bone–conduction auditory experiment. The ITR scores resulted in the range from 0.62 bit/min to 6.00 bit/min, which shall be considered to be a good outcome. The ITR scores are usually calculated as follows,

$$ITR = V \cdot R \tag{1}$$

$$R = \log_2 N + P \cdot \log_2 P + (1 - P) \cdot \log_2 \left(\frac{1 - R}{N - 1} \right), \tag{2}$$

where R stands for the number of bits/selection; N is the number of classes (four in this study); P is the classification accuracy (see Table V); and V is the classification speed in selections/minute (3 selections/minute in this case). The summary of ITR results obtained in this study is presented in the Table VI.

Detailed brain wave responses in form of grand mean averages are presented in Figures 5 and 7. Figure 5 depicts the separated electrode plots with *target* ERPs in red and *non–targets* in black. The very obvious and significant differences (as visualized by non–overlapping standard errors plotted around the mean traces of the P300 peaks) between the two response types are visible in a latency ranges of $400 \sim 800$ ms. Figure 7 presents also color coded *target* and *non–targets* responses together with area under the curve (AUC) distributions dissimilarities allowing to visualize the latencies at which machine learning classifiers shall be able to properly classify the responses (here again the same ERP latency range $400 \sim 800$ ms is preferable). The top panels depict also EEG electrodes locations and responses visualization at the maximum and minimum AUC latencies. Finally, Figure 6 presents a very interesting phenomenon observed

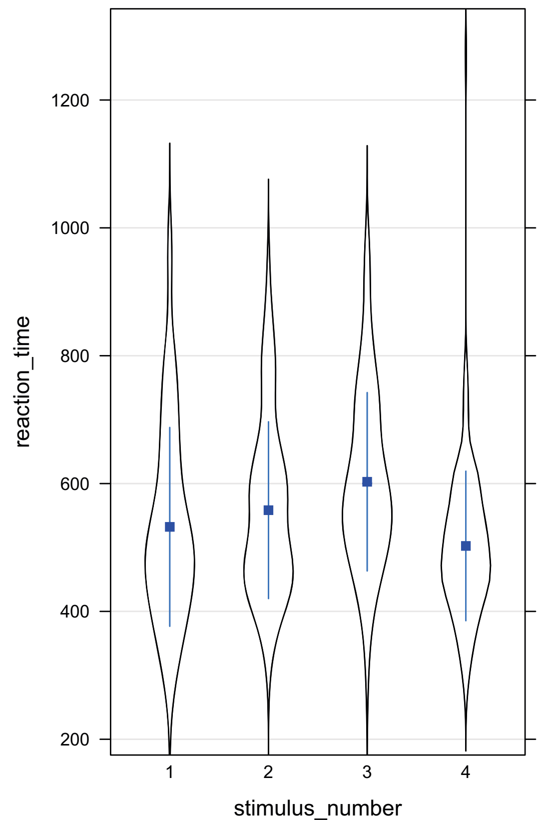

Figure 3. Psychophysical experiment response time probability distributions of all subjects together summarized in form of *the violin–plots* depicting also medians and interquartile ranges. Each number at the horizontal axis represents the stimuli pattern $\#1 \sim \#4$. The horizontal axis represents the reaction (behavioral response) time delays in [ms].

Table V
SINGLE TRIAL BASED BCI ACCURACY (NOTE, THIS IS NOT BINARY P300 CLASSIFICATION RESULT BUT RESULTING SPELLING RESULT WITH A THEORETICAL CHANCE LEVEL OF 25%) IN BONE CONDUCTION AUDITORY BCI SPELLING TASK USING THE CLASSICAL SWLDA CLASSIFIER.

Subject number	Online BCI experiment SWLDA accuracy
#1	100%
#2	75%
#3	25%
#4	100%
#5	75%
#6	75%
#7	50%
Average:	**71.4%**

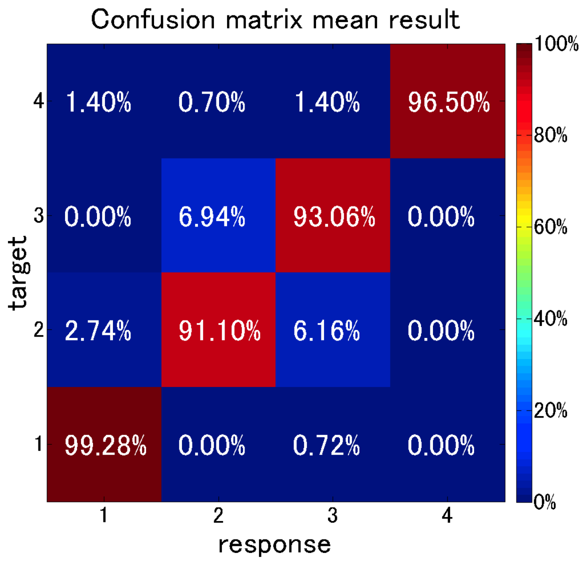

Figure 4. Psychophysical experiment response grand mean average accuracy of the seven subjects confusion matrix is presented in form of color coded matrix. The horizontal axis represents the instructed *targets* and vertical axis the subject response. The off–diagonal responses and accuracies represent the marginal errors made by the subjects.

Table VI
SINGLE TRIAL BASED SPELLING ACCURACY (SEE TABLE V) BASED ITR RESULTS.

Subject number	ITR scores
#1	6.00 bit/min
#2	2.38 bit/min
#3	0.00 bit/min
#4	6.00 bit/min
#5	2.38 bit/min
#6	2.38 bit/min
#7	0.62 bit/min
Average:	**2.82** bit/min

in our study where the P300 responses turned to have modulated latencies depending on the bone–conducted stimulus type. The separately plotted and color–coded *targets* show slight shifts. The "fastest" response seems to be caused by the simple pattern #1 (see Table II), while the remaining responses have delayed and extended latencies. This phenomenon shall be a target of our further research, since the varying P300 response latencies could be used for training separate classifiers in order to boost the overall BCI accuracies [15].

IV. CONCLUSIONS

The purpose of our project was to develop a bone–conduction auditory BCI paradigm. In order to realize the purpose, we aimed to test the four *Morse–code* auditory bone conducted patterns as in a classical BCI–speller included in the original BCI2000 package. There have been conventional studies which have reported difficulty in the auditory stimuli perception by some ALS patients due to the so–called *ear–stacking–syndrome.* Therefore, we proposed to utilize the bone–conduction auditory BCI in order to bypass an obstructed auditory air–conduction channel. This paper has reported a successful implementation of the four bone–conduction based auditory BCI. We conducted experiments to verify the efficiency of such a proposal. According to the results obtained with seven subjects, six of them could perform online spelling interfacing above a chance level, while two of them reached 100% accuracy. This result supports the efficiency of our approach.

Additionally a very interesting observation was reported showing a possible room for further improvement of the proposed approach by utilizing variable latencies of the P300 responses to various bone–conduction patterns. We aim to approach this problem in our future research.

AUTHOR CONTRIBUTIONS

Designed and performed the EEG experiments, as well as analyzed the data: DA, TMR. Conceived the concept of the bone–conduction BCI: TMR, KM. Supported the project: SM, TM. Wrote the paper: DA, TMR, TM.

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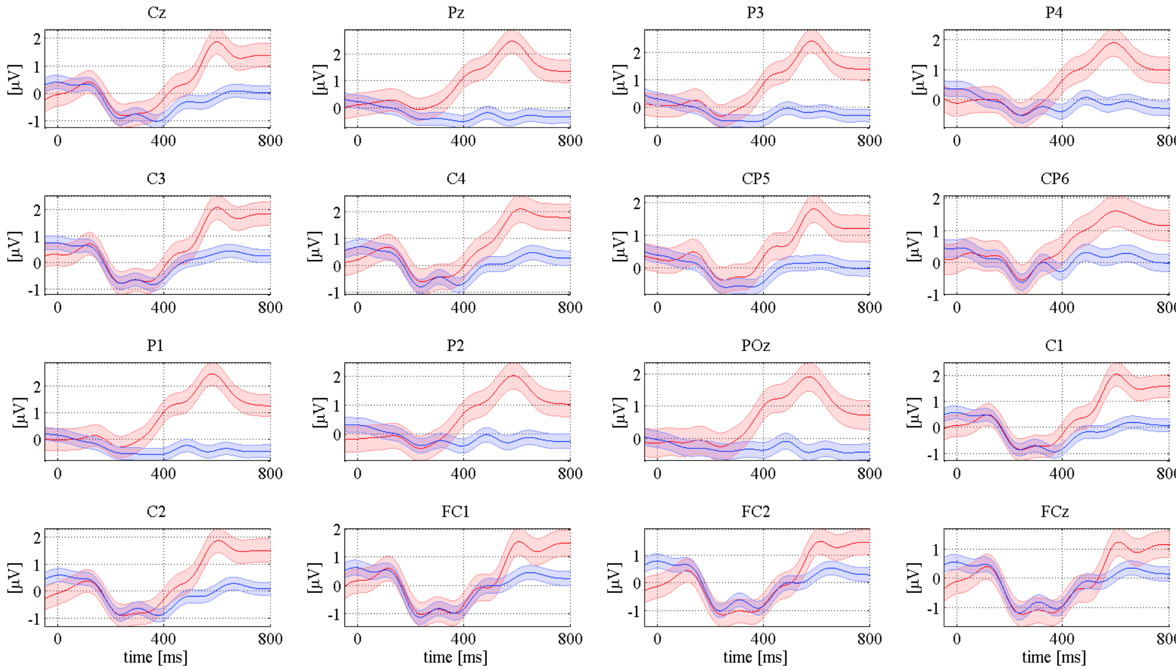

Figure 5. Grand mean averaged ERP responses for all participating subjects presented for all EEG electrodes separately. The ERP responses were further low–pass filtered below 8 Hz. The red lines depict *targets* and blue *non–targets* respectively. The very clear P300 responses are visible in latency ranges of 400 $\sim$ 800 ms, while the 0 ms stand for the stimulus onsets.

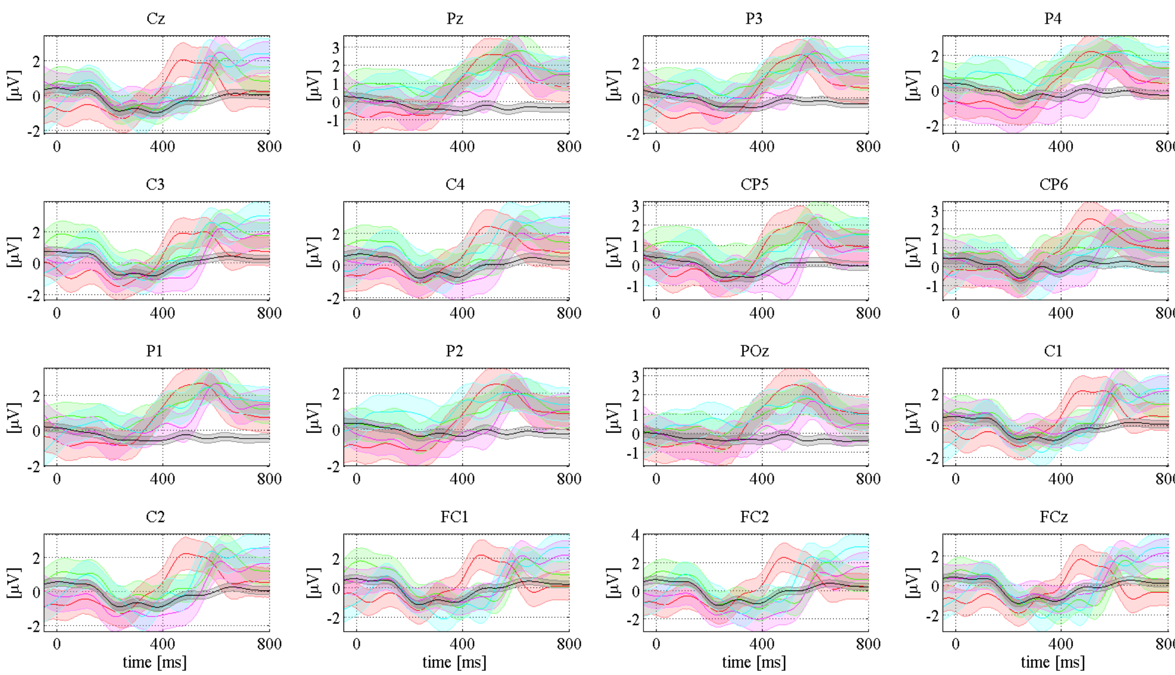

Figure 6. The separated grand mean ERP from the EEG electrodes used in the experiments for the four stimulus patterns showing different P300 response shapes. The black lines represent non–targets, and *red, green, cyan,* and *magenta* for target patterns $\#1, \#2, \#3, \#4$, respectively. The most interesting differences are in pattern number 1 and 4 where the P300 and late responses differ the most significantly.

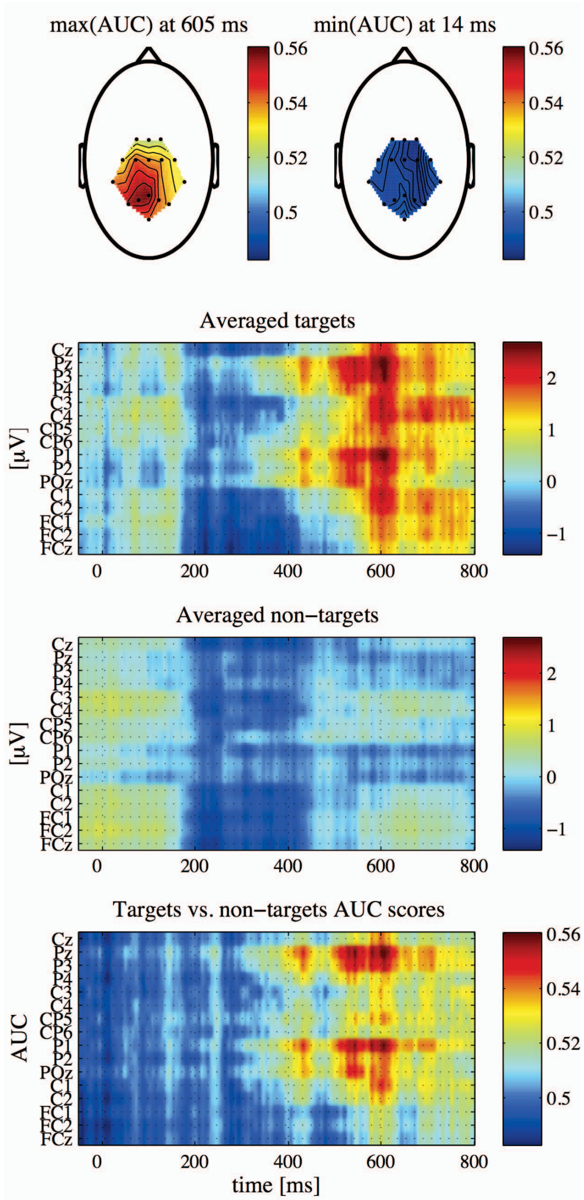

Figure 7. Grand mean ERP and AUC scores leading to final classification results of the all participating subjects. The top panels represent the head topographic plots of the *target* versus *non–target* area under the curve (AUC), which is a measure commonly used in machine learning intra-class discriminative analysis (AUC > 0.5 is usually assumed to be confirmation of features separability). The top left panel represents a latency of the largest difference as obtained from the data displayed in the bottom panel of the figure. The top right panel represent the smallest AUC latency. Those topographic plots also show the electrode positions. The fact that all the electrodes received similar AUC values (red) supports the initial electrode placement. The second panel from top represents averaged EEG responses to the *target* stimuli (P300 response in the range of 400-800 ms). The third panel from top represents averaged EEG responses to the *non–target* stimuli (no P300 response). Finally, the bottom panel depicts the AUC of *target* versus *non–target* responses (P300 response latencies could be again easily identified here by red color–coded values).

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