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EEG Signal Processing and Classification for the Novel Tactile–Force Brain–Computer Interface Paradigm

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***Abstract*—The presented study explores the extent to which tactile–force stimulus delivered to a hand holding a force–feedback joystick can serve as a platform for a brain–computer interface (BCI). The four pressure directions are used to evoke tactile brain potential responses, thus defining a tactile–force brain computer interface (tfBCI). We present brain signal processing and classification procedures leading to successful online interfacing results. Experimental results with seven subjects performing online BCI experiments provide a validation of the hand location tfBCI paradigm, while the feasibility of the concept is illuminated through remarkable information–transfer rates.**

***Index Terms*—EEG, tactile BCI, brain signal processing, brain somatosensory evoked response.**

I. Introduction

The state–of–the–art BCI is usually based on mental visual and motor imagery paradigms, which require substantial user training and good eyesight from the subject [1]. Alternative solutions have been proposed recently to make use of spatial auditory [2] or tactile (somatosensory) modalities [3], [4], [5], [6], [7] to enhance brain-computer interfacing comfort. The concept proposed and reported based on a conducted pilot study in this paper further extends the previously reported by the authors [6], [8] brain somatosensory (tactile) channel to allow for tactile–force based stimulus application. The rationale behind the use of the tactile–force tactile channel is that it is usually far less loaded and more intuitive to learn comparing with auditory or even visual modality interfacing applications. A very recent report [7] additionally has confirmed superiority of the tactile BCI in comparison with visual and auditory modalities as tested with a locked–in syndrome (LIS) subject [9].

Another report [5] proposed to utilize as the tactile BCI a Braille–code stimulator with 100 ms static force push stimulus delivered to each of six fingers to generate a somatosensory evoked potential (SEP) response and the following P300 attentional modulation. The P300 response is a positive electroencephalogram SEP deflection starting at around 300 ms and lasting for 200 – 300 ms after an expected stimulus in an oddball (random) series of distractors [1]. Examples of averaged P300 responses are depicted in form of color coded diagrams in Figure 5 and using time series plot red lines with standard errors in Figure 6.

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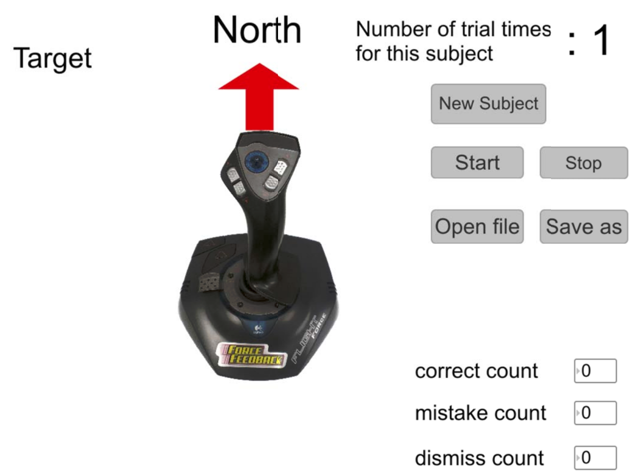

Fig. 1. The visual instruction screen presented to the subjects during the psychophysical experiment developed in MAX 6 [11].

The P300 brain response is considered to be the most reliable and easy to capture from EEG in majority of human subjects. Thus, the P300 is commonly used in BCI applications [1], [10].

This paper reports on the novel successful application of the tactile–force BCI. We present very encouraging results obtained with seven healthy subjects of whom the majority scored with 100% accuracy in online BCI experiments.

The rest of the paper from now on is organized as follows. The next section introduces the materials and methods used in the tactile–force BCI study. It also outlines the experiments conducted. The results obtained in EEG online experiments with seven healthy BCI subjects are then discussed. Finally, conclusions are formulated and directions for future research are outlined.

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II. Materials and Methods

The experiments in the reported study involved seven healthy subjects (six males and one female; mean age of 24.71 years, with a standard deviation of 7.5 years). All the experiments were performed at the Life Science Center of TARA, University of Tsukuba, Japan. The 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 psychophysical and EEG recording for BCI paradigm experimental procedures were approved by the Ethical Committee of the Faculty of Engineering, Information and Systems at University of Tsukuba, Tsukuba, Japan. The participants agreed voluntarily to take part in the experiments. The details of the tactile–force stimulus creation, psychophysical and EEG experimental protocols are described in the following subsections.

A. Tactile–Force Stimulus

The tactile stimuli were delivered as movements generated by a portable computer in MAX 6 [11] environment as depicted in form of visual interface with instructions to the subject in Figure 1. Each tactile stimulus was generated via a Force Feedback Joystick Driver for Java [12]. The stimuli were delivered to the subject's right palm via the FLIGHT FORCE joystick by Logitech.

There were four stimulus tactile–force direction patterns delivered in random order to the subject hand. The directions were labeled as *North, East, West,* and *South* as depicted in Figure 2. For example, the *North* directions stimulus interaction caused the joystick generate a forward tactile–force pressure on the subject's hand holding it. Similarly the *South, East,* and *West* stimulus directions were causing backward, right, and left tactile–force pressures on the subject hand respectively. The joystick returned to the center position (no pressure) after the each presented stimulus after the presentation time of 100 ms (see Tables I and II with experimental condition details summarized).

During the both psychophysical and EEG experiments the subject held the joystick handle using a dominant hand (right in case of all the subjects participating in this study) and responded (button press in psychophysical– and mental confirmation/counting in case of EEG–experiment) only to the instructed direction. The instruction which directions to attend were presented visually using the same MAX 6 environment program that created the stimulus and communicated it via the Java driver to joystick as depicted in Figure 1.

B. Tactile–Force Psychophysical Experiment Protocol

The psychophysical experiment was conducted to investigate the stimulus tactile–force direction influence on the subject behavioral response time and accuracy. The behavioral responses were collected using a trigger button on the joystick handle and the MAX 6 program. The subject was instructed which stimulus to attend in each session by an arrow on the computer display pointing the direction of *an target* as depicted in Figure 1. In the each psychophysical experiment the subject was presented with 80 *target* and 240 *non–target* directions as stimuli.

Fig. 2. The force–feedback (or tactile–force) joystick FLIGHT FORCE by Logitech used in experiments reported in this paper. The tactile–force stimulus was delivered to the subject's dominant hand. Four movements, defined as *North, East, South* and *West* directions, were executed randomly from a computer causing the joystick handle to move and push the subject's hand automatically.

Each trial was composed of 100 ms tactile–force pressures delivered to subject hand in randomized order with an inter–stimulus–interval (ISI) of 900 ms. Every random sequence thus contained a single *target* and three *non–targets*. A single session was composed of the ten trials for each tactile–force *target*. The choice of the relatively long ISI was justified by a slow behavioral response in comparison to the EEG evoked potential, as described in the next section. The tactile–force psychophysical experiment protocol details are summarized in Table I.

The behavioral response times were registered with the same

TABLE I
Tactile–force psychophysical experiment protocol conditions and details

Condition	Detail
Number of subjects	7
Tactile stimulus length	100 ms
Inter–stimulus–interval (ISI)	900 ms
Stimulus generation	FLIGHT FORCE joystick by Logitech
Number of trials for each subject	10

TABLE II
CONDITIONS AND DETAILS OF THE TFBCI EEG EXPERIMENT

Condition	Detail
Number of subjects	7
Tactile stimulus length	100 ms
Inter–stimulus–interval (ISI)	300 ms
EEG recording system	gUSBamp active wet EEG electrodes system
Number of the EEG channels	16
EEG electrode positions	Cz, CPz, P3, P4, C3, C4, CP5, CP6, P1, P2, POz, C1, C2, FC1, FC2, FCz
Reference electrode	Behind the subject's left ear
Ground electrode	On the forehead (FPz)
Stimulus generation	FLIGHT FORCE joystick by Logitech
Number of trials for each subject	10

MAX 6 program, also used for the stimulus generation and instruction presentation as depicted in Figure 1. The goal of the psychophysical experiment was to investigate the behavioral response times and *target* recognition accuracies in order to test cognitive loads (tasks difficulties) generated by the four various tactile–force stimuli. The results of the experiment are discussed in the Section III-A.

C. EEG tfBCI Experiment Protocol

In the BCI experiments EEG signals were captured with a portable EEG amplifier system g.USBamp by g.tec Medical Instruments GmbH, Austria. Sixteen active wet EEG electrodes were used to capture brain waves with event related potentials (ERP) with attentional modulation elucidated by the so–called “aha–” or P300–response [1]. The EEG electrodes were attached to the head locations *Cz, CPz, P3, P4, C3, C4, CP5, CP6, P1, P2, POz, C1, C2, FC1, FC2,* and *FCz,* as in $10/10$ intentional system [13]. A reference electrode was attached to a left mastoid and a ground electrode on a forehead at *FPz* position respectively. No electromagnetic or electromyographic (EMG) interference was observed from the moving joystick. Details of the EEG experimental protocol are summarized in Table II.

The EEG signals were recorded and preprocessed by a BCI2000–based application [10], using a stepwise linear discriminant analysis (SWLDA) classifier [14] with features drawn from the $0 - 800$ ms ERP interval. The sampling rate was set to 256 Hz, the high–pass filter at 0.1 Hz, and the low–pass filter at 40 Hz. The ISI was 300 ms and each tactile–force stimulus duration of 100 ms.

Instructions to the subject which tactile–force stimulus direction to attend were presented visually as in the previous psychophysical experiments using the MAX 6 program (see Figure 1). Each *target* was presented 10 times in a random series with the remaining 30 *non–targets* in a single intended direction classification step. A procedure of ten single ERP responses averaging was used in order to enhance the P300 response in noisy EEG [10], [14].

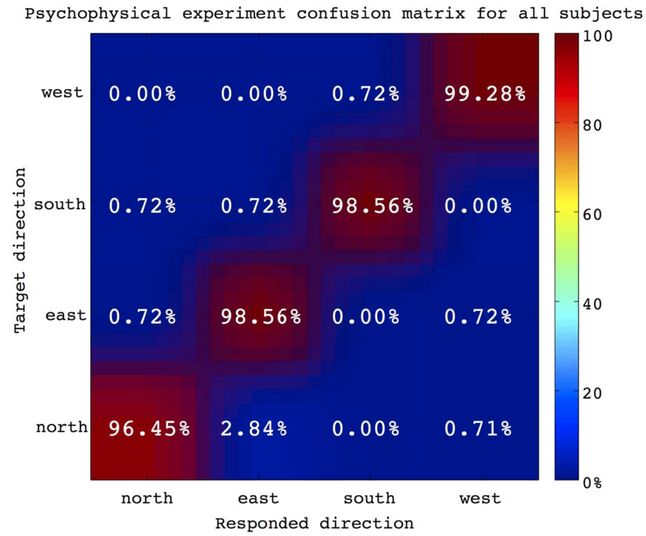

Fig. 3. Tactile–force interface psychophysical experiment results in form of a confusion matrix of the grand mean averaged subject accuracy results. Rows of the above matrix denote the instructed *targets* and columns the subject response. A diagonal of the matrix visualizes the correct response, while the off–diagonal values the subject errors. Numerical percentage values represent the response accuracies. In the contacted experiments the mean errors were marginal (below one percent). There were also no systematic errors observed (common mistakes between pairs of patterns), which further validated the tactile–force stimulus design.

III. RESULTS

This section presents and discusses results that we obtained in the psychophysical and in the online tfBCI experiments. The very encouraging results obtained in the psychophysical and tfBCI paradigm experiment support the proposed concept of the tactile–force modality.

A. Tactile–force Psychophysical Experiment Results

The psychophysical experiment accuracy results are summarized in Table III, depicted in form of a confusion matrix in Figure 3, and as boxplot response time distributions in Figure 4, where the median response time and the range are depicted for each direction as the boxplots (see also Figure 1 for the directions).

This result confirmed the stimulus related cognitive load similarity since the behavioral responses for all the directions were basically the same (as resulted with non–significant median differences from a pairwise *Wilcoxon*–test). This finding validated the design of the following tfBCI EEG experiment, since the four tactile–force patterns resulted with similar cognitive loads as confirmed by the same accuracies in Table III and Figure 3, as well as by response times depicted in Figure 4.

B. Online EEG Tactile–Force BCI Experiment Results

The results of the conducted online tfBCI paradigm EEG experiment with the seven subjects are presented in Figure 5 in

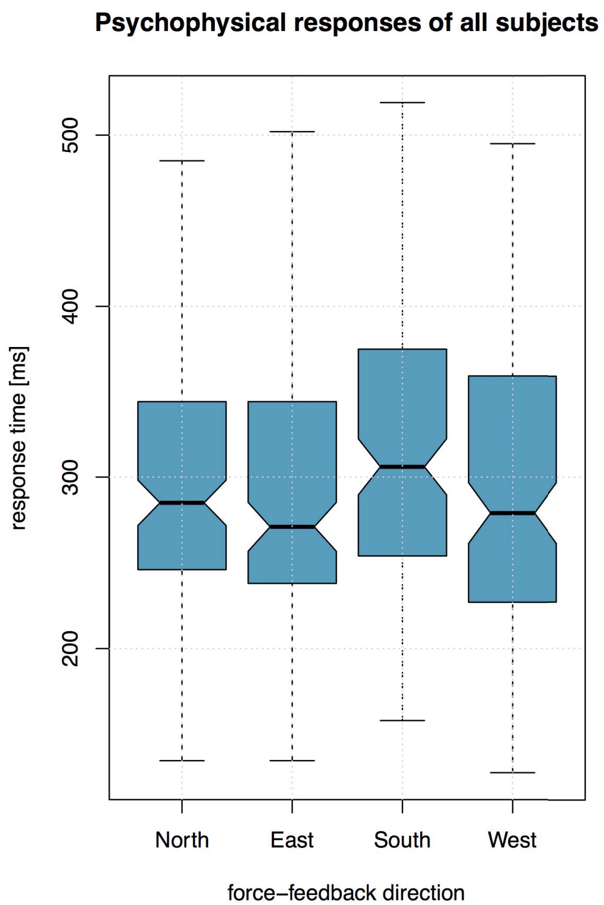

Fig. 4. Boxplots of the tactile–force psychophysical experiment response time distributions of the four *North, East, South* and *West* joystick directions. The differences among median were not significantly different (as tested with pairwise *Wilcoxon* statistical test). The boxplots depict also response time interquartile ranges (edges of the boxes) of the response time distributions, which almost completely cover each other in the above plot.

form of matrices depicting ERP latencies with P300 response together with areas under the curve (AUC) feature separability analyses. We also present averaged topographic plots of the

TABLE III
PSYCHOPHYSICAL EXPERIMENT RESULTS (NOTE, THIS IS NOT A BINARY ACCURACY CASE YET THE ONE WITH A THEORETICAL CHANCE LEVEL OF 25%) IN TACTILE–FORCE INTERFACE TASK.

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

evoked responses at the highest and lowest ERP separability latencies in the *target vs. non–target* averaging scenario. The highest average difference was found at 434 ms (as calculated by AUC), which perfectly represented the P300 response peak as could be seen also in Figure 6, where *target* and *non–target* responses are visualized separately for each electrode. Figure 6 presents also a very interesting *post–P300* attentional modulation, which in the majority of chosen for our experiments electrodes, had extended positive ERP modulation beyond the classical P300 peak in a range exceeding the $300-600$ ms range up to 1000 ms.

The online tfBCI accuracies (as obtained with SWLDA classifier) of the all seven participating subjects are summarized in Table IV. All the seven subjects scored well above the chance level of 25 %. Four out of the seven subjects reached 100% accuracy based on the 10 ERP responses averaging, which is a very good outcome of the proposed tfBCI prototype. Based on the obtained accuracies we calculated the ITR scores, in order to allow a simple comparison of the proposed tfBCI paradigm with other published approaches. The obtained IRT scores were in the range from 1.04 bit/min to 10.00 bit/min (see Table V). The ITR was calculated as follows,

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

where V is the classification speed in selections/minute (5 selections/minute in this case) and R stands for the number of bits/selection calculated as,

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

where N represents the number of classes (four in this study); and P the classification accuracy (see Table IV). The ITR scores obtained by the BCI subjects in our study have been summarized in Table V. The results shall be considered as good outcomes in comparison of the state–of–the–art BCI [1].

IV. CONCLUSIONS

The psychophysical and EEG experiments case study have beed presented with obtained results which confirmed the practical application feasibility of the novel four–commands tactile–force BCI. The results from experiments with seven healthy subjects confirmed our hypothesis of the tfBCI application validity.

The EEG experiment in the tfBCI paradigm has confirmed that tactile–force stimuli could be used easily (without any prior training) and successfully with ITR scores ranging from 1.04 bit/min to 10.00 bit/min in the online interfacing case using the SWLDA classifier.

The results presented offer a step forward in the development of the novel neurotechnology application. The current paradigm obviously needs still improvements and modifications to implement online with faster ISI and lower averaging rate necessary to improve the EEG features separability. These calls to determine the major lines of study for future research. However, even in its current form, the proposed tfBCI can be regarded as a practical solution for LIS patients (locked into

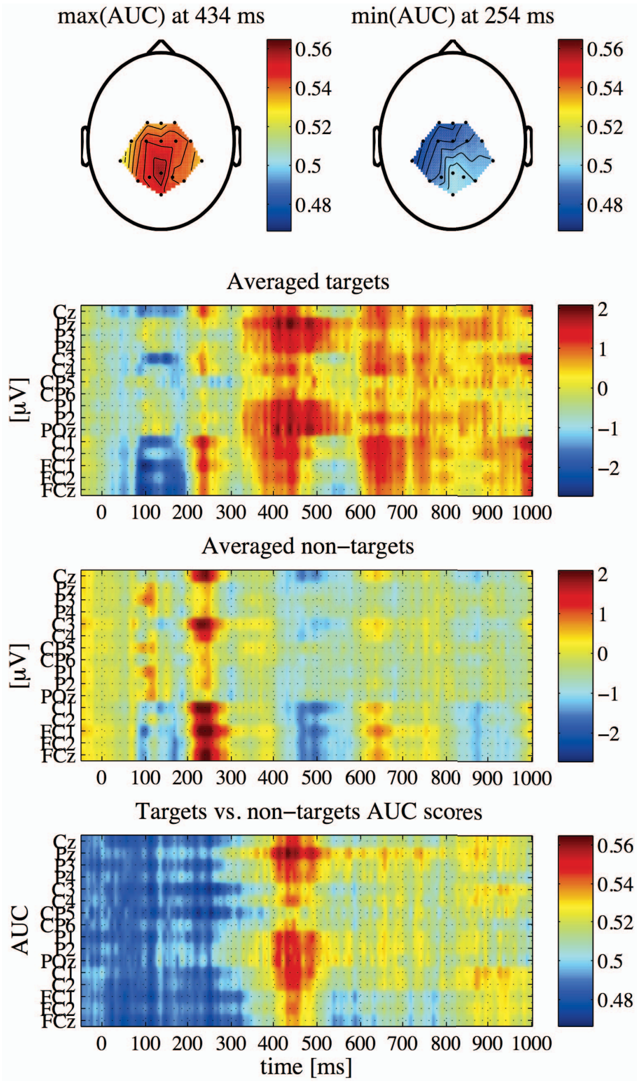

Fig. 5. Grand mean ERP and AUC scores leading to final classification results of the participating seven subjects. The top panels represent head topographic plots of the *target* versus *non–target* area under the curve (AUC) scores (AUC is a measure commonly used in machine learning intra-class discriminative analysis and AUC > 0.5 confirms usually 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 depicts the smallest AUC latency. Those topographic plots also show the electrode positions. All the electrodes received similar AUC values (red) supports the initial electrode placement in the conducted tfBCI EEG experiments. 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).

their own bodies despite often intact cognitive functioning), who cannot use vision or auditory based interfaces due to sensory or other disabilities.

We plan to continue this line of the tactile–force BCI research in order to further optimize the feature extraction, signal processing and machine learning (classification) methods. Next we will test the paradigm with the LIS patients in need for BCI technology.

TABLE IV
TEN TRIALS AVERAGING CLASSIFICATION BCI ACCURACY (NOTE, THIS IS NOT BINARY P300 CLASSIFICATION RESULT BUT RESULTING SPELLING RESULT WITH A THEORETICAL CHANCE LEVEL OF 25%) IN TACTILE–FORCE TASK USING THE CLASSICAL SWLDA CLASSIFIER [14].

Subject number	Online BCI experiment SWLDA accuracy
#1	100%
#2	75%
#3	100%
#4	100%
#5	50%
#6	100%
#7	50%
Average:	**82.1**%

TABLE V
TEN TRIALS AVERAGING CLASSIFICATION ACCURACY BASED ITR RESULTS (SEE TABLE IV).

Subject number	ITR scores
#1	10.00 bit/min
#2	3.96 bit/min
#3	10.00 bit/min
#4	10.00 bit/min
#5	1.04 bit/min
#6	10.00 bit/min
#7	1.04 bit/min
Average:	**6.58** bit/min

AUTHOR CONTRIBUTIONS

Programmed the tactile–force stimulus generating and delivering interface: SK, DA, TMR. Performed the EEG experiments: SK, TMR. Analyzed the data: SK, TMR. Conceived the concept of the tactile–force BCI: TMR. Supported the project: SM. Wrote the paper: SK, TMR.

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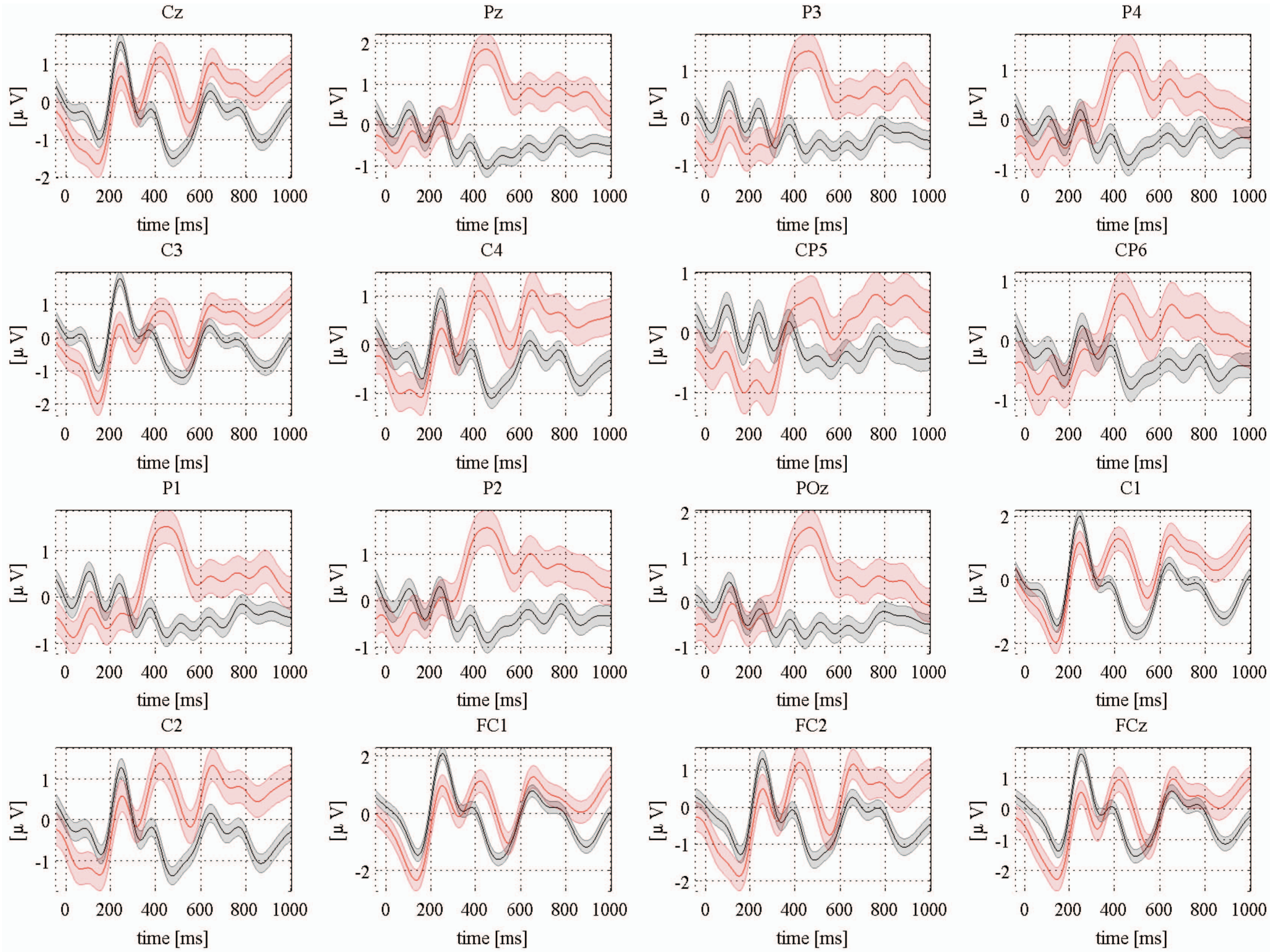

Fig. 6. Grand mean averaged ERP of all participating subjects together. Each panel depicts responses from each electrode used in the study (see Table II for details). The red lines depict *targets* and black *non–targets*. The clear P300 responses could be seen in the range of $300 - 600$ ms. The further attentional modulation of *target* responses extends till 1000 ms.

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