Tactile Brain–computer Interface Using Classification of P300 Responses Evoked by Full Body Spatial Vibrotactile Stimuli

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***Abstract*—In this study we propose a novel stimulus–driven brain–computer interface (BCI) paradigm, which generates control commands based on classification of somatosensory modality P300 responses. Six spatial vibrotactile stimulus patterns are applied to entire back and limbs of a user. The aim of the current project is to validate an effectiveness of the vibrotactile stimulus patterns for BCI purposes and to establish a novel concept of tactile modality communication link, which shall help locked–in syndrome (LIS) patients, who lose their sight and hearing due to sensory disabilities. We define this approach as a full–body BCI (fbBCI) and we conduct psychophysical stimulus evaluation and realtime EEG response classification experiments with ten healthy body–able users. The grand mean averaged psychophysical stimulus pattern recognition accuracy have resulted at 98.18%, whereas the realtime EEG accuracy at 53.67%. An information–transfer–rate (ITR) scores of all the tested users have ranged from 0.042 to 4.154 bit/minute.**

I. Introduction

Past decades have seen the rapid development of a brain–computer interface (BCI) neurotechnology. The BCI is a human computer–interaction technique, which enables people to express their thoughts through any computer devices without their muscle movements [1], [2]. Achievements of this interface contribute to a life improvement of amyotrophic lateral sclerosis (ALS) patients, who have difficulty to communicate since they cannot move their muscles due to neuro–motor disabilities. This symptom restricts interaction with care–takers and their environments. Thus, the BCI technology shall create an alternative communication tool for the patients, because it does not require the users to move their muscles [3]–[5].

One major approach in the BCI research field is the P300–based oddball paradigm [2]. This approach makes use of a mental attention modulation resulting in brainwave variabilities. An event related potential (ERP), generated in response to an attended rare event within the oddball experimental design, is characterized by a positive EEG deflection usually in latencies of about $300 - 600$ ms and it could be finally classified [6] for the BCI command generation purposes [5], [7].

So far, a large number of studies describing P300–based BCI have been published [8] and majority of them have focused on visual and auditory stimuli [9] in order to evoke the above mentioned P300 responses. However, the locked–in syndrome (LIS) patients who lose their sight and hearing as a result of a progression of the ALS symptoms, for example, might be not

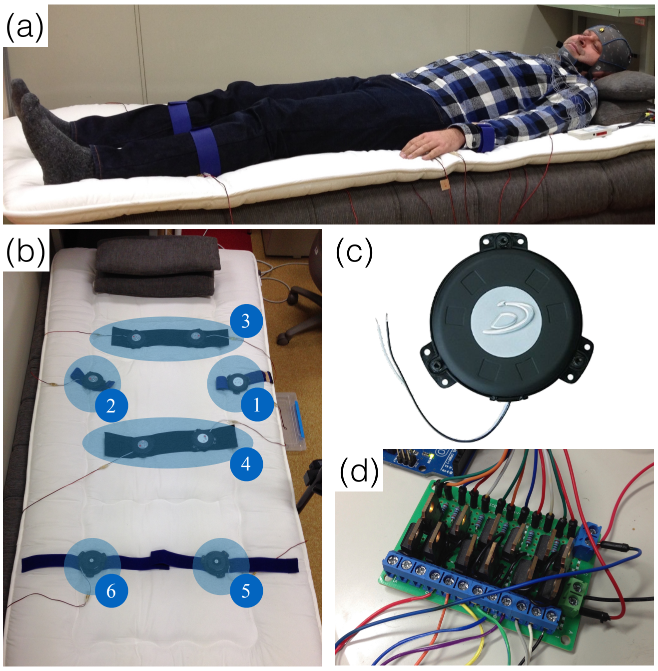

Fig. 1. The experimental apparatus and conditions. Panel (a) presents the fbBCI user lying down on a Japanese–style mattress with embedded vibrotactile transducers. The user have been instructed to distinguish six vibrotactile stimulus patterns given to his entire back and limbs throughout the fbBCI experiment. The photograph was included with the user permission. Panel (b) depicts eight vibrotactile transducers placed on the mattress to create six fbBCI stimulus patterns, which are #1 left arm; #2 right arm; #3 shoulder; #4 waist; #5 left leg; and #6 right leg, respectively. A longer distance among the transducers is used comparing to usual hand or facial area applications. Panel (c) presents a vibrotactile transducer Dayton Audio TT25-16 employed in the current study to generate vibration stimuli within the fbBCI paradigm. Panel (d) shows an in–house developed amplifier as a part of the fbBCI experimental system. The amplifier delivers electric signals to the transducers using a battery–based power supply for the user safety.

TABLE I
EEG EXPERIMENT CONDITIONS

Condition	Detail
Number of users	10 (5 males and 5 females)
Users mean age	21.9 years old
EEG recording system	g.USBamp with active electrodes
EEG electrode positions	Cz, Pz, P3, P4, C3, C4, CP5, and CP6
EEG sampling rate	512 Hz
Stimulus exciters	Dayton Audio TT25-16 transducers
Vibrotactile frequency	40 Hz
EEG acquisition environment	BCI2000 [20], [21]
Target stimulus length	100 ms
Inter–stimulus interval (ISI)	$400 \sim 430$ ms
Classifier algorithm	Stepwise Linear Discriminant Analysis
Classifier inputs	$0 \sim 800$ ms interval (3276 features)

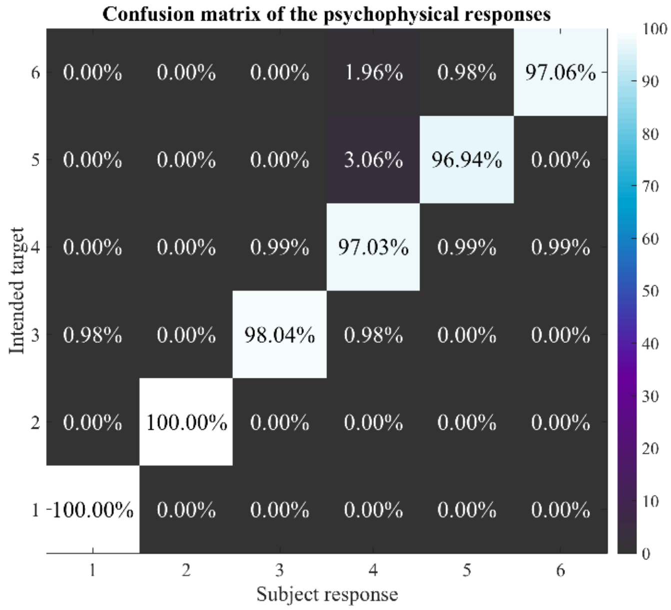

Fig. 2. A confusion matrix depicts the grand mean averaged behavioral response accuracies for each stimulus pattern of all the ten users in the fbBCI psychophysical experiment. The vertical axis represents the instructed target stimulus patterns and the horizontal user response numbers. The maximum correct rate was of 100.0% for stimulus patterns #1 (left arm) and #2 (right arm), whereas the minimum was of 96.94% for the pattern #5 (left leg). The grand mean averaged result of all the stimulus patterns was of 98.18%.

able to utilize such typical BCI modalities [5], [10], [11]. In such cases, the BCI using the remaining three senses, which are the touch, taste and smell, shall be alternative modalities for those patients. Within the three alternatives, the BCI using touch sensation, in other words the tactile modality, have been identified and already implemented in several pilot studies [5], [12]–[19]. The tactile BCI research findings in the past decade have confirmed that a touch (somatosensory or tactile) stimulus would be an alternative comparing to the remaining sensory modalities [12]. More recent studies also have confirmed the validity of the P300–based BCIs [5], [13]–[19] by applying somatosensory stimuli to various areas of a human body.

It should be noted, however, that most of the studies have only been carried out in the limited areas of the human body, such as hands, fingers or around a head [15]–[17]. An application–based problem arrises in case of some totally locked–in (TLS) patients who may be not able to utilize such types of BCI modalities due to impaired afferent neural fibers in those specific areas of their bodies. Furthermore, in order to help the users more easily distinguish those tactile stimuli, it shall be more practical to place the vibrotactile transducers in spatially distant locations, which means, with a larger distances apart from each other [18], [19].

Accordingly, we present a study of the novel P300–based tactile BCI, in which spatial vibrotactile stimulus patterns are applied to the user entire back and limbs in order to evoke the somatosensory P300 responses. We define this modality as the full body tactile BCI (fbBCI). In the fbBCI, large vibrotactile transducers are employed to apply tactile stimuli to the users. The transducers are placed with larger distances within a mattress. Users in our study participate in experiments with their body lying down on the mattress since the fbBCI is developed for patients who are in bedridden conditions. During the experiment, in the classification algorithm of fbBCI paradigm the somatosensory P300 responses are detected and translated into interfacing commands.

From now on the paper is organized as follows. In the next section methods used and developed within the presented project are discussed. Presentation of obtained results, their discussion, together with conclusions, summarize this paper.

II. METHODS

In the presented project, psychophysical and realtime *electroencephalogram* (EEG) BCI experiments were carried out with ten naive users (BCI–beginners). Healthy five males and five females participated in the fbBCI experiments with a mean age of 21.9 ± 1.45 years. All the users were paid for their contributions. The informed consents were provided by all users in the experiments and they agreed to participate by signing experimental user agreement forms. All the experiments were conducted in a soundproof room at the Life Science Center of TARA, University of Tsukuba, Japan. Likewise, they were conducted in accordance with The World Medical Association Declaration of Helsinki - Ethical Principles for Medical Research Involving Human Users. The procedures for all the experiments of the fbBCI paradigm were approved and designed in an agreement with the guidelines of the Ethical Committee of the Faculty of Engineering, Information and Systems at the University of Tsukuba, Tsukuba, Japan. The participating users were asked to lay down in a silent environment on a Japanese–style mattress containing a polyester filling as presented in Figure 1(a). Eight vibrotactile transducers Dayton Audio TT25-16, as depicted in Figure 1(c), were placed on the mattress to create six fbBCI stimulus patterns transmitted to arms, shoulder, waist and legs, as shown in Figure 1(b). Two

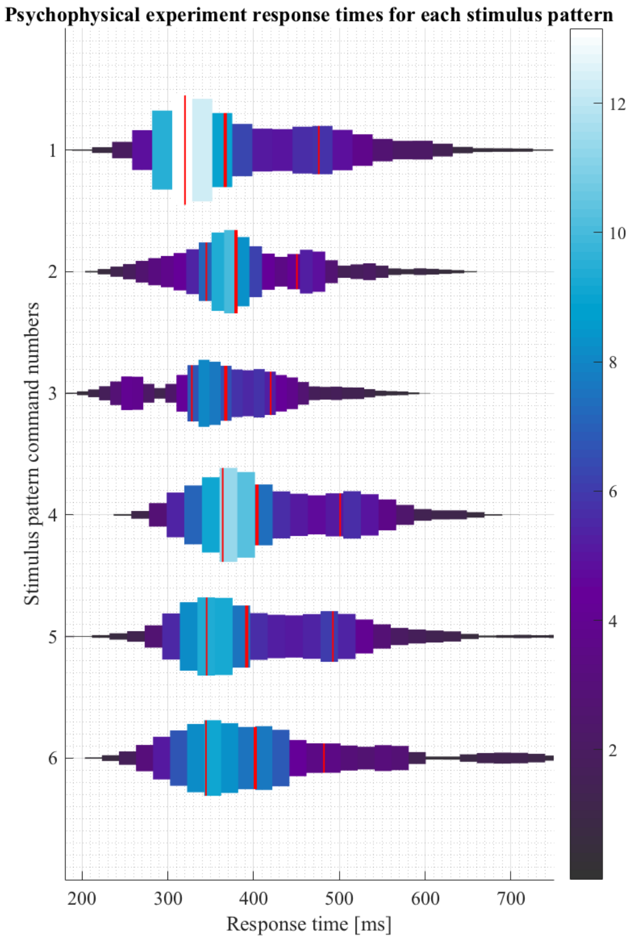

Fig. 3. Distribution plots illustrate the grand mean averaged response times of behavioral button–presses to each stimulus pattern of all the ten users in the fbBCI psychophysical experiment. The vertical axis shows the fbBCI stimulus pattern numbers ($\#1 \sim \#6$), whereas horizontal the response times after the stimulus onsets. The red lines in each plot indicate a lower quartile, a median and an upper quartile, respectively. From the Wilcoxon rank sum test evaluation, there were no statistically significant differences among all median value pairs ($p < 0.05$) except for the pair of stimulus patterns $\#3$ and $\#4$.

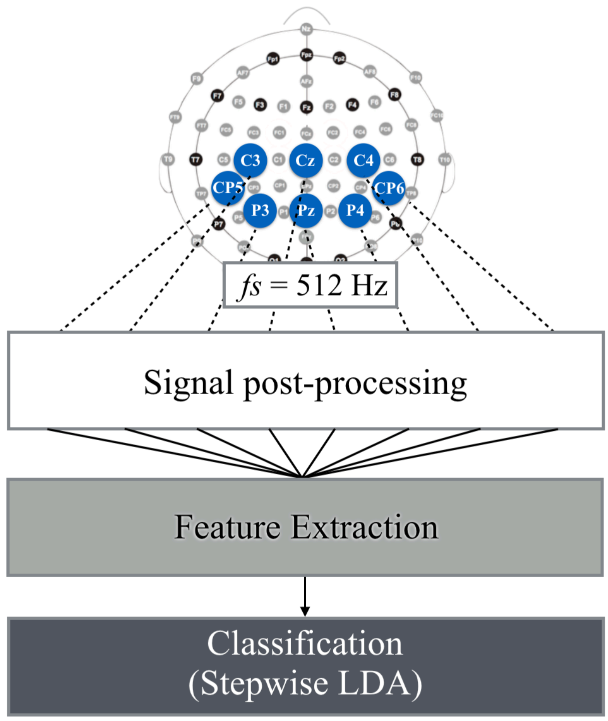

Fig. 4. A summary diagram of the fbBCI realtime EEG experiment signal acquisition and processing stages. The EEG brain signals were captured from eight EEG electrodes attached on a user scalp (positions Cz, Pz, P3, P4, C3, C4, CP5 and CP6). Next, the captured EEG signals were processed to reduce noise by a bandpass filtering and a decimation. After that, every the processed EEG signals were concatenated to create feature vectors. Finally, the generated feature vectors were classified by the SWLDA method. We used an in–house modified BCI2000 software [20], [21].

transducers were applied to the shoulder and waist, and only single one to each arm and leg. The stimulus frequency of the transducers was set to 40 Hz. Arduino UNO [22] micro–controller board was used to generate the electric signals transmitted to the transducers. In addition a battery powered electronic amplifier, shown in Figure 1(d), was employed to increase electric currents required by the tactile transducers Dayton Audio TT25-16.

A. The psychophysical experiment protocol

The main objective of the psychophysical experiment was to investigate recognition accuracies and response times to each stimulus patterns delivered from the vibrotactile transducers attached to the mattress [23]. A MAX (Cycling '74, USA) visual programming environment was employed to control the experimental procedure and to present instructions to the users. The software during the experiments also transmitted experimental triggers to the Arduino micro–controller board via a serial connection.

During the psychophysical experiments, the behavioral responses were collected by pressing a keyboard button as soon as the user recognized a target stimulus pattern. Each single session was comprised of 10 targets and 50 non–targets stimulus patterns presented randomly. Within a single trial, the session was repeated until all the six stimulus patterns became the rare targets (as required by the oddball paradigm), namely 60 targets and 300 non–targets were delivered altogether. Only a single experimental trial was conducted for each user. A single stimulus duration was set to 100 ms and an inter–stimulus–interval (ISI) to 400 ms, respectively.

B. The fbBCI realtime EEG experiment protocol

A reason to conduct the fbBCI realtime EEG experiment was to evaluate the full–body vibrotactile stimulus pattern feasibility. Likewise, this experiment was performed to reveal the stimulus pattern classification accuracy from EEG. In the fbBCI realtime experiment, the EEG signals were captured with a bio–signal amplifier system g.USBamp (g.tec Medical

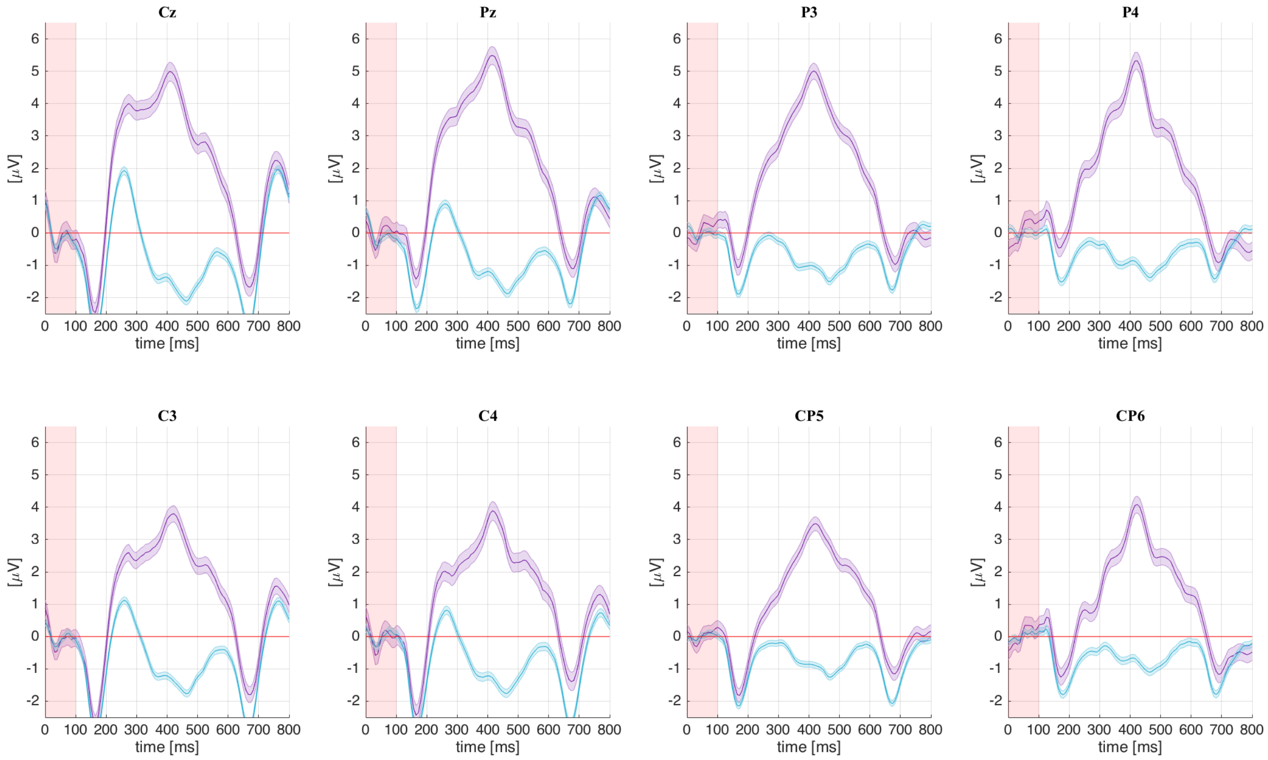

Fig. 5. Grand mean averaged ERP results of all the ten users in the fbBCI realtime EEG experiment for target (purple lines) and non-target (blue lines) stimulus patterns with the locations of the eight EEG electrodes (Cz, Pz, P3, P4, C3, C4, CP5 and CP6). The vertical axis of each ERP result graph represents the electrical potentials and the horizontal the time after stimulus onsets. Somatosensory P300 responses were clearly confirmed for every electrode in the $200 \sim 600$ ms latency ranges.

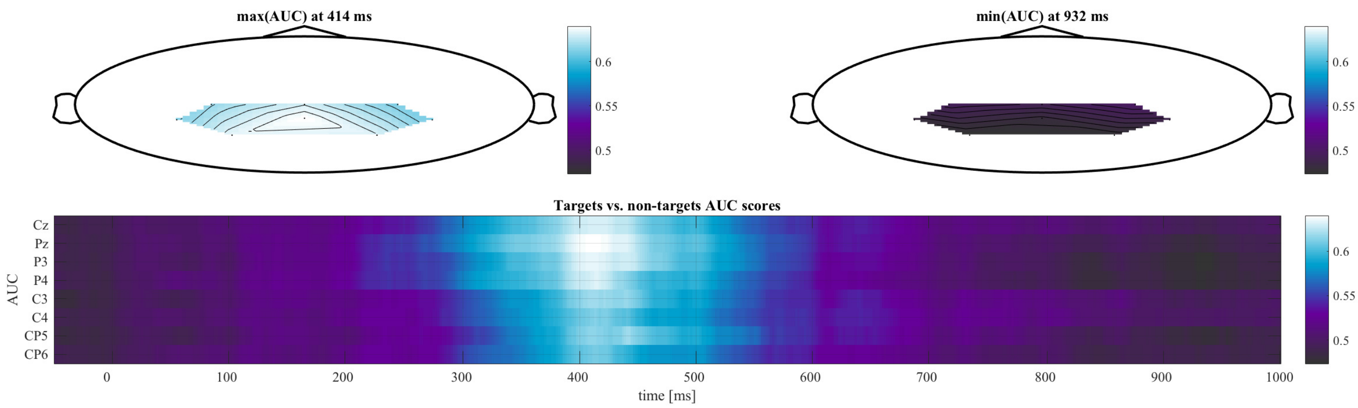

Fig. 6. Grand mean area under the ROC curve (AUC) scores of all the ten users in the fbBCI realtime EEG experiment. Both the top topographic maps show head plots of the target stimulus pattern and non–target AUC scores for eight electrode positions. The top left panel depicts a maximum AUC score for each electrode position for a latency at 414 ms and the right panel a minimum AUC score at a latency of 932 ms. The bottom panel represents the detailed time series of the target stimulus pattern versus non-target AUC scores after the stimulus onsets.

Instruments, Austria). Following a $10/10$ international system, eight active EEG electrodes were placed at Cz, Pz, P3, P4, C3, C4, CP5 and CP6 head locations in order to cover a primary somatosensory cortex on the scalp [24] as shown in Figure 4. A reference electrode was attached to the left mastoid, and a ground electrode to the forehead at the FPz position. The EEG recording sampling frequency was set to 512 Hz. The high– and low–pass filters were set at 0.1 Hz and 60 Hz, respectively. A notch filter to remove power line interference was set in a rejection band of 48 to 52 Hz. Details of the EEG

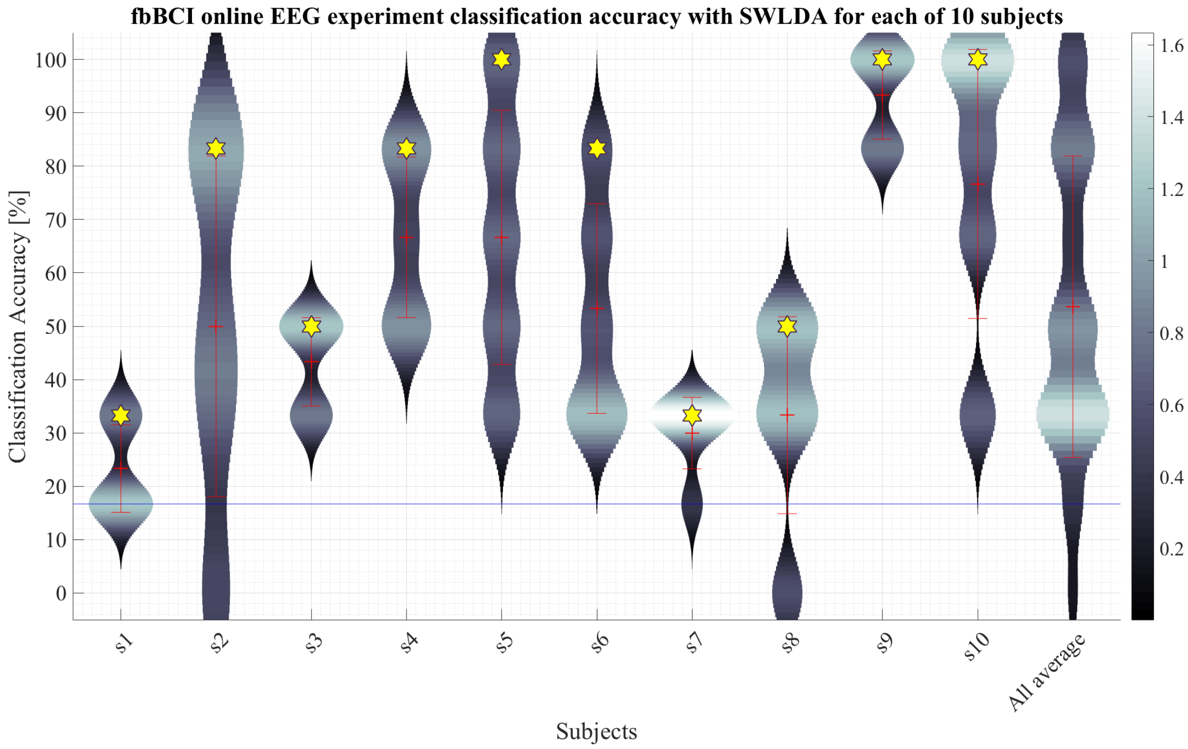

Fig. 7. Results of vibrotactile stimulus pattern classification accuracies using the SWLDA classifier algorithm during the fbBCI realtime EEG experiments. Score of all ten participating users are depicted in form of violin plots. The vertical axis represents a percentage of the fbBCI classification accuracies. The horizontal axis represents user numbers $s1, s2, \ldots, s10$ and an average of all. Each violin plot contains median, both quartiles, as well as a probability density from five trial conducted by each user. A yellow stars inside each violin plot indicates the best classification accuracy obtained throughout five trials. A blue reference line depicts a chance level of 16.7%. The grand mean classification accuracy resulted in 53.67%.

experimental protocol are summarized in Table I.

The EEG signals were captured and classified by an in–house extended BCI2000 EEG acquisition and ERP classification software [20], [21] using a stepwise linear discriminant analysis (SWLDA) classifier [25]. The procedure to evaluate whether the somatosensory P300 responses were observed or not in an user's EEG signals was described in Figure 4.

The BCI2000 software was also employed to give experimental instructions for users on a computer display. Unlike in the previous psychophysical experiment, the main role of the MAX environment was to receive trigger onsets generated by BCI2000 software via a UDP protocol. Those triggers were converted to signals in a function box of the MAX environment and sent to the Arduino micro–controller board via serial connection alike in the psychophysical experiment.

The experimental flow of the single trial was comprised of the same steps as in the psychophysical experiment. Each user participated in five fbBCI trials and the vibrotactile EEG respnese classification accuracies were calculated by taking the average of all the five trials. In each trial, the stimulus duration was set to 100 ms and the ISI to random values in a range of 400 ms to 430 ms in order to break rhythmic patterns presentation.

III. Results and Discussion

The results of the both psychophysical and realtime EEG experiments have been reported in the following sections. Overall, the experimental results have been very encouraging and proven an effectiveness of the proposed P300 response–based tactile BCI paradigm.

A. *The fbBCI psychophysical experimental results*

The psychophysical experiment results have been summarized in Figures 2 and 3, as a confusion matrix and a user behavioral response time distribution plots, respectively. In Figure 2 the behavioral response accuracies to the instructed target stimulus patterns and marginal errors are depicted together. The grand mean averaged response accuracy was of 98.18%, indicating that the fbBCI vibrotactile stimulus patterns were suitable for the subsequent BCI experiments. The most encouraging finding was that all users obtained discrimination scores for stimulus pattern number $\#1$ and $\#2$, namely the stimulus patterns for the left and right arms, without any mistakes.

The behavioral response times collected from the users have been summarized in Figure 3. The medians of each the response time for stimulus pattern were settled in the range of 360 ms to 410 ms. The statistical significances among the

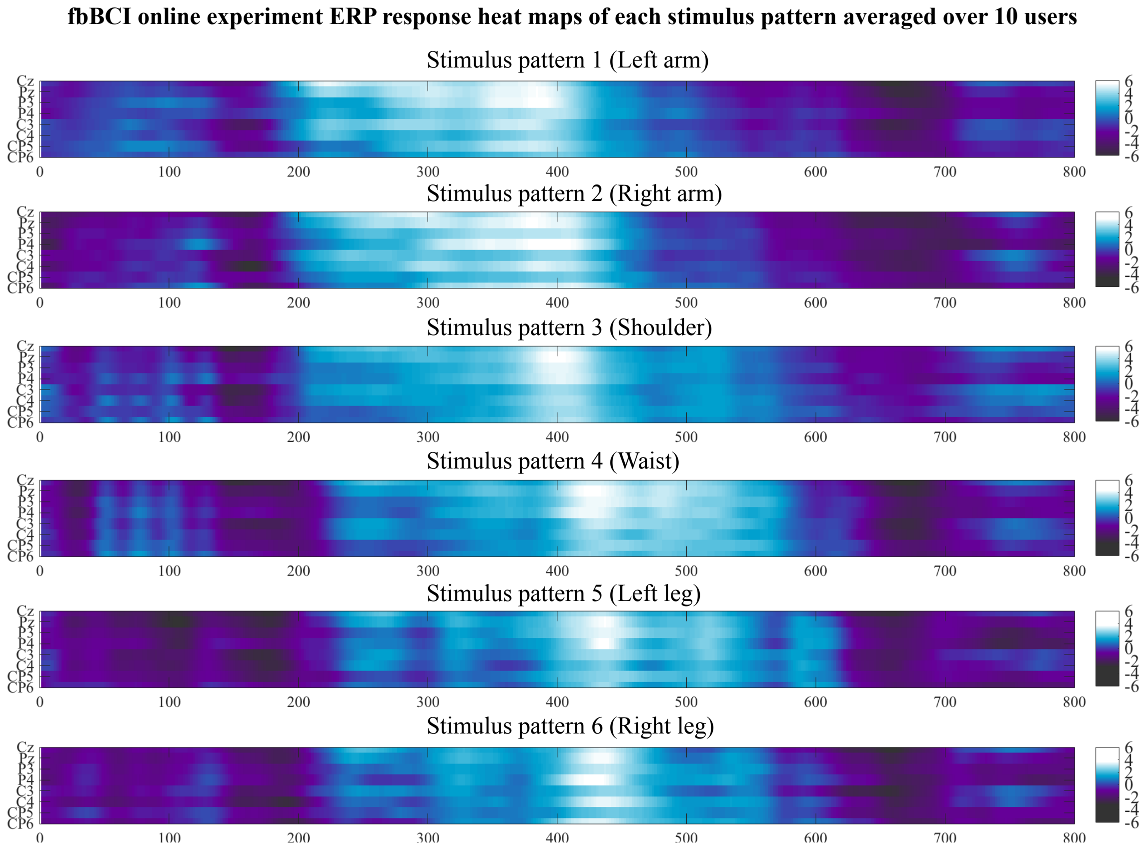

Fig. 8. ERP response result heatmaps for each fbBCI stimulus pattern averaged over all the realtime experiments of ten users. Vertical axis represent EEG electrodes, whereas the horizontal represents the elapsed time after stimulus onsets. The P300 response peaks are gradually shifted toward later latencies for stimulus patterns from #1 (left arm) to #6 (right leg). The differing P300 latencies shall reflect the varying neural pathway processing times (arms versus legs, etc.).

median difference pairs were only found between stimulus pattern number #3 and #4, as result of the Wilcoxon rank sum tests.

B. The fbBCI realtime EEG experimental results

The grand mean averaged ERP EEG responses of all the ten users participating in the realtime fbBCI experiments have been depicted in Figure 5. In each electrode position, somatosensory P300 responses were confirmed in latency ranges from 200 ms to 600 ms after the target stimulus patterns presented. It is noteworthy that the potentials of P300 responses reached around 5 μV and their durations were up to approximately 400 ms long. These characteristics were often observed in somatosensory P300 responses [18] and they enhanced classification accuracy in terms of a better discrimination of the feature vectors.

In Figure 6, an area under the curve (AUC) of an receiver operating characteristic (ROC) results of all the EEG experiments have been plotted showing contrasts among responses to targets and non–targets (rare events) stimulus patterns. The topographic maps in the top panel of Figure 6 illustrated both the maximum and minimum AUC scores for each electrode position and their latencies from the stimulus onset. The latency with the grand mean average maximum AUC score was at 414 ms.

Vibrotactile stimulus pattern classification accuracies using the step–wise linear discriminant analysis (SWLDA) classifier algorithm results of the realtime EEG experiment have been summarized in Figure 7. The horizontal violin plots depicted each user stimulus pattern classification accuracy averaged over five trials using the SWLDA classifier. The accuracy results were in a range of 23.33% to 93.33%, which rate was calculated over 30 sessions. The yellow stars inside of the violin plots marked the best classification accuracies for each user. The best accuracies of users were in a range of 33.3% to 100.0%. A grand mean average rate was of 53.67%, as well as the mean best rate of 71.67%, for each user. The resulting classification accuracies exceeded a theoretical chance level rate of 16.7% in the six–command based BCI experiments.

The differences of averaged ERP response peaks for each stimulus pattern within the fbBCI realtime experiments have

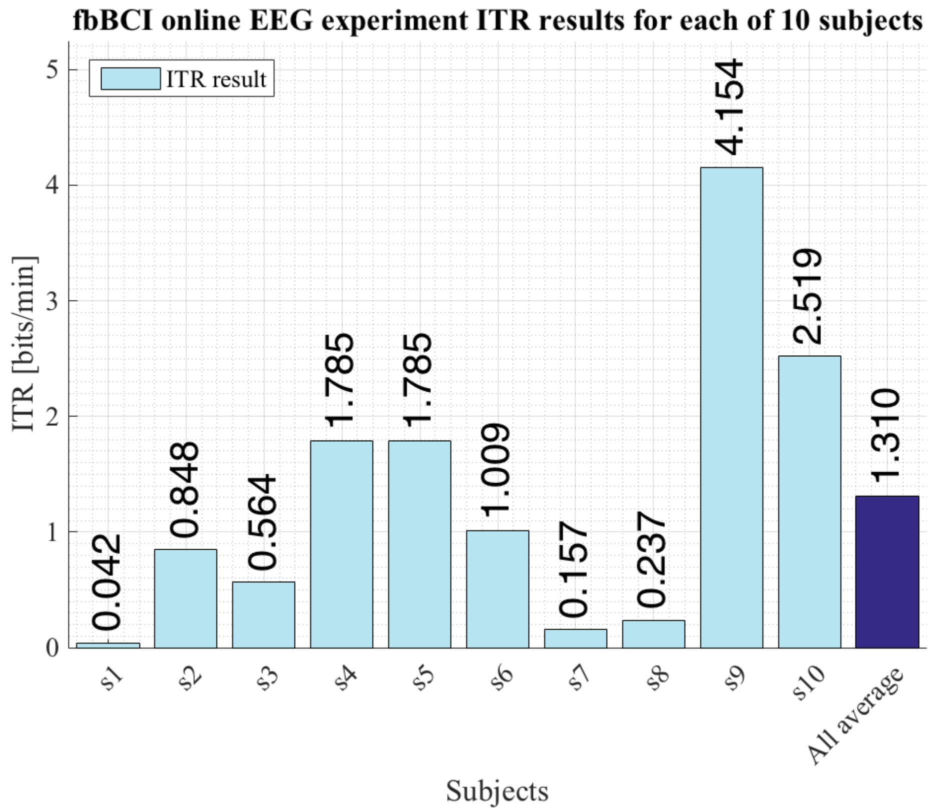

Fig. 9. ITR score results of each participant of the fbBCI realtime EEG experiment are summarized in a form of a bar–graph. The vertical axis represents the ITR scores in bit/minute. The horizontal axis represents user numbers. The average ITR score of all users was of 1.3 bit/minute.

been illustrated in Figure 8. All the ERP response peaks were confirmed around 400 ms after the stimulus onsets with no significant EEG amplitude differences. Although, there were significant differences observed between stimulus pattern $\#3$ (shoulder) and $\#4$ (waist) in the psychophysical experiments (see Figure 3). This fact further supported the choice of the vibrotactile stimulus modality for user full–body BCI experiment set-up. Another finding from heatmaps in Figure 8 was that the P300 response peaks of the upper body ($\#1$ left arm, $\#2$ right arm and $\#3$ shoulder) were slightly faster than the lower body ($\#4$ waist, $\#5$ left leg and $\#6$ right leg). This phenomena might be directly related to the difference of the reaction and perception speed to the vibrotactile stimulus patterns.

The bars in Figure 9 have depicted each user information–transfer–rate (ITR, see equations (1) and (2) for details) score, which evaluated a communication speed possible to realized with the tested BCI paradigm [26]. The ITR score results were obtained as in the following equation,

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

where V represented a stimulus pattern classification speed in selection/minute and R was a number of bits per selection obtained as,

$$\begin{aligned} R &= log_2 N + P \cdot log_2 P + \\ &+ (1-P) \cdot log_2(\frac{1-P}{N-1}), \end{aligned} \tag{2}$$

with N being the number of classes (six in this study), and P the stimulus pattern classification accuracy. Each user's ITR score result ranged from 0.042 to 4.154 bit/minute. The resulting mean ITR score of all the participated users was of 1.31 bit/minute.

IV. Conclusions

This project was undertaken to verify the effectiveness of the proposed vibrotactile stimulus patterns given to user entire back and limbs for BCI–based interaction purposes. The main goal of the reported project was to design the novel P300 EEG response–based tactile BCI paradigm.

Both, the fbBCI psychophysical and the realtime EEG experiment results confirmed our hypothesis that the proposed full–body tactile stimulation–based modality could be applied for bedridden patients (for example those suffering from locked–inn syndrome, etc.) who could not utilize visual or auditory based interfaces. However, at the current stage of the reported project, the BCI experiments have been conducted only with healthy (body–able) users. The mean BCI digit spelling classification accuracy was of 53.67% in the proposed realtime EEG experiments. This accuracy exceeded our previous related study result of 43.34% [19] by applying six vibrotactile stimulus patterns to the user's shoulder and waist. An improvement of the classification accuracy shall be expected from more user–centered tactile equipment design, as well as from more user–friendly experimental paradigm design. The currently presented results have been not yet fully satisfactory, as compared to the competitive visual or auditory BCI paradigms. The obtained outcomes shall be considered as good. Hence, the current project would obviously require more improvements and modifications in terms of experimental parameters such as inter–stimulus–interval; longer stimulus durations; or introduction of more flexible classification algorithms (e.g. deep learning, transfer learning, or unsupervised methods), which till now have not been investigated for tactile BCIs.

Overall, the results from the presented full–body tactile BCI study were encouraging. We demonstrated that the P300 response–based full–body tactile BCI paradigm has proven to be a viable concept. We are confident that future developments in this field will help improve a quality of life of those patients in need who cannot rely on vision– or audition–based modalities.

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