Abstract—This paper aims to improve tactile and bone–
condution brain computer interface (tbaBCI) classification ac-
curacy based on a new stimulus pattern search in order to trigger
more separable P300 responses. We propose and investigate three
approaches to stimulus spatial and frequency content modifica-
tion. As result of the online tbaBCI classification accuracy tests
with six subjects we conclude that frequency modification in
the previously reported single vibrotactile exciter–based patterns
leads to border of significance statistical improvements.

I. INTRODUCTION

The contemporary brain–computer interfaces (BCIs) are
typically based on mental visual or motor imagery paradigms,
which require extensive user training and good eyesight from
the users [1]. Recently alternative solutions have been adopted
successfully to make use of spatial auditory [2] or tactile
(somatosensory) sensory modalities [3], [4], [5], [6], [7] to
improve BCI usage comfort and to increase the information
transfer rate (ITR) achieved by users. Two recent reports
published by the authors in [8], [9] have shown combination
of two above–mentioned modalities, which rely on P300
response evoked by the audio and tactile stimuli delivered
simultaneously via vibrotactile exciters attached to the head
positions, thus benefiting from the bone–conduction effect
for audio. This offers a viable alternative for individuals
lacking somatosensory afferent neural fibers transmission from
peripheral body locations.

This paper reports improvement of our previously reported
tbaBCI paradigm [8] based on suitable stimulus spatial pat-
terns that subject can easily distinguish and as a result evoked
stronger in amplitude in EEG the P300 responses. We propose
to create stimulus patterns using multiple subsets of the
vibrotactile exciters using also various stimulation frequencies.
The above steps are meaning to give the user a clear spatial and
frequency pattern based cues leading to simpler discrimination
among the presented tactile and bone–condution auditory
stimuli.

The rest of the paper is organized as follows. The next
section introduces the materials and methods used in the
study. It also outlines the experiments conducted within the
presented project. The results obtained in EEG online and
offline experiments with six BCI subjects are then discussed.
Finally, conclusions are formulated and directions for future
research are outlined.

II. MATERIALS AND METHODS

Six volunteer male BCI subjects participated in the experi-
ments. The subject’s mean age was 25.83, with a standard
deviation of 8.17. All the experiments were performed at the
Life Science Center of TARA, University of Tsukuba,
Japan. The psychophysical and online (real–time) EEG tbaBCI
paradigm experiments were conducted in accordance with the
WMA Declaration of Helsinki Ethical Principles for Med-
ical Research Involving Human Subjects. The experimental
procedures were reviewed by the Ethical Committee of the
Faculty of Engineering, Information and Systems at University
of Tsukuba, Tsukuba, Japan (experimental permission number
2013R7).

A. Tactile and Bone–condution Auditory Stimulus

The tactile and bone–condution auditory stimulus was
created as a square acoustic frequency wave generated by
the ARDUINO micro–controller board with a custom built
battery–driven and electrically isolated multichannel power
amplifier. An in–house developed software managed the above
device from MAX/MSP visual programming environment. The
stimuli were delivered to the subject’s head locations via
the vibrotactile exciters HiWave HIA19C01-8 operating in the
acoustic frequencies of 300 ∼ 20,000 Hz, as depicted
in Figure 1. The subject attended (button–press responded
in case of psychophysical or mentally counted only in case
of EEG experiments) only to the instructed target
locations, while ignoring the other stimuli (we assigned labels to the
attended stimulus as target and to the other ignored as non–
target). The instructions were presented visually by means of
the MAX/MSP program in psychophysical experiment and
BCI2000 program in EEG experiment.
In this study, we conducted three experiments to test the proposed new stimulus patterns’ effectiveness. In each of the conducted experiments six different stimulus patterns were used. In the experiment #1 the stimuli were delivered to the user’s head by single vibrotactile exciters as depicted in Figure 2. This setting was the same as in our previous studies [8], [9] in order to compare brainwave responses with the current setup of the tactile and bone–conduction auditory stimulus patterns introduced in this paper. In the experiment #2 the stimuli were composed of multiple vibrotactile exciters combined together. Each stimulus pattern in the experiment #2 has been also depicted in the middle column of Figure 2. Based on our previous studies [8], [9] and user reports we decided to stimulate larger head areas to avoid mistakes caused often by close spatial proximity of the vibrotactile exciters embedded within the EEG cap. In the both experiments #1 and #2 the same stimulus frequency of 350 Hz was used. Only in the experiment #3 we used various frequencies in order to add more discriminative features for the users (see also Figure 2 for details).

B. Psychophysical Experiment Protocol

The psychophysical experiment was conducted to investigate the stimulus pattern possible influences on the subject’s response time and accuracy. The behavioral responses were collected using a computer keyboard and the MAX/MSP program. Each subject was instructed which stimulus to attend by a red color circle shown on a computer display and generated by the instruction program as shown in Figure 3. The subject was instructed to press the response button (any key on a keyboard) with the dominant hand when the target stimulus was presented in a series of random distractors (as in a classical oddball paradigm [1]).

Each trial was composed of 100 ms long tactile stimuli delivered in a randomized order to each head location separately with an inter–stimulus–interval (ISI) of 900 ms. Every random sequence thus contained a single target and five non–targets. A single run included 10 sequences (resulting in 60 targets and 300 non–targets). Details of the psychophysical experimental protocol are summarized in Table I.

C. EEG Experiment Protocol

EEG signals were captured with an EEG amplifier system vAmp by Brain Products GmbH, Germany, using g.GAMMAbox with connected active electrodes g.LADYbird by g.tec Medical Instruments GmbH, Austria. The electrodes were attached to the head locations: Cz, Pz, P3, P4, C3, C4, P7, P8, O1, O2.
C4, CP5, and CP6 as in the 10/10 extended international system [10]. The ground electrode was attached to FPz and reference to the left earlobe respectively. No electromagnetic interference was observed from the vibrotactile exciters operating in higher frequencies comparing to the EEG frequency spectrum. Details of the EEG experimental protocol are summarized in Table II.

The recorded EEG signals were processed by the in–house extended BCI2000 [11], [12], [13] using a stepwise linear discriminant analysis (SWLDA) classifier [14] with features drawn from the 0 ~ 800 ms ERP latency intervals. The sampling rate was set at 500 Hz, the high pass filter at 0.1 Hz, and the low pass filter at 40 Hz. The ISI was set to 400 ms, and each stimulus duration was 100 ms. The subjects were instructed which stimulus to attend by visual instruction presented on a computer screen using the same interface as in the psychophysical experiment presented in Figure 3. Each run included ten sequences (randomized 60 targets and 300 non–targets each), and the averages of ten ERPs were later used for the classification. Each subject performed three runs (resulting in 180 targets and 900 non–targets), which were later averaged as discussed in the next section.

### III. RESULTS

The results comparison the three setups tested in psychophysical and online BCI EEG experiments are summarized in the following sections.

#### TABLE I

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<td>Stimulus length</td>
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<tr>
<td>Vibrotactile frequency</td>
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<tr>
<td>Inter–stimulus–interval (ISI)</td>
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<td>Subject response input device</td>
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#### TABLE II

<table>
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#### A. Psychophysical Experiment Results

The psychophysical experiment accuracy results are depicted in form of a confusion matrices in Figures 4, 5, and 6. The confusion matrices with majority of accurate responses depicted on diagonals confirmed experimental designs validity and low difficulties for the tested participants. The boxplot psychophysical response time distributions are presented in Figures 7, 8, and 9. Each response time distribution results further confirmed the stimulus related cognitive load similarity since the behavioral responses for all the patterns were basically the same (as resulted with non–significant median differences from pairwise Wilcoxon–tests). This finding validated the design of the following tbaBCI EEG experiments.

#### B. EEG Experiment Results

The grand mean averaged results of the conducted online BCI EEG experiments with the six participating subjects are presented in Figures 10, 11, and 12 in form of matrices depicting ERP latencies with P300 responses together with the area under the curve (AUC) feature separability analyses. We report also the averaged head topographic plots of the evoked responses at the highest and lowest ERP separability latencies in the target versus non–target averaging scenario as elucidated by AUC maxima and minima. The highest averaged differences were found at 398 ms, 444 ms and 392 ms, which perfectly aligned the P300 response peaks in grand mean average ERP plots.

Figure 13 depicts time series of all electrodes with target and non–target responses from the three EEG experiments.
collected together. The black lines in the above figure indicate non–target responses which resulted the same ERP shapes. The color lines represent P300 responses which remained enhanced even after 500 ms mark when the next stimulus started.

The results comparison of the three online BCI EEG experiments classification accuracies are presented in Figure 14. The majority of the averaged classification accuracies resulted above chance levels of 16.66%. The red bars in Figure 14 show results of the experiment #1, while the blue bars depict results of the experiment #2, and the green bars represent results of the experiment #3. The classification accuracies of the new proposed stimulus patterns (experiments #2 and #3) were not significantly improved comparing with the previously proposed approach in the experiment #1, but we could show improvements between patterns #2 and #3. We conducted pairwise t–test analyses using classification accuracies. As results, we obtained the border of significance results with $p < 0.06$ between the patterns #2 and #3, which supported the initial research hypothesis of the new patterns search.

**IV. Conclusions**

This case study demonstrated results obtained with a comparison of three six–commands tactile and bone–conduction auditory approaches to BCI paradigms improvements. The experiment results obtained in this study confirmed the initial research hypothesis and stimulation patterns optimization could lead to the final BCI accuracy improvements.

The EEG experiment with the paradigm has confirmed that tactile and bone–conduction BCI paradigm can be used easily improved for online case using SWLDA classifier.

The results presented offer a step forward in the development of novel neurotechnology application. The current
paradigm obviously needs still improvements and further optimizations to implement online successfully. These needs determine the major lines of study for future research.

We plan to continue this line of the tactile and bone-conduction auditory BCI research in order to further optimize stimulus patterns design.

ACKNOWLEDGMENTS

We would like to express our gratitude to Yoshihiro Matsumoto, the BCI-lab-group and the Multimedia Laboratory alumni, who supported the project in the early stages with programming of BCI2000 updates.

This research was supported in part by the Strategic Information and Communications R&D Promotion Programme no. 121803027 of The Ministry of Internal Affairs and Communication in Japan, and by KAKENHI, the Japan Society for the Promotion of Science grant no. 24243062.

REFERENCES


Fig. 11. All the six subjects grand mean averaged results of the EEG experiment#2. The left two panels present the head topographic plot of the target versus non-target area under the curve (AUC), a measure commonly used in machine learning intra-class discriminative analysis. (AUC > 0.5 is usually assumed to be confirmation of feature separability). The right three panels present the averaged ERPs (six subjects; three experimental runs each with six targets repeated ten times) for target in the top panel; non-target in the middle; and target versus non-target AUC at the bottom.

Fig. 12. All the six subjects grand mean averaged results of the EEG experiment#3. The left two panels present the head topographic plot of the target versus non-target area under the curve (AUC), a measure commonly used in machine learning intra-class discriminative analysis. (AUC > 0.5 is usually assumed to be confirmation of feature separability). The right three panels present the averaged ERPs (six subjects; three experimental runs each with six targets repeated ten times) for target in the top panel; non-target in the middle; and target versus non-target AUC at the bottom.

Fig. 13. ERP to real and virtual sound image stimuli for all EEG electrodes used in the experiments conducted. The red lines represent the grand mean averaged target responses to the EEG experiment#1, while the green lines indicate target responses to the EEG experiment#2, and the blue lines show target response to the EEG experiment#3, remaining black lines mean non-target response to all of EEG experiment, respectively. Error bars depicting standard errors are also drawn around each of the averaged responses.

Fig. 14. The accuracy results comparing of the three experiments with various stimulus patterns. Blue, red and green bars stand for experiments #1, #2 and #3 respectively. The horizontal axis represents the subject numbers and the vertical one the accuracy rates in percents. Error bars depict standard errors.


