Fingertip Stimulus Cue–based Tactile Brain–computer Interface

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***Abstract*—The reported project aims to confirm whether a tactile glove fingertips' stimulator is effective for a brain–computer interface (BCI) paradigm using somatosensory event potential (SEP) responses with possible attentional modulation. The proposed simplified stimulator device is presented in detail together with psychophysical and EEG BCI experiment protocols. Results supporting the proposed simple tactile glove device are presented in form of online BCI classification accuracy results using shrinkage linear discriminant analysis (sLDA) technique. Finally, we discuss future possible paradigm improvement steps.**

I. Introduction

Brain computer interfaces (BCIs) belong to the so–called neurotechnology applications, which are expected to create possibilities for operation of any computing or mechanical devices using brainwaves only [1]. The neurotechnology shall allow handicapped people, e.g. the amyotrophic lateral sclerosis (ALS) users or locked–in syndrome (LIS) patients, to operate devices without any muscle activity necessary [1]. There are also many possible applications for healthy users, such as computer gaming or neurofeedback–based neuro–rehabilitation.

The most popular BCIs these days are a visual or auditory [2], [3] modalities in which a user communicates mental commands to be classified from brainwave carrying intentional responses to ocular or auditory stimuli. Those modalities, however, prevent users from paying attention visually or auditorily to surrounding environment causing often difficulties in an application operation [4]. Such BCIs are not available also for users suffering from lost or bad vision [5], as well as hearing problems due to the so—called ear stacking syndrome.

The reported in this paper research project aims to utilize a tactile BCI (tBCI) modality realized with a mechanical vibration small generators (vibrotactile transducers). This modality shall derive the so called "aha–" or P300–responses which are usually obtained by attending to intentionally attended targets and they appear as positive EEG signal deflections around 300 ms after stimulus onsets [1]. Although an auditory modality [6], [7], which is also an alternative to the vision, could also derive the P300 responses, it could not be used in case of advanced ALS/LIS patients (e.g. totally–locked–in syndrome) [5], [7]. Our project aims to further improve tBCI prototypes [5], [8], [9] and to develop a practical and stimulation device comparing to our group previous study [10]. We search for the most suitable tactile stimuli patterns and finger locations leading to a successful multi–command tactile paradigm. There are many recent active BCI research projects utilizing event related potentials (ERPs) [2], [3], [3]–[5], [9]. The brainwave features derived from ERPs are also very suitable to identify the so called "aha–" or P300–responses (positive ERP deflections after about 300 ms from the stimulus onset [1]). The contemporary tBCIs use mostly large receptive fields of fingertips [8], whole palm [11], face [12] or the whole body [13] stimulation to evoke the P300 responses. Thus, we propose to optimize smaller receptive fields of fingertip–based tactile stimulation device for practical use and analyzed EEG signals.

The rest of the paper is organized as follows. In the next section we introduce methods used and developed within the small receptive field–based tBCI project. Next, results and discussion are presented. Finally, conclusions and future research directions summarize the paper.

II. Methods

In this section, we explain details of the proposed fingertips–based tBCI paradigm. Within the presented project we conducted psychophysical and online BCI EEG recording experiments. The psychophysical and EEG experiments were conducted in agreement with the ethical committee guidelines of the Faculty of Engineering, Information and Systems at University of Tsukuba, Tsukuba, Japan. Five volunteer users participated in the experiments without any monetary compensation. The users agreed to participate by signing an informed consent. All the recorded datasets were next anonymized.

The P300 response used in the proposed tBCI paradigm to identify intentional choices is a positive brainwave deflection starting at around 300 ms after the user attends stimulus and it does not appear to the ignored one [1]. The P300 response–based BCIs usually employ visual and auditory modalities [2]. The P300–based BCI discriminates the attended and ignored

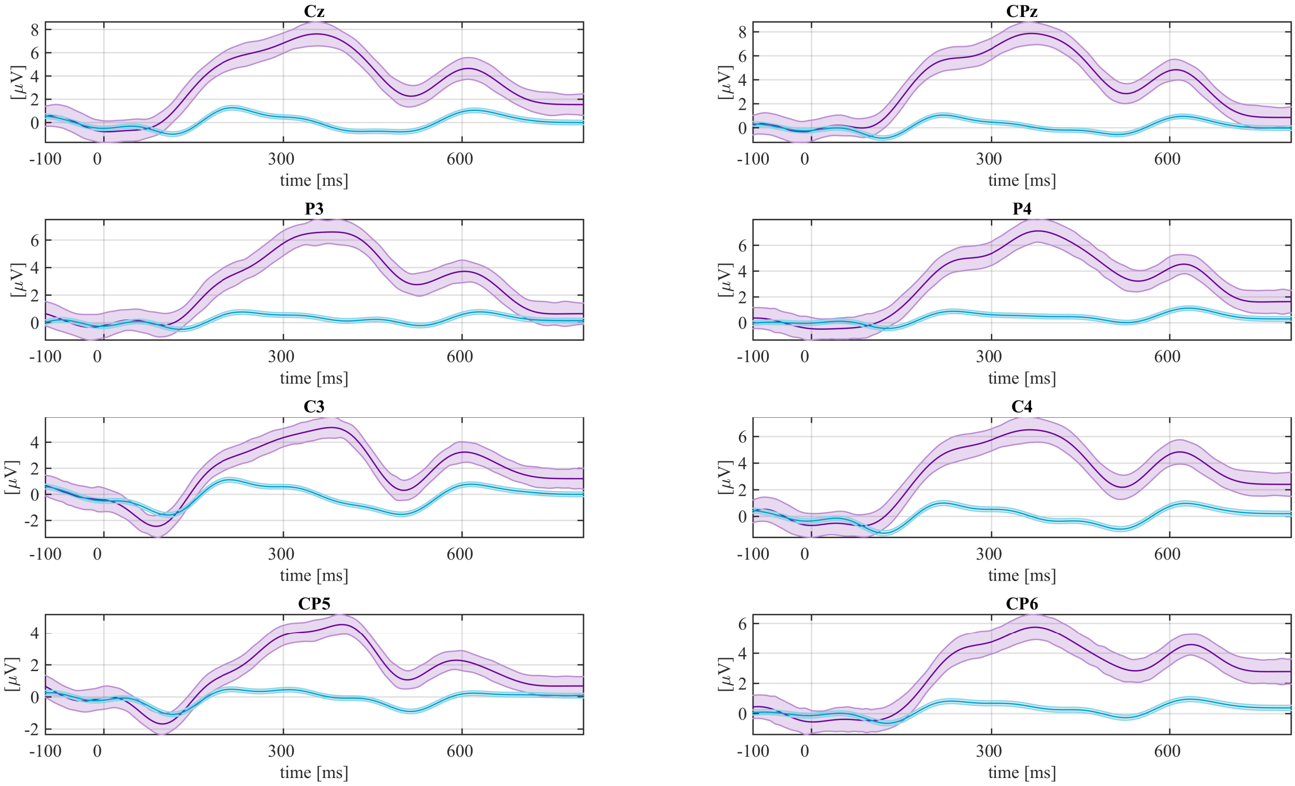

Fig. 1. Grand mean averaged ERP responses with clear P300 deflections depicted with purple colors. Blue traces represent the ignored non–target responses. All averaged lines are surrounded by standard error intervals.

stimuli from the differences in the ERP amplitudes of the target latencies. Examples of the averaged P300 responses evoked to an expected *target* stimuli in comparison to the ignored *non–targets* from experiments reported in this paper are presented in Figure 1.

We propose the new and simplified somatosensory stimulator, comparing to our previous study [10]. The new stimulator is a form of a glove named "the fingertip–sense glove" as shown in Figure 2. Five vibrotactile exciters are attached to user fingertips only. The reason of vibrotactile transducers attachment to a glove, instead directly to the fingertips, is to improve convenience of an experimental setup avoiding manual attachment of five devices separately each time. Moreover, the user wearing the stimulator can feel the stimulators attached with equal forces among different experimental sessions conducted even on different days. An usual garden–work–glove serves also as a safety electric insulator to avoid any current leakage causing a possible interference with recorded EEG. The simplified somatosensory stimulator serves as a different point of the current study comparing with previously reported results [10]. Also the presented concept is less expensive comparing to the hygienic and completely contactless solution using ultrasonic tactile stimulation [11]. This fingertip–sense glove allows for indirect somatosensory stimulation, so it results in increased application hygiene comparing with classical contact tactile BCIs.

We first conducted psychophysical experiments in order to determine the tactile task difficulty related to fingertip stimuli's perception from recorded behavioral "button–press" responses delay distributions. After that, in order to evaluate the P300 response occurrences and a possible online BCI application based on classification accuracies, we conducted EEG experiments with the same users as in the pilot study psychophysical experiments. The proposed in the reported project fingertip–sense glove allowed for non–direct skin application, which increased a hygiene comparing to the state–of–the–art tactile BCI stimulators.

ARDUINO DUE micro–controller board was used to generate the square wave signals delivered to the fingertips' attached vibrotactile transducers. The control of the ARDUINO DUE board was based on an in–house programed $C-$language application communicating with a portable computer via an USB port with the RS232 serial communication protocol embedded. The serial communication with ARDUINO DUE board was controlled by *MAX 6* [14] program developed also by our project team. The vibrotactile transducers (see Figure 2 for details) used in the experiments were attached to ARDUINO DUE via a custom made multichannel electronic amplifier developed also in our laboratory.

In psychophysical and EEG experiments, there were five 100 ms long stimulus patterns employed. Each stimulus instruction pattern was presented on a user in a training session using an interface display as shown in Figure 3.

Fig. 2. The fingertip–sense glove used in the experiments. Five vibrotactile transducers are attached at fingertips.

A. Psychophysical Experiment Protocol

The psychophysical experimental procedure consisted of the following steps:

1) An instruction, of which finger to focus attention on, was displayed on a computer screen and the tactile stimulus to the user's finger was given.
2) A random sequence of tactile stimuli was delivered to the fingertips.
3) The user responded by pushing the computer keyboard button only to the instructed pattern (the target) while ignoring the others.
4) The above three steps were repeated until all the stimulus patterns become the targets.

TABLE I
THE PSYCHOPHYSICAL EXPERIMENT CONDITIONS

Psychophysical experimental condition	Setting
Number of users	5
Mean age	27.8
Stimulus duration	100 ms
Stimulus frequency	300 Hz
Inter–stimulus–interval (ISI)	500 ms
Stimulus device	5 vibrotactile transducers
Number of runs for each user	1
Number of targets in each run	5 (50 targets
Number of non–targets in each run	and 200 non–targets)

The above four steps defined a single experimental sequence. We conducted five trials of psychophysical experiments because of five different target stimulus patterns. We allocated all sequences to a single experimental session and we conducted two sessions for each user. A single trial was composed of 50 random order stimuli, which consisted of 10 targets and 40 non–targets. If the number of button–press responses in each trial was lower than the designed number, we treated it as a no response case. Each trial consisted of the randomized order presentations with fixed inter–stimulus–interval (ISI) and the stimulus durations. All psychophysical experiments were using a portable computer running MAX 6 [14] program. The same MAX 6 program registered also behavioral button–press response times and stimulus numbers to which the user responded. Detailed psychophysical experiment conditions have been summarized in Table I. During the psychophysical experiment the user was instructed to attend to the target pattern presented in advance before each random stimulus sequence. The user instruction of which pattern to attend was delivered on a computer screen as presented in Figure 3. At each trial, the user could confirm the answer rate success of the executed button–presses. The user executed the behavioral responses with a free second hand.

B. EEG Experiment Protocol

The EEG experiments did not require the users to respond behaviorally by pressing a button, but only mental intentional confirmation were instructed to be generated.

The user's brainwaves were captured using wet active EEG electrodes g.LADYbird and g.USBamp amplifier, all by g.tec medical instruments GmbH, Austria. The EEG electrodes were attached to following scalp locations Cz, CPz, P3, P4, C3, C4, CP5, and CP6. The ground was attached to the Fpz location and a reference electrode to a left earlobe. The EEG signal sampling rate was set to 512 Hz. A notch filter to remove power line interferences was set at a rejection band of $48 \sim 52$ Hz.

The captured and filtered EEG were segmented and classified with a shrinkage linear discriminant analysis (sLDA) classifier [15] trained using brainwaves form a first training session using a OpenVibe software [15]. Next, the EEG signals were digitally bandpass processed be high–pass and low–pass filters set at 0.1 Hz and 40.0 Hz respectively. A procedure of 15 trials averaging in sLDA classifier training and 5 in online BCI testing sessions were used in order to enhance the P300 amplitudes. In EEG experiment, we also presented the same instruction screen as shown in Figure 3.

The EEG experimental procedure consisted of the the similar steps as in the above described psychophysical experiments. P300 (the user intentions) classification results were presented visually in form of numeric values also at the instruction screen.

III. Results

In this section, we present results of the two experimental sessions conducted, namely the psychophysical and online BCI

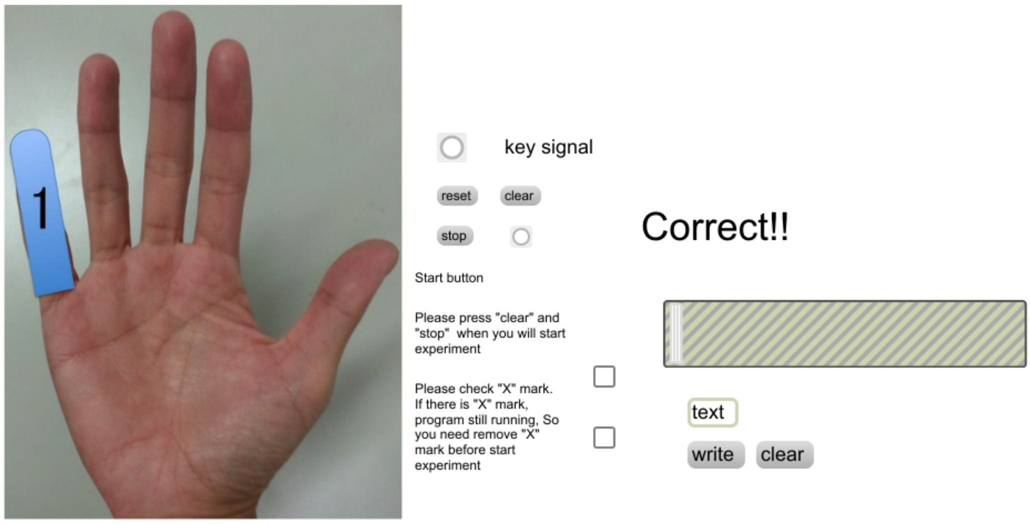

Fig. 3. An user interface with the psychophysical experiment instructions. A blue shade over a finger in the photographs depicts a target stimulus instruction. User responses have been collected using a computer keyboard. The correct answer rates were displayed after each trial to update the user with accuracy results.

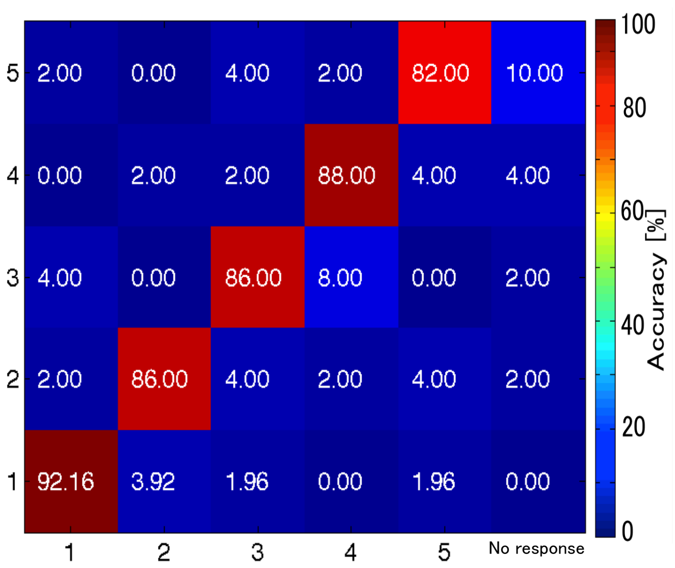

Fig. 4. A confusion matrix of the grand mean averaged user accuracy results in psychophysical experiments. The horizontal axis represents user response numbers and the vertical the instructed targets respectively. The numbers within the matrix represent percentages. A "no response" column indicates the missed responses. A diagonal indicates the correct responses, while off diagonals the mistakes. The obtained accuracy values are also presented with color coding.

session outcomes. All the results were above experimental chance levels and the both experimental paradigms are outlined in the following sections.

TABLE II
THE EEG EXPERIMENT CONDITIONS

EEG experimental condition	**Setting**
Number of users	5
Mean age	27.8
Stimulus duration	100 ms
Inter-stimulus-interval (ISI)	300 ms
Stimulus devices	5 HIHX09C005-8 transducers
Number of stimuli	5 (all finger tips of a single hand)
EEG recording system	g.USBamp amplifier by g.tec
EEG electrodes	Active wet (gel–based)
Number of EEG channels	8
EEG electrode positions	Cz, CPz, P3, P4, C3, C4, CP5, CP6
Sampling rate	512 Hz
High–pass EEG filter	0.1 Hz
Low–pass EEG filter	60 Hz
Notch EEG filter	48 $\sim$ 52 Hz
Reference electrode	Left mastoid
Ground electrode	FPz
Number of runs	3
Number of trials in each run	5 (25 targets and 100 non–targets)

A. Psychophysical Experiment Results

As a result of the performed psychophysical experiments we obtained user response accuracies and delay times. A confusion matrix depicted in Figure 4 was generated based on the averaged response accuracies of the all five users who took part in the psychophysical experiments. A horizontal axis in in Figure 4 represents the stimulus numbers, while the

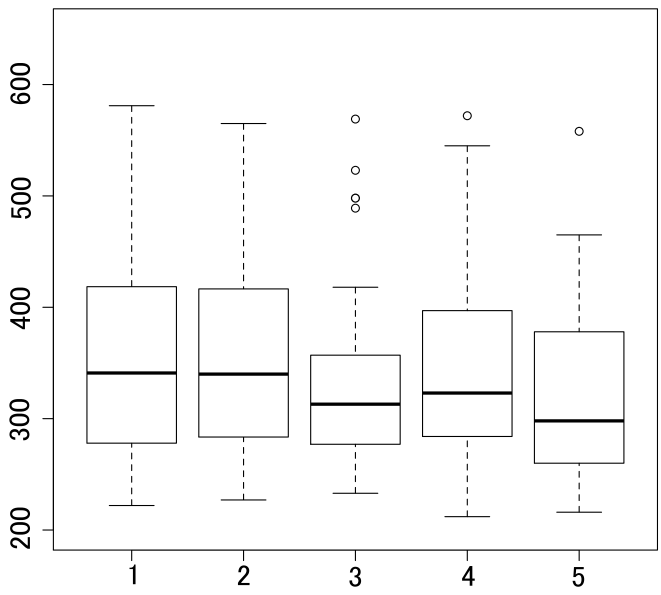

Fig. 5. The psychophysical experiment results in form of boxplots of the grand mean averaged user response times (behavioral button–presses). The horizontal axis represents the stimulus numbers and the vertical one the response times, respectively. No significant differences among the stimulus patterns were observed.

vertical one the button–press response times. A "no response" column was included to represent the possibly omitted replies. A diagonal line of the confusion matrix represents correct responses. A color coding has been used also to visualize the psychophysical experiment accuracies. The resulting accuracies were above 80% level, which were considered as good outcomes and way above a chance level of 20%. As result of the psychophysical trials we confirmed that the users in our experiments could distinguish all five vibrotacltile stimulus patterns delivered to fingertips using the propose generator. Figure 5 reports behavioral response time distributions in form of boxplots with medians and quartiles depicted. A horizontal axis in this figure lists the stimulus numbers, while the vertical one the button–press (behavioral) response times in milliseconds. This median response times were in a range of 290 $\sim$ 350 ms. No significant differences among response times to various patterns were observed.

B. EEG Experiment Results

The brainwaves resulting from the conducted BCI experiments have been depicted in form of grand mean averages in Figure 1. The above results clearly indicated P300 responses in the latencies of 200 $\sim$ 550 ms. The online tBCI experiments results have been also summarized in form of user achieved accuracies (a chance level was of 20%) and information transfer rates [10] in Table III. We also presented the maximum accuracies achieved by the users in the online BCI experiments with scores reaching 60.0% for three out of five participants taking part in the study. The lowest mean accuracy was of 6.7%, but the remaining user scores were above the chance level of 20% in the presented study. The obtained ITR results would allow for a slow yet already comfortable interaction using the proposed tBCI paradigm for the majority of the users tested in this study.

TABLE III
THE EEG EXPERIMENT BCI CLASSIFICATION (THEORETICAL CHANCE LEVEL OF 20%) AND ITR SCORES (THE AVERAGED BEST ITR WAS 3.94)

User number	Maximum BCI accuracy	Averaged BCI accuracy	Maximum ITR
1	40.0%	40.0%	1.2 bit/min
2	80.0%	60.0%	9.6 bit/min
3	80.0%	60.0%	9.6 bit/min
4	20.0%	6.7%	0.0 bit/min
5	80.0%	60.0%	9.6 bit/min

IV. CONCLUSIONS

Psychophysical and EEG experiments presented in the paper further confirmed our research hypothesis of the usability of small receptive field–based fingertips only stimulation for the novel tBCI paradigm.

In the series of psychophysical (behavioral) experiments we confirmed that the users could distinguish five vibrotactile stimulus patterns delivered to the fingertips on a single hand. We could also observe clear and possible to discriminate brainwave P300 responses in the online EEG BCI experiments.

The tBCI concept was evaluated in online classification experiments with five trails averaging setup using sLDA classifier for the P300 responses classification leading to the final BCI commands' execution. The obtained results have shown that the averaged classification accuracies resulted above the chance level scores of 20% for majority of the users. The online tBCI averaged accuracy results were in a range of 6.7% $\sim$ 60.0%. The best obtained ITR was of 9.6 bit/min.

In near future to be conducted research project we plan test experiments with shorter ISIs and with single trial–based classification sequences, as well as an extension of the number of the vibrotactile transducers used.

REFERENCES

[1] J. Wolpaw and E. W. Wolpaw, Eds., *Brain-Computer Interfaces: Principles and Practice*. Oxford University Press, 2012.

[2] M. Chang, N. Nishikawa, Z. R. Struzik, K. Mori, S. Makino, D. Mandic, and T. M. Rutkowski, "Comparison of P300 responses in auditory, visual and audiovisual spatial speller BCI paradigms," in *Proceedings of the Fifth International Brain-Computer Interface Meeting 2013*. Asilomar Conference Center, Pacific Grove, CA USA: Graz University of Technology Publishing House, Austria, June 3-7, 2013, p. Article ID: 156. [Online]. Available: http://castor.tugraz.at/doku/BCIMeeting2013/156.pdf

[3] J. E. Huggins, C. Guger, B. Allison, C. W. Anderson, A. Batista, A.-M. Brouwer, C. Brunner, R. Chavarriaga, M. Fried-Oken, A. Gunduz, D. Gupta, A. Kübler, R. Leeb, F. Lotte, L. E. Miller, G. Müller-Putz, T. Rutkowski, M. Tangermann, and D. E. Thompson, "Workshops of the fifth international brain-computer interface meeting: Defining the future," *Brain-Computer Interfaces*, vol. 1, no. 1, pp. 27–49, 2014. [Online]. Available: http://www.tandfonline.com/doi/abs/10.1080/2326263X.2013.876724

[4] S. Kono and T. M. Rutkowski, "Tactile-force brain-computer interface paradigm," *Multimedia Tools and Applications*, vol. 'Online First' on SpringerLink, pp. 1–13, December 2014. [Online]. Available: http://dx.doi.org/10.1007/s11042-014-2351-1
[5] T. M. Rutkowski and H. Mori, "Tactile and bone–conduction auditory brain computer interface for vision and hearing impaired users," *Journal of Neuroscience Methods*, p. Available online 21 April 2014, 2014. [Online]. Available: http://dx.doi.org/10.1016/j.jneumeth.2014.04.010
[6] T. M. Rutkowski, A. Cichocki, and D. P. Mandic, "Spatial auditory paradigms for brain computer/machine interfacing," in *International Workshop On The Principles and Applications of Spatial Hearing 2009 (IWPASH 2009) - Proceedings of the International Workshop*, Miyagi-Zao Royal Hotel, Sendai, Japan, November 11-13, 2009, p. P5.
[7] Y. Matsumoto, N. Nishikawa, S. Makino, T. Yamada, and T. M. Rutkowski, "Auditory steady-state response stimuli based bci application-the optimization of the stimuli types and lengths," pp. 1–7, 2012.
[8] H. Mori, Y. Matsumoto, S. Makino, V. Kryssanov, and T. M. Rutkowski, "Vibrotactile stimulus frequency optimization for the haptic BCI prototype," in *Proceedings of The 6th International Conference on Soft Computing and Intelligent Systems, and The 13th International Symposium on Advanced Intelligent Systems*, Kobe, Japan, November 20-24, 2012, pp. 2150–2153. [Online]. Available: http://arxiv.org/abs/1210.2942
[9] H. Mori, Y. Matsumoto, V. Kryssanov, E. Cooper, H. Ogawa, S. Makino, Z. R. Struzik, and T. M. Rutkowski, "Multi-command tactile brain computer interface: A feasibility study," in *Haptic and Audio Interaction Design*. Springer, 2013, pp. 50–59.
[10] H. Yajima, S. Makino, and T. M. Rutkowski, "P300 responses classification improvement in tactile bci with touch-sense glove," in *Asia-Pacific Signal and Information Processing Association, 2014 Annual Summit and Conference (APSIPA)*. IEEE, December 2014, pp. 1–7. [Online]. Available: http://dx.doi.org/10.1109/APSIPA.2014.7041770
[11] K. Hamada, H. Mori, H. Shinoda, and T. M. Rutkowski, "Airborne ultrasonic tactile display brain-computer interface paradigm," in *Proceedings of the 6th International Brain-Computer Interface Conference 2014*, G. Mueller-Putz, G. Bauernfeind, C. Brunner, D. Steyrl, S. Wriessnegger, and R. Scherer, Eds. Graz University of Technology Publishing House, 2014, pp. Article ID 018–1–4. [Online]. Available: http://castor.tugraz.at/doku/BCIMeeting2014/bci2014_018.pdf
[12] H. Mori, Y. Matsumoto, Z. R. Struzik, K. Mori, S. Makino, D. Mandic, and T. M. Rutkowski, "Multi-command tactile and auditory brain computer interface based on head position stimulation," in *Proceedings of the Fifth International Brain-Computer Interface Meeting 2013*. Asilomar Conference Center, Pacific Grove, CA USA: Graz University of Technology Publishing House, Austria, June 3-7, 2013, p. Article ID: 095. [Online]. Available: http://castor.tugraz.at/doku/BCIMeeting2013/095.pdf
[13] T. Kodama, S. Makino, and T. M. Rutkowski, "Spatial tactile brain-computer interface paradigm applying vibration stimuli to large areas of user's back," in *Proceedings of the 6th International Brain-Computer Interface Conference 2014*, G. Mueller-Putz, G. Bauernfeind, C. Brunner, D. Steyrl, S. Wriessnegger, and R. Scherer, Eds. Graz University of Technology Publishing House, 2014, pp. Article ID 032–1–4. [Online]. Available: http://castor.tugraz.at/doku/BCIMeeting2014/bci2014_032.pdf
[14] "Max 6," 2012. [Online]. Available: http://cycling74.com/
[15] Y. Renard, F. Lotte, G. Gibert, M. Congedo, E. Maby, V. Delannoy, O. Bertrand, and A. Lécuyer, "Openvibe: an open-source software platform to design, test, and use brain-computer interfaces in real and virtual environments," *Presence: teleoperators and virtual environments*, vol. 19, no. 1, pp. 35–53, 2010.