Classification Improvement of P300 Response Based Auditory Spatial Speller Brain–Computer Interface Paradigm

Moonjeong Chang
Life Science Center of TARA
University of Tsukuba
Tsukuba, Ibaraki, 305-8577 Japan
Email: moonjeong@bci-lab.info

Shoji Makino
Life Science Center of TARA
University of Tsukuba
Tsukuba, Ibaraki, 305-8577 Japan
Email: maki@tara.tsukuba.ac.jp

Tomasz M. Rutkowski[1,†,‡]
†Life Science Center of TARA
University of Tsukuba
Tsukuba, Ibaraki, 305-8577 Japan
‡RIKEN Brain Science Institute
Wako-shi, Saitama, 351-0198 Japan
Email: tomek@tara.tsukuba.ac.jp

***Abstract*—The aim of the presented study is to provide a comprehensive test of the EEG evoked response potential (ERP) feature selection techniques for the spatial auditory BCI–speller paradigm, which creates a novel communication option for paralyzed subjects or body–able individuals requiring a direct brain–computer interfacing application. For rigor, the study is conducted with 16 BCI–naive healthy subjects in an experimental setup based on five Japanese hiragana characters in an offline processing mode. In our previous studies the spatial auditory stimuli related P300 responses resulted with encouragingly separable target vs. non-target latencies in averaged responses, yet that finding was not well reproduced in the online BCI single trial based settings. We present the case study indicating that the auditory spatial unimodal paradigm classification accuracy can be enhanced with an AUC based feature selection approach, as far as BCI-naive healthy subjects are concerned.**

I. Introduction

Contemporary brain–computer interface (BCI) paradigms rely mostly on unimodal approaches [1] with still not fully satisfactory online interfacing accuracy results. The recently proposed solutions enhance the existing paradigms by adding spatial stimuli variability [2], [3], [4], [5] in order to augment the brain–computer interfacing comfort or to boost the information-transfer-rate (ITR) achieved by the users in real–time.

We enhance classification accuracy of the previously published by the authors [6], [7] simple five Japanese hiragana characters (a,i,u,e,o) auditory spatial speller task in order to boost interfacing accuracy variability and users' subjective comfort. The concept is tested with 16 BCI–naive subjects in an offline BCI processing mode. In order to do so, we design the auditory task with synthetic vowel representations originating from the five spatial directions using a vector based amplitude panning (VBAP) [8] technique. Next we propose a new evoked response potential (ERP) feature selection technique based on the area under the curve (AUC) [9] distributions separability test. We compare the results with the classical coefficient of determination based methods [10].

The paper is organized as follows. In the next section we introduce BCI psychophysical and EEG experimental protocols. After that results of the experiments are discussed together with the proposed ERP feature selection enhancement technique. Discussion and future research directions concluded the paper.

[1]The corresponding author.

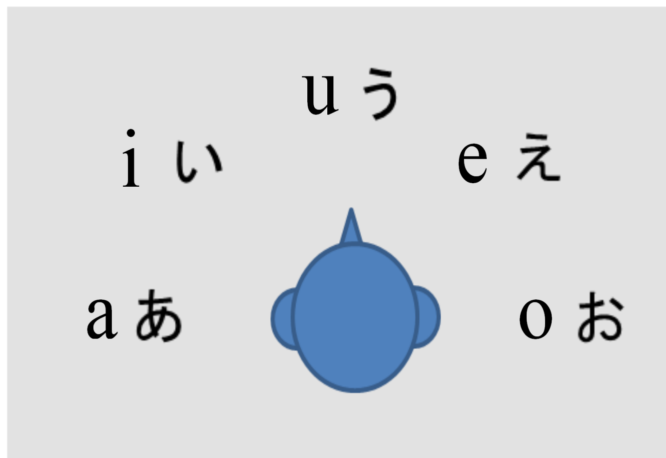

Fig. 1. The auditory spatial BCI–speller paradigm realized with VBAP technique [8].

II. Methods

In the experiments reported in this paper, 16 healthy BCI–naive subjects took part (mean age 21.81, standard deviation of 0.75). All the experiments were performed in the Life Science Center of TARA, University of Tsukuba, Japan. The online EEG BCI experiments were conducted in accordance with *WMA Declaration of Helsinki - Ethical Principles for Medical Research Involving Human Subjects*. The subjects performed the experiments with monetary gratification.

The 200 ms long spatial unimodal auditory stimuli were presented from five distinct spatial locations. We designed a VBAP [8] application that positions virtual sound images at spatial locations positioned at $-90°, -45°, 0°, 45°$, and $90°$ in respect to the front of the subject head as depicted in Figure 1. Each subject first conducted a short psychophysical test with a button press response to confirm understanding of

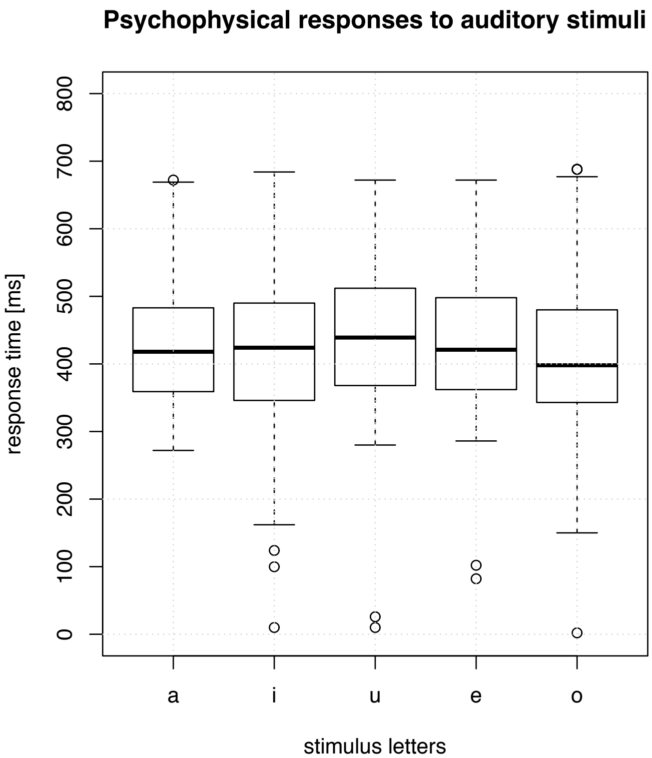

Fig. 2. Results of the psychophysical experiment in a form of boxplots with averaged response delays from the 16 subjects for each auditory spatial letter separately. The "hiragana" spatial stimulus letters (a, i, u, e, o) are represented by the numbers $(1, 2, 3, 4, 5)$ in the figure.

the experimental setup. During the online BCI experiments, the EEG signals were captured with a 16 active electrodes EEG amplifier system g.USBamp by g.tec. The electrodes were attached to the following head locations Cz, CPz, POz, Pz, P1, P2, C3, C4, O1, O2, T7, T8, P3, P4, F3, and F4, as in the $10/10$ extended international system [11] (see topographic plots in Figures 4 and 6). The ground and reference electrodes were attached at FCz and the left earlobe respectively. The recorded EEG signals were processed by the in-house enhanced BCI2000 application using an SWLDA classifier with features drawn from $0 - 600$ ms ERP intervals. The sampling frequency was set to 512 Hz, a high pass filter at 0.1 Hz, the low pass filter at 100 Hz, with an electric power line interference notch filter set in a band $48 - 52$ Hz. An inter–stimulus–interval (ISI) was set to 500 ms and each stimuli had length of 200 ms. The subject was instructed to spell five hiragana letters random sequences as in a classical P300 based oddball paradigm [1]. Each target was presented ten times in a single spelling trial and the averages of ten ERPs were later used for the classification in order to make the experiment easier for novices.

In this paper we report the off–line postprocessing of the EEG data in order to enhance the classification results by the new AUC–based feature extraction method.

III. RESULTS

The averaged results of the spatial auditory psychophysical experiments conducted with the 16 subjects are summarized in

TABLE I. SPATIAL AUDIO BCI–SPELLER CLASSIFICATION ACCURACY IMPROVEMENT WITH THE PROPOSED AUC–BASED ERP FEATURE SELECTION (NaN - STANDS FOR NOT–A–NUMBER WHEN IT WAS NOT POSSIBLE TO TRAIN THE CLASSIFIER). THE CLASSICAL SWLDA CLASSIFIER WAS APPLIED IN THE SAME CONFIGURATION FOR THE TWO FEATURE SELECTION CASES. THE TEN ERP AVERAGES METHOD [1], [10] WAS USED IN ORDER TO ENHANCE THE EEG FEATURES FROM THE BCI–NAIVE SUBJECTS. PLEASE NOTE, THAT WHILE IN SIX CASES THE PROPOSED ERP FEATURE EXTRACTION METHOD DID NOT IMPROVE THE RESULTS, THERE WAS NO CASE OF A RESULT DECREASE.

Subject	r^2–based accuracy	AUC–based accuracy	Improvement
#1	100%	100%	0%
#2	40%	80%	40%
#3	40%	80%	40%
#4	20%	20%	0%
#5	20%	20%	0%
#6	60%	60%	0%
#7	80%	80%	0%
#8	20%	80%	60%
#9	20%	60%	40%
#10	40%	60%	20%
#11	40%	60%	20%
#12	80%	80%	0%
#13	40%	80%	40%
#14	0%	60%	60%
#15	0%	60%	60%
#16	0%	20%	20%

the Figure 2 confirming the experimental hypothesis that all the chosen sound location stimuli had the same cognitive loads resulting with the equal behavioral time response results (no significant differences as tested with the pairwise $Wilcoxon$–test).

The averaged EEG ERP responses from the same 16 BCI–naive subjects are reported in Figure 3 and for a single subject with the best accuracy boost with the proposed method (see Table I) in Figure 5. The P300 response is clearly depicted in the target averages in the range of $400 - 500$ ms in case of all subject averages. The results of r^2 versus AUC scores comparison depicted in Figure 4 and even with stronger effect of the single subject results in Figure 6 confirm the superiority of the second method (AUC) for the successful feature selection.

The resulting classification enhancement using a standard SWLDA classifier (the same configuration for the both r^2 and AUC based features) is reported in Table I. For the majority of subjects performing spatial auditory BCI–speller task the AUC based ERP features resulted in classification accuracy boosts. Only six out of sixteen subject results remained unchanged. None of the results suffered accuracy decrease. The single subject #15 results are plotted in Figure 5 separately since this has been the most difficult case resulting with the best improvement of 60%. Figures 5 and 6 clearly show the superior of AUC based features since they were not drawn from the region of $400 - 600$ ms which that particular subject had somehow more active for the both targets and non–targets. The r^2 based measure unfortunately identified this region (see middle panel of the Figure 6) as "a potentially separable."

IV. CONCLUSIONS

In the paper we reported the results obtained with AUC–based EEG ERP feature selection technique which turned out superior comparing with the traditional r^2 based method. AUC–based EEG ERP feature extraction is the data–driven

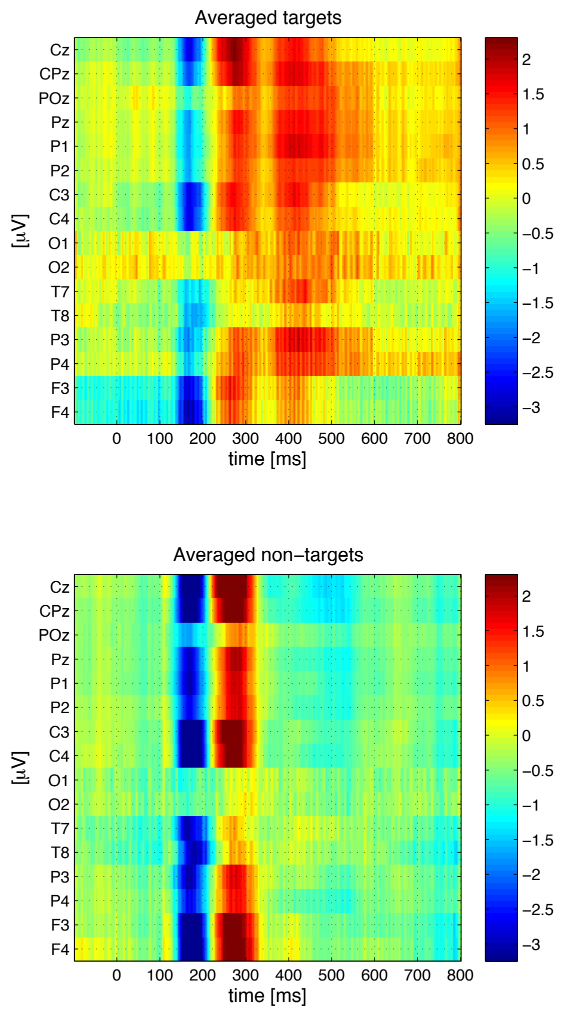

Fig. 3. EEG ERP averaged responses of the 16 BCI–naive subjects to targets in the upper panel and non–targets in the lower one. P300 response is easy to identify in the range of $300 - 600$ ms. The associated head topographic plots, r^2 and AUC results are depicted in Figure 4.

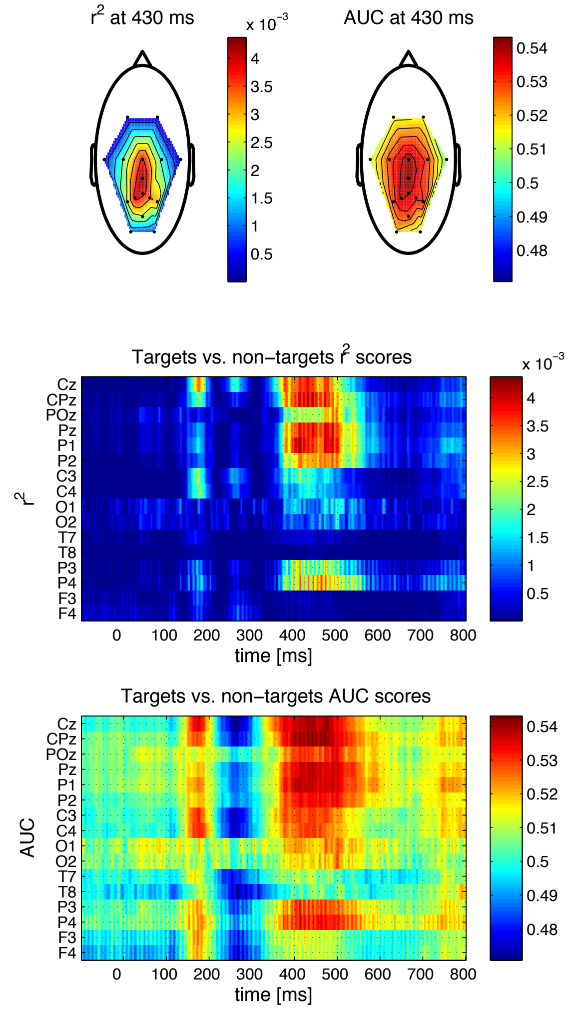

Fig. 4. The results of the 16 subjects averaged r^2 versus AUC based ERP feature selection in form of respective topographic plots in the top panels. Time series of r^2 (middle panel) and AUC (bottom panel) scores are also depicted.

approach without assumptions on data distribution, which apparently results with longer latencies leading to improved classification results.

The obtained results allowed for the boost up to 60% of the offline BCI mode classification results in the five–commands spatial auditory paradigm as reported in the Table I.

The presented preliminary, yet encouraging results, call for more research on spatial auditory BCI paradigms. The next research steps will include the spatial auditory stimulus optimization for handicapped or bedridden subjects, who cannot utilize the fully surround acoustic environment.

We plan to continue this research in order to apply the method in online BCI application for those patients suffering amyotrophic–lateral–sclerosis (ALS), also known as Lou Gehrig's disease, or totally–locked–in–syndrome (TLS) to create a new communication possibility for such users in need.

Acknowledgments

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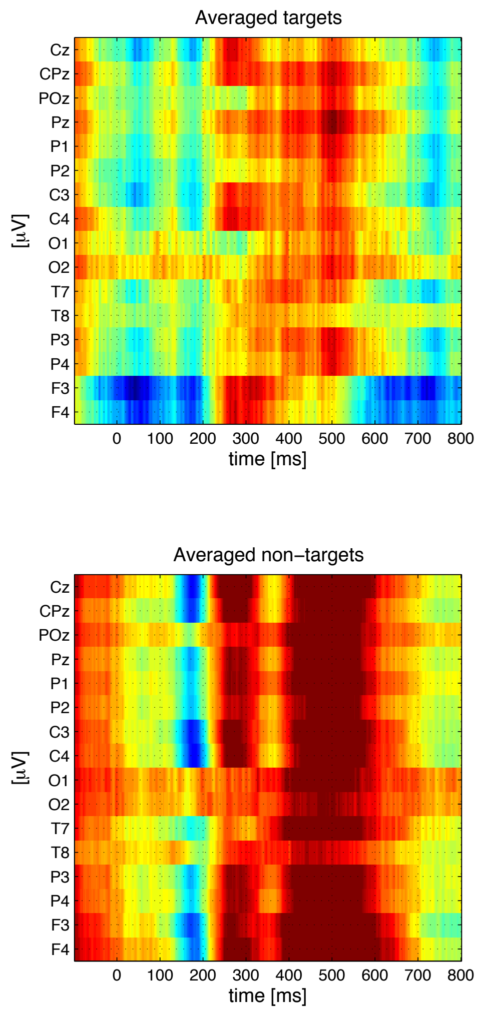

Fig. 5. EEG ERP averaged responses of the subject #15 whose target (upper panel) and non–target (lower panel) responses did not differ significantly as if in this case the user fired P300 response for each stimuli. Fortunately, the propose AUC–based feature selection allowed for 60% classification boost (see Table I). The associated head topographic plots, r^2 and AUC results are depicted in Figure 6.

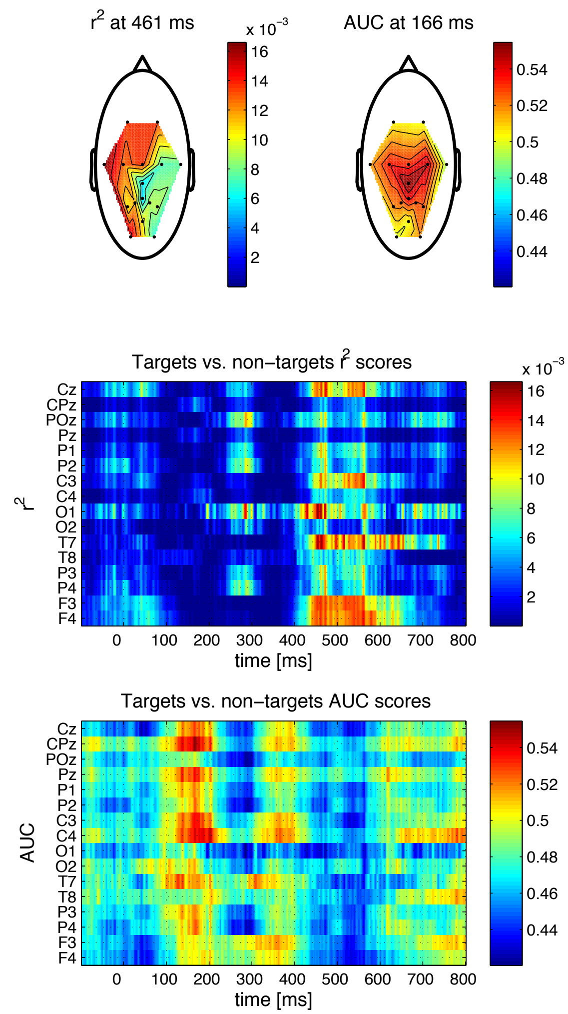

Fig. 6. The comparison of the single subject #15 results of r^2 versus AUC–based ERP feature selection in form of respective topographic plots in the top panels. Time series of r^2 (middle panel) and AUC (bottom panel) scores are also depicted. In this case the difference between r^2 and AUC measures is significant for the $400-500$ ms latencies with the troublesome for this subject P300 response fired for the both targets and non-targets (compare the both panels in Figure 5). The AUC based features were not drawn from this latency range.

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