Head-related Impulse Response Cues for Spatial Auditory Brain-computer Interface

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Abstract—This study provides a comprehensive test of a head-related impulse response (HRIR) cues for a spatial auditory brain-computer interface (saBCI) speller paradigm. We present a comparison with the conventional virtual sound headphone-based spatial auditory modality. We propose and optimize the three types of sound spatialization settings using a variable elevation in order to evaluate the HRIR efficacy for the saBCI. Three experienced and seven naive BCI users participated in the three experimental setups based on ten presented Japanese syllables. The obtained EEG auditory evoked potentials (AEP) resulted with encouragingly good and stable P300 responses in online BCI experiments. Our case study indicated that users could perceive elevation in the saBCI experiments generated using the HRIR measured from a general head model. The saBCI accuracy and information transfer rate (ITR) scores have been improved comparing to the classical horizontal plane-based virtual spatial sound reproduction modality, as far as the healthy users in the current pilot study are concerned.

I. INTRODUCTION

BCI is a technology that uses brain neuronal signals to operate a computer without any muscle movements. Therefore, it is expected to provide a speller for disabled people such as patients suffering from the amyotrophic lateral sclerosis (ALS) [1]. Although currently a successful visual BCI modality could provide a fast speller, the advanced patients who are in a locked-in state cannot use it because they lose any intentional muscle control including even eye blinks [2]. Auditory BCI can be an alternative method because it does not require a good sight or eye movements [1], [3]–[6]. We propose an alternative method to extend the previously published by our group spatial auditory BCI (saBCI) paradigms [3], [6] by making use of a head related impulse response (HRIR) for the virtual spatial sound images reproduction with headphones. Our research target is the virtual sound saBCI using the HRIR-based spatial cues to create the non-invasive and auditory stimulus-driven paradigm, which does not require a long training. HRIR appends interaural-intensity-differences (IID), interauraltime-differences (ITD), and spectral modifications to create the spatial stimuli, while a vector-based amplitude panning

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(VBAP) appends only the IID. The HRIR allows for more precise and fully spatial virtual sound images positioning utilizing even the user not own HRIR measurements [7].

In our previous study [8] we evaluated saBCI feasibility with the HRIR-based spatial sound generator, and compared it with a formerly reported vector-based-amplitude-panning (VBAP)-based spatial auditory experiments [6]. The above study used only five Japanese vowels distributed horizontally every 40° in front of a subject head. The pilot study resulted with clear P300 responses and it has shown that HRIR modality could improve spelling accuracy comparing to the conventional spatial sound generation methods. In the study presented in this paper we introduce ten Japanese kana syllables-based speller using the sound elevation features as the second step. We also compare various sound elevation settings. However, it is usually difficult to precisely perceive various sound elevations using not the user own HRIR, because the elevation perception is highly individual and it is influenced by the shape of an auricle [7]. Unfortunately, it would be very difficult to record a bedridden ALSpatient own HRIR. Therefore, we propose to test the HRIRbased saBCI efficacy using a general head model (KEMAR). We conduct psychophysical and EEG experiments in online saBCI ten Japanese kana syllables spelling experiments in order to test our research hypothesis of the KEMAR HRIRbased paradigm practical feasibility.

From now on the paper is organized as follows: next section describes methods and experimental set up; third section reports results of the *P*300 response–based saBCI speller classification accuracies and information transfer rate (ITR) in comparison to a conventional method; finally, conclusions and future research directions summarize the paper.

II. MATERIALS AND METHODS

In order to prepare the saBCI stimuli to create an oddball paradigm generating the P300 responses [2], all spatial sound images were created using HRIR of the general head model. Ten Japanese syllables with a vowel "a" were selected for as sound stimuli in this project. The spoken syllables were taken from a public Japanese sound dataset of a female speech [9]. The monaural sound stimuli were spatially distributed using a public domain KEMAR'S HRTF DATABASE provided by the MIT Media Lab [10]. In order to generate a stereo sound placed at a spatial location at an azimuth of θ and an elevation of ϕ the following procedure was applied. Let $h_{l,\theta,\phi}$ and $h_{r,\theta,\phi}$ be the minimum–phase impulse responses from the KEMAR HRTF DATABASE measured at the chosen azimuth θ and the elevation ϕ at the left (*l*) and right (*r*) ears. The

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Fig. 1. A diagram of the three proposed virtual spatial stimulus sound settings. The left box depicts the horizontal only placement–based setting; the middle the elevation use–based case; and the right box the elevation use with an additional frequency shifting set up.

stereo spatial sound delivered via headphones to the left and right ears respectively could be constructed, in time domain using HRIR, as a two-dimensional signal composed of the left $x_l(t)$ and right $x_r(t)$ headphone channels as follows,

$$x_{l}(t) = \sum_{\tau=0}^{n-1} h_{l,\theta,\phi}(\tau) s(t-\tau),$$

$$x_{r}(t) = \sum_{\tau=0}^{n-1} h_{r,\theta,\phi}(\tau) s(t-\tau),$$
(1)

where τ denotes sample time delay and *n* is the HRIR length as obtained from the HRTF DATABASE [11]. The so created spatial acoustic stimuli were delivered to the left and right ears of the user through the ear-fitting portable headphones SENNHEISER CX 400II. Three proposed spatial settings to evaluate the feasibility of the sound elevation using the HRIR for the saBCI are presented in Figure 1. The first spatial stimulus setting included only the horizontal sound images' placement of the ten saBCI commands. The sound images were distributed at five directions every 45° on the horizontal plane at the user ears' level. Two types of commands were delivered from the same spatial directions. The second stimulus setting included the sound elevation variability. Ten stitmuli were distributed among the all different directions. Five commands were localized at elevation of 50° from the user ears' level and every 45° horizontally. The third setting included also the variable elevation and an additional option of a frequency modulation appended to discriminate the sound images originating from various elevations. In the psychoacoustics there is a well-known property called a tonal bell causing a higher-frequency sound to be perceived as originating from a higher elevation [7]. To simulate the above effect we shifted in frequency domain the stimuli, which shall be perceived at higher elevations, using the TANDEM-STRAIGHT method [12]. The sound stimuli to be perceived at elevation of 50° had shifted up their fundamental frequencies by 24 Hz.

All of the experiments reported in this paper were performed in the Life Science Center of TARA, University of Tsukuba, Japan. Ten healthy users participated in our study. They were comprised of seven naive and three experienced BCI users. The average age was of 24.7 years old (standard deviation 6.48 years old, three males and seven females). The psychophysical and online EEG saBCI experiments were conducted in accordance with *The World Medical Association Declaration of Helsinki - Ethical Principles for Medical Research Involving Human Subjects*. The experimental procedures were approved and designed in agreement with the ethical committee guidelines of the Faculty of Engineering, Information and Systems at University of Tsukuba, Japan.

The psychophysical experiments were conducted to examine a perception of elevation and preferences for each spatial sound setting. The users were instructed to respond by pressing the button as soon as possible after they perceived the *target* stimulus as in the classical oddball paradigm [2]. In a single experimental session 10 targets and 90 non-targets were presented. Each experiment was comprised of three sessions for every spatial sound setting. The stimulus duration was set to 300 ms and the inter-stimulus-interval (ISI) to 700 ms. The online EEG experiments were conducted to investigate whether P300 responses could be evoked in the various spatial sound settings and to compare the saBCI classification accuracies, as well as an efficaty of each set up. The brain signals were collected by a bio-signal amplifier system g.USBamp by g.tec Medical Engineering GmbH, Austria. The EEG signals were captured by sixteen active gel-based electrodes g.LADYbird attached to the following head locations Cz, Pz, P3, P4, Cp5, Cp6, P1, P2, Poz, C1, C2, FC1, FC2, and FCz as in the extended 10/10international system [2]. The ground electrode was attached on the forehead at the FPz location, and the reference on the user's left earlobe respectively. An in-house extended BCI2000 [13] software was used for the saBCI experiments to present stimuli and display online classification results.

A single EEG experimental session was comprised of one training and two test runs for each spatial stimulus setting. In the training run, EEG brainwaves were recorded and next classifier parameters were calculated. In order to spell a single character, 15 targets and 135 non-targets were presented for ERP response averaging. In the test runs, user spelled two sets of the three words that the covered ten targets (a-ta-ma; ha-ra; sa-wa-ya-ka-na; wa-ta; ha-na*va*; *a*–*ka*–*ra*–*sa*–*ma*). For spelling single character, 5 *target* and 45 non-target stimuli were presented continuously as for single syllable (five ERPs averaging scenario). Experiment order of every spatial sound setting and spelled words were randomized for each subject. The sound stimulus duration was set to 300 ms and the inter-stimulus-interval (ISI) to 150 ms. The EEG sampling rate was of 512 Hz and a notch filter to remove electric power lines interface of 50 Hz was applied in a rejection band of $48 \sim 52$ Hz. The band-pass filter was set at 0.1 Hz and 60 Hz cutoff frequencies. The acquired EEG brain signals were classified online by the inhouse extended BCI2000 application using a stepwise linear discriminant analysis (SWLDA) [14] classifier with features drawn from the $0 \sim 800$ ms ERP interval, with removal of the least significant input features, having p > 0.15, and with the final discriminant function restricted to contain a maximum of 60 features. The participating users answered also questionnaires, asking about which modality they preferred,



Fig. 2. Grand mean averaged EEG ERP responses together with standard error bars for all the participating users in the study plotted for representative electrodes separately. Purple lines depict the grand mean averaged *targets* with clear P300 responses, while blue traces are the *non-targets*. Eye blink artifacts were removed with 80 μV thresholding.

after finishing psychophysical and EEG experiments.

III. RESULTS

In the psychophysical experiments the users could perceive the various elevation settings. The questionnaire answers indicated that the frequency shifting supported the stimulus discrimination. The elevation and frequency variable setting resulted with the best perception of the spatial sound image stimuli. Four out of six participants preferred elevation and frequency-based spatial sound setting. The results of the saBCI EEG experiment are depicted in Figure 2. Each column presents the grand mean averaged ERP results at representative four electrodes for the three proposed spatial sound settings. We confirmed the clear P300 responses in latency ranges of $400 \sim 1000$ ms and their usability for the subsequent classification. Figure 3 presents the classification accuracies of the P300 responses as obtained with the SWLDA classifier. The theoretical chance level was of 10% in this study. All users scored with accuracies above 70% at the best. There were three users who resulted with 100% accuracies as the best in the reported experiments. The average scores were obtained as mean values calculated from the two saBCI test spelling sessions of all the users (training sessions were not included in the saBCI accuracy calculations). The results are shown in Figure 4. There were significant differences between horizontal and elevation use; elevation only versus elevation and frequency spatial sound settings as calculated with the t-test (the significant level was p < 0.05). The 70% of the users preferred elevation-based spatial sound setting. The important outcome of the presented study was that the users could clearly perceive elevation variability using not their own HRIR filters. Although the results of psychophysical experiments have shown that the



Fig. 3. The average saBCI spelling accuracies of all the users. The chance level was of 10%. The blue bars depict the saBCI accuracy of horizontal sound images placement; green bars represent elevation–based results; and the orange color the elevation and frequency settings, respectively. Th users #4,#5 and #10 were the experienced BCI users, while the remaining were the naive participants.

users preferred elevation and frequency spatial sound setting, the online saBCI accuracies suggested that P300 responses generated in elevation variability setting where the best. In order to compare the developed HRIR–based saBCI we calculated the information transfer rate (ITR) scores considered as a major comparison measure among the BCI paradigms [4]. ITR scores were calculated as follows:

$$ITR = V \cdot R,$$

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

where V was the classification speed in selections/minute; Rrepresented the number of bits/selection; N was the number of classes (10 in this study), and P the classification accuracy. The conditions contributing to ITR were in a trade-off relationship with the task easiness. For example, the short ISI could improve the ITR, but it could cause the task to be difficult. ITR could increase with larger number of commands, higher accuracies, shorter ISI, and a smaller number of the averaged trials. We also compared the ITR scores of the three proposed modalities with our previous project results and with the vector-based-amplitude-panning (VBAP)-based spatial auditory approach, which was regarded as a conventional method [6]. The VBAP experiment was conducted for two sessions and with 16 BCI-naive users [6]. The electrode positions were the same as in the experiments reported in this paper. The sound stimuli were presented with small ear-fitting headphones (SENNHEISER CX 400II) in the all the studies. The spatial locations of the stimulus sound images, the number of commands, and ISI settings are summarized in Table I. The ITR scores of the elevation use spatial setting reached 14.92 bit/min. The other proposed modalities scored above 8.5 bit/min and also exceeded our previous research results [8]. The headphone-based virtual saBCI took one step forward. Although the HRIR based saBCI resulted with better accuracy scores, this results cannot



Fig. 4. This averaged saBCI spelling accuracies for each of the tested spatial sound settings. The theoretical chance level was of 10%. The blue color depicts the accuracy of horizontal sound setting; green the elevation variability; and orange the elevation and frequency case, respectively. The right side pie chart depicts the user preferences of the three spatial sound settings with the same color coding, respectively.

be compared for a statistical significance with the former study due to the different subject groups. We also analyzed spelling accuracy for the various horizontal azimuths as shown in Table II. Compared with the horizontal placement modality, the remaining two spatial sound settings resulted with reduced accuracy errors. The results have shown that the variable stimuli elevation helped the users to distinguish better the horizontal sound locations either.

IV. CONCLUSIONS

The presented EEG results confirmed the P300 responses feasibility among the experienced and naive saBCI users. The proposed spatial sound stimulus settings for various elevations obtained using HRIR were effective for saBCI paradigm. Additionally, the short ISI did not distract the users' perception, rather it apparently sharpened it resulting with the better saBCI accuracies.

The obtained ITRs resulted with better scores comparing to our previous study using simple HRIR and VBAP–based spatial sound virtualization.

Nevertheless, current study is not yet ready to compete with the faster visual BCI spellers. Furthermore, it is necessary to improve the ITR for a comfortable online saBCI– based spelling. We plan to extend the proposed saBCI to

TABLE I

THE AVERAGED ACCURACIES AND ITRS OF THE PROPOSED, OUR PREVIOUS HRIR PROJECT AND THE CONVENTIONAL VBAP METHODS

Spatial sound mode		Averaged accuracy	ITR (bit/min)
The proposed method with	Horizontal	59.5%	8.51
the use of various HRIRs;	Elevation	78.0%	14.92
10 commands; ISI=150 ms	Elev. and freq.	60.5%	8.81
Previous HRIR	Horizontal	55.8%	1.79
5 commands; ISI=300 ms			
Conventional VBAP; 5 commands; ISI=500 ms	Horizontal	45.6%	0.57

TABLE II THE MEAN SPELLING ACCURACY FOR VARIOUS HORIZONTAL AZIMUTHS

Sound mode	Sound azimuth-based saBCI mean accuracies				
Sound mode	-90°	-45°	0°	45°	90°
Horizontal	85%	80%	95%	90%	90%
Elevation	90%	95%	95%	90%	95%
Elevation and frequency	90%	95%	90%	85%	100%

realize the full set Japanese kana characters-based speller, and to design a more effective spatial sound placement using more precise elevation settings.

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