A Comparison of P300-speller Stimuli Presentation Paradigms for Brain-computer Interface

Jiahui Pan*† , Yuanqing Li* , Tianyou Yu*
* South China University of Technology, Guangzhou
E-mail: auyqli@scut.edu.cn
† South China Normal University, Guangzhou
E-mail: panjiahui1222@gmail.com

***Abstract*—Brain-Computer Interface (BCI) exploits the ability of human communication and control bypassing the classical neuromuscular communication channels. The BCI system described in this work is P300 speller. Two different paradigms of the P300 speller were proposed for higher accuracy: (i) the Single display (SD) paradigm that flashes each character individually in one stage and (ii) the Region-based (RB) paradigm that arranges six groups of characters into different regions and flashes in two stages. In this paper, we investigated the accuracy of both paradigms by experiments. We present results of two tasks based on 7 subjects who participated in our experiments. Using experimental results, it is shown that comparative or higher spelling accuracy can be achieved with RB paradigm. Further factors that are possibly important for obtaining better accuracy in RB paradigm are discussed.[1].**

I. Introduction

Brain-computer interface (BCI) exploits the ability of human communication to interact directly with computer using their brain signals [1] [2]. Several different features of scalp recorded electroencephalography (EEG) signals are being used. One of them is the P300 event-related potential (ERP). The P300 is a positive displacement occurring around 300 ms after the presentation of a rare target stimulus during a random sequence of target and non-target stimuli (oddball paradigm) [3]. The oddball paradigm relies on the fact that, on average, attended rare stimuli produce larger P300 potentials than attended frequent ones [4].

Farwell and Donchin developed the first P300 BCI application [5]. A 6×6 matrix containing all 26 letters of the alphabet and 10 digits (0-9) was presented to the user. The rows and columns were flashed randomly and the participant was asked to concentrate exclusively on the letter to be selected and to ignore the other letters. The probability of target being flashed is 0.17 (2/12). Therefore, the desired stimuli served as the rare event or oddball, while all unattended stimuli were standard stimuli. The P300 elicited by the oddball was detected, translated into the desired character and presented on a computer screen. This Farwell-Donchin (FD) paradigm was an enormous step toward P300 BCI systems and has been a benchmark for P300-speller.

Due to the low signal-to-noise ratio of EEG, the classification of the P300 potential has to happen over a number of trials. Based on this fact, the speed and accuracy of the P300-speller are not satisfied. Much effort had been put into improving the spelling performance in the P300-speller. Most of the improvements have been achieved at the signal processing and detection level algorithms. In contrast, the P300-speller graphical user interface has not much been evolving for more than two decades.

On one hand, the individual parameters of the graphical interface have been studied and optimized, such as matrix size [6], stimulation frequency [7], stimulation intensity [8], and other factors [9] [10]. On the other hand, various P300 stimuli presentation paradigms have been proposed [11] [12] [13]. In this paper, we focused on two different versions of the P300-speller: (i) the Single display (SD) paradigm and (ii) the Region-based (RB) paradigm. Guan compared both FD and SD paradigm and results suggested that SD-Speller outperformed FD-Speller [11]. Fazel-Rezai tested both FD and RB paradigm and results showed that RB-Speller achieved better accuracy [12]. However, it is not yet clear which one is better between SD and RB paradigm. This is an important issue to clarify, which may allow further improvements of the BCI system.

In this paper, SD and RB speller were compared to examine if one paradigm produces higher accuracy than the other. Experimental results showed that RB-speller can achieve a better accuracy. We hope to extend these findings to the visual design of P300 BCI application.

II. Methods

A. Single display paradigm (SD-Speller)

In SD-Speller, a subject was presented with a six by six matrix of characters (Fig. 1). When the speller starts, each single character is flipped for 60ms in a random order. Unlike in the FD-Speller, characters in the SD-Speller were intensified one by one. The subject was to focus his attention on one target character in the matrix at a time. By detecting the P300, the single target character can be found after several intensifications.

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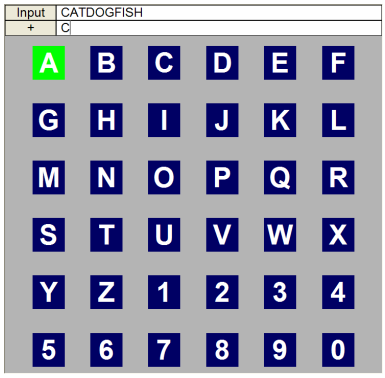


Fig. 1. Single display speller paradigm. The target character "A" is intensified.

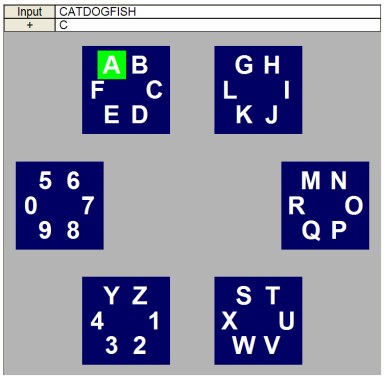
B. Region-based paradigm (RB-Speller)

In this speller, six groups of characters arranged into different regions (Fig. 2a). At the level 1, these regions are intensified to the user in random order. After initial selection, the speller descends to the second level (Fig. 2b), where characters in the selected region are subdivided into another six regions. The individual target characters are again intensified in a random order to be selected in level 2. Thus, one round of RB-Speller included 12 flashes (6 regions; and 6 items). The RB-Speller flashes a single region or character for 150ms. Each set of items highlight for 75ms while there is a short time 75ms between the intensifications. Note that, the regions were spatially arranged at the corners of a hexagon in order to get the max space.

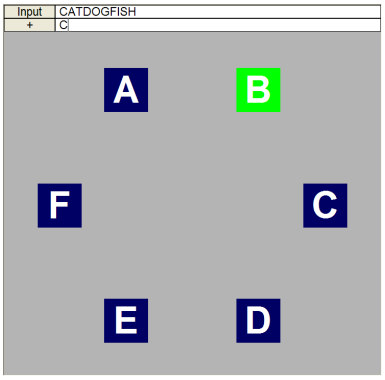
As we want to compare RB-Speller with SD-Speller, they both should work at the same configuration. In other words, they should have the same size and the same speed. The number of items has been equal to 36 in both paradigms. They both take up the same area of 700×700 px^2 for stimuli presentation. In SD-Speller, 10 rounds of intensifications take $60\times36\times10$ms. It is a two-stage process in RB-Speller. Both level 1 and level 2 need $150\times6\times10$ms in a series of 10 rounds. In addition, each stage of RB-Speller needs 1800ms to switch different levels. Thus, both paradigms need 21600ms for stimuli presentation. Under this configuration, we can compare their accuracy.

C. Experiment Setting

Seven healthy subjects, all males aged from 21 to 31, attended the experiment for both SD-Speller and RB-Speller. Two of them had limited prior experience in the P300 speller during the system's development. The other five subjects were naive users. The EEG was recorded with a 32-channel cap. All channels were referenced to the right ear and grounded to the mastoid. The signals were amplified and digitized by NeuroScan SynsAmps2, digitized at a sampling rate of 250 Hz, and bandpass filtered at 0.1-30 Hz. In the experiment, only electrodes Fz, Cz, P3, Pz, P4, P7, P8 and Oz were used for BCI operation. Stimuli were presented on a 19" TFT screen with a refresh rate of 60Hz. The subject was asked to silently



(a) Level 1



(b) Level 2

Fig. 2. Region-based speller paradigm. (a) The level 1 of intensification, each region contains 6 symbols. The region containing the target character "A" (region"ABCDEF") is intensified. (b) One of the regions is subdivided in level 2. The nontarget character "B" is intensified.

count the number of the target flashes.

Each subject sat in a comfortable chair approximately 1m in front of a computer monitor. At the beginning of the experiment, each subject had 3 minutes to understand the procedure of speller and adapt to the blinking stimuli. Nothing was recorded in this step. After a screening necessary to adjust the BCI to the individual user, subjects had to fulfill two different tasks. The first task was used in accuracy evaluation for both spellers. Each participant first underwent a training session which lasted around 5 min. During the training, the subject was requested to follow prompts on the screen to spell 10 random characters "FXLBCKYP9E". An SVM model was trained for each subject with these training data [14]. Then, the subject started to do on-line test. The test task is also copy-spelling to input three words: CAT, DOG, and FISH. The total number of target items is 10. In the first task, the repeat is fixed. 10 rounds of intensifications were presented for each character.

The second task was to test the performance of different repeats on accuracy. The dataset was from BCI 2003 competition by Blankertz et al. [15] (dataset IIb). This dataset was selected, because the results can be compared with the results of other works. The signals collected from each subject in two sessions. Each session consisted of a number of runs. In each run,

the subject focused attention on a series of characters. Target words presented to the subject were: BOWL, GLOVE, HAT, SHOES, and WATER. The total number of target characters is 22. To make it easier for the subjects to maintain their level of concentration, the spelling was split into two sessions allowing for short breaks after the third word.

III. Result and Discussion

In the first task, we can observe the result for 10 random characters to find the corresponding accuracy for seven subjects. A summary of individual accuracies can be seen in Table I. The combined average accuracy for the 10 characters for each user was shown in the last row of Table I. It can be seen from the graph that the average accuracy for RB-Speller is greater than that of SD-Speller.

TABLE I
ACCURACY OF SPELLING 10 CHARACTERS FOR TWO PARADIGMS

Subject	Paradigms	
	SD-Speller	RB-Speller
Subject1	90%	100%
Subject2	90%	90%
Subject3	80%	70%
Subject4	80%	90%
Subject5	70%	80%
Subject6	90%	100%
Subject7	90%	90%
Average	84.26%	88.57%

In the second task, the average accuracy of seven subjects under various repeats is listed in Table II for comparison. The repeats range from 1 to 10 rounds for ensemble average. The RB-Speller outperforms SD-Speller in all the condition of various repeatsa, as is shown in Table II. The accuracy is as high as up to 90% for 4 repeats in RB-Speller, while the SD-Speller needs 6 repeats. This means that RB-Speller is a faster P300 speller because smaller number of flashing is required for a successful P300 detection. In other words, when the classification accuracy is at 90% respectively, the information transfer rate of RB-Speller is almost 1.5 times of SD-Speller.

TABLE II
CHARACTER CLASSIFICATION ACCURACY FOR SD-SPELLER AND RB-SPELLER UNDER VARIOUS REPEATS

	Character Classification Accuracy				
Repeats	1	2	3	4	5
SD-Speller	34.3	52.9	71.0	81.4	89.0
RB-Speller	58.6	72.9	83.0	90.0	92.9
Repeats	6	7	8	9	10
SD-Speller	91.4	91.0	92.9	94.0	94.3
RB-Speller	95.7	97.0	94.0	97.0	98.6

The oddball probability in RB-Speller is 1/6, while this is reduced to 1/36 in SD-Speller. Higher P300 amplitude should be expected with the SD-Speller because it is more unlikely that the target character appears [4]. However, in comparing the accuracy of the SD and RB paradigms, it is clear that RB-Speller outperforms SD-Speller. One of the reasons can be explained by the comparison for discriminating power of EEG signal. The Fisher Ratio is defined as the ratio of the interclass difference to the intraclass spread [16]. Denote $P_{l,i}(f)(l = 1, ..., N, i = 1, ..., d)$ as the discrete power spectral density function of a segment of EEG signal which is extracted from the lth channel and ith trial. N denotes the number of channels and d represents the number of trials. Then the power feature of each channel is calculated as

$$\overline{P}_{l,i} = \sum_{f \in F} P_{l,i}(f) \tag{1}$$

where F is the selected set of frequency band indices.

The Fisher Ratio score of the lth channel is defined as

$$FR_l = \frac{(mean(\overline{P}_{l,i}, i \in Cl_1) - mean(\overline{P}_{l,i}, i \in Cl_2))^2}{\delta^2(\overline{P}_{l,i}, i \in Cl_1) + \delta^2(\overline{P}_{l,i}, i \in Cl_2)} \tag{2}$$

where Cl_1 and Cl_2 denote two classes of trials with labels being +1 and -1, respectively. Mean and δ represent mean and standard deviation, respectively.

The relevance of the lth channel is quantified by the Fisher Ratio score FR_l, and $\{ FR_l \, | l = 1, ..., N \}$ are used for ranking all selected channels.

The Fisher Ratio score under dynamic repeats shown in Table III were obtained by (1) and (2). The combined average score for each subject was shown in the last row of Table III. All seven subjects have clearly higher score in RB-Speller than in SD-Speller. As the Fisher Ratio can be considered as a "Signal-to-Noise" Ratio measurement, this result also means that the RB-Speller has better performance on rejecting the noisy components in the feature domain.

IV. Conclusion

The purpose of this study was to find out which stimuli presentation paradigm is better between SD-Speller and RB-Speller. For the 7 subjects that used both paradigms, there was a trend toward higher accuracy in the RB-Speller. Our test also showed that RB-Speller can achieve accuracy as high as up to 90% in only 4 rounds. In the experiment, all subjects preferred RB-Speller to SD-Speller because the former caused less fatigue. All these results enable us to design better BCI application which is based on dividing graphical interface to different regions. We are currently working on an extension of this study considering for more subjects involved. Further research about RB-Speller could possibly help BCI users, who desire accuracy, speed, and ease of use.

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TABLE III
THE COMPARISON OF FISHER RATIO SCORE IN DIFFERENT REPEATS

Subject	Paradigms	Fisher Ratio Score		
		Repeats:2	Repeats:5	Repeats:10
Subject1	SD-Speller	0.0013	0.0020	0.0024
	RB-Speller	0.0073	0.0145	0.0260
Subject2	SD-Speller	0.0010	0.0040	0.0079
	RB-Speller	0.0151	0.0337	0.0565
Subject3	SD-Speller	0.0001	0.0004	0.0008
	RB-Speller	0.0010	0.0025	0.0047
Subject4	SD-Speller	0.0002	0.0005	0.0025
	RB-Speller	0.0041	0.0094	0.0136
Subject5	SD-Speller	0.0001	0.0003	0.0007
	RB-Speller	0.0006	0.0017	0.0043
Subject6	SD-Speller	0.0008	0.0028	0.0038
	RB-Speller	0.0057	0.0163	0.0295
Subject7	SD-Speller	0.0009	0.0028	0.0060
	RB-Speller	0.0047	0.0310	0.0494
Average	SD-Speller	0.0006	0.0018	0.0034
	RB-Speller	0.0055	0.0156	0.0263

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