Proceedings of the
7th Graz Brain-Computer Interface Conference 2017 DOI: 10.3217/978-3-85125-533-1-94

IMPROVING CLASSIFICATION PERFORMANCE OF A BCI SYSTEM BY SHIFTING RAPID SERIAL VISUAL PRESENTATION

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ABSTRACT: Most of event-related potential (ERP)-based brain-computer interface (BCI) spellers are limited practical value for paralyzed patients with severe oculomotor impairments. Recently, a gaze-independent BCI speller was proposed that uses rapid serial visual presentation (RSVP), but it is difficult to recognize targets because of the rapid presentation of characters. We developed two ERP-based BCI spellers using RSVP with motion, and non-motion stimulation. We evaluated the effect of the two different stimulus conditions on the performance of the speller system with eight participants. The stimulation methods that employ motion stimulation inside the foveal vision demonstrate not only gaze-independence but also higher performance than method that uses non-motion stimulation (73.61±22.57% for non-motion RSVP, 92.36±11.09% for motion RSVP). The performance of the different stimulation methods was susceptible to ERP latency and amplitudes. As a result, motion-type RSVP stimulation condition (i.e., motion RSVP) had shorter latency and higher amplitudes than the non-motion RSVP stimulation condition. It is expected that the proposed motion RSVP stimulation method could be used for developing a gaze independent BCI system with high performance.

INTRODUCTION

A brain-computer interface (BCI) uses brain signals instead of muscles to control external devices such as an exoskeleton, robot arm, or communication system [1, 2]. Electroencephalography (EEG) signals have a good temporal resolution, can be recorded non-invasively, and enable real-time control, and its associated equipment is portable and inexpensive [3]. One of the most widely studied BCI systems is EEG-based BCI, which can monitor conscious electrical brain activity and detect distinct patterns that are generated by the brain. After the EEG signal is digitized, it can be processed via digital signal processing algorithms to convert it into a real-time control signal [5]. Several EEG-based BCIs have been categorized according to the type of brain activity used for BCIs, for example, P300, steady-state visual evoked potential, event-related (de)synchronization, and slow cortical potential.

The EEG-based speller is a typical application of BCI systems, which enables the user to write on a screen without muscle movements. Many BCI studies have shown that BCI spelling systems can be implemented using event-related potentials (ERPs). The ERP based speller (or P300 speller) devices acquire neural activity generated by user attention to a target speller. Accordingly, the ERP-based speller recognizes user's intentions. ERPs distinguish attention and non-attention (target and non-target). The conventional ERP-based speller consists of a 6 × 6 symbol matrix. The row and columns alternately flicker in a random order, where the user concentrates on the target symbol. These conventional spellers can achieve excellent performance.

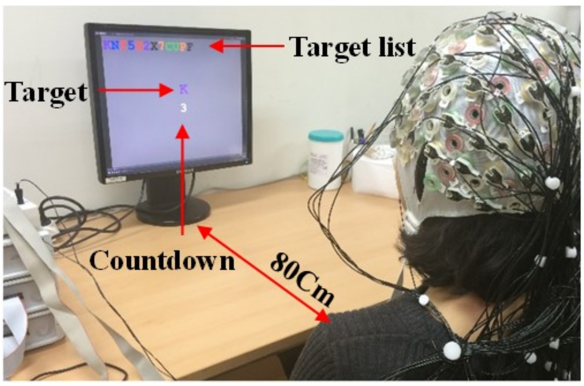

Figure 1: Experimental environment setup.

Recently, some studies based on ERP based spellers have considered gaze-independence [4-6]. Gaze-independence means that there is no involvement of eye movements for controlling BCIs. Several studies solve gaze-independence issues with other sensory activities, such as auditory and tactile activity. However, these activities not only generate weaker signals than visual stimuli but also are constrained to a limited num-

 DOI: 10.3217/978-3-85125-533-1-94

(a)

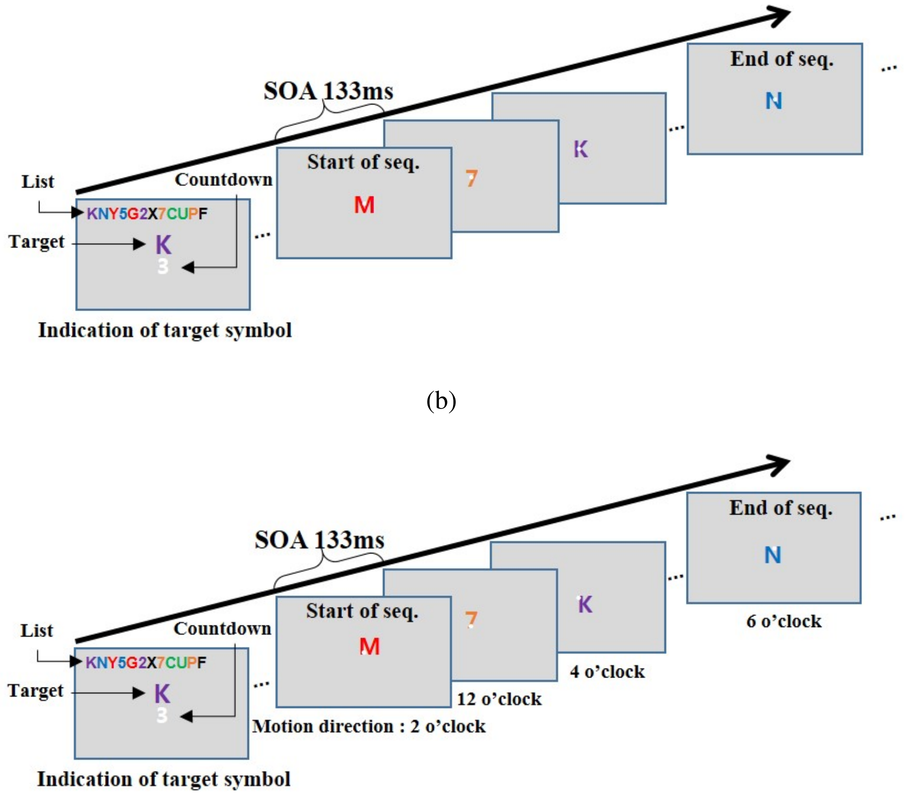

Figure 2: Experimental visual stimuli presentation setup (a) S-RSVP paradigm, (b) M-RSVP paradigm.

ber of targets. Other current visual ERP-based gaze-independent spellers have been successfully implemented using visual stimuli paradigms such as the covert attention paradigm, rapid serial visual presentation (RSVP) paradigm, and motion-onset visually evoked potentials (mVEPs) paradigm [4-6]. The RSVP-based speller is implemented using RSVP visual stimuli [6]. In RSVP, targets (e. g., symbols or pictures) are presented one-by-one in the same location of a display. The RSVP characteristic not only made it difficult to recognize targets but also cause visual discomfort.

In the present study, we proposed a gaze-independent speller with more easily recognized targets and less visual fatigue than one that uses conventional RSVP speller (e.g., requirements of low luminance and contrast) [6]. We proposed a novel visual oddball paradigm using RSVP and shifting (motion) stimuli. We implemented a gaze-independent speller that utilizes standard RSVP (S-RSVP) and motion RSVP (M-RSVP). Whenever the M-RSVP stimulus presentations start, all the symbols are presented center position with one-by-one [5]. The motion characters were moved one of the six directions within the near-central visual field (i.e., the 2, 4, 6, 8, 10, and 12 o'clock directions). The visual stimuli moved within the near-central visual field and the participants focused on the central point. Finally, we evaluated the ERP patterns and the classification performance for different gaze independent systems (i.e., S-RSVP and M-RSVP).

MATERIALS AND METHODS

A. Subjects: The experiment included 8 participants (6 males and 2 females; mean = 24.73±5.53 years). All participants had no history of visual disorders and corrected-to-normal or normal vision. The experiments were conducted in accordance with the principles described in the Declaration of Helsinki. This study was approved by the Institutional Review Board of Korea University [1040548-KU-IRB-15-163-A-1].

Red Group	Blue Group	Green Group	Orange Group	Magenta Group	Black Group
A	B	C	D	E	F
G	H	I	J	K	L
M	N	O	P	Q	R
S	T	U	V	W	X
Y	Z	-	1	2	3
4	5	6	7	8	9

Figure 3: Characters in each of the color and direction groups.

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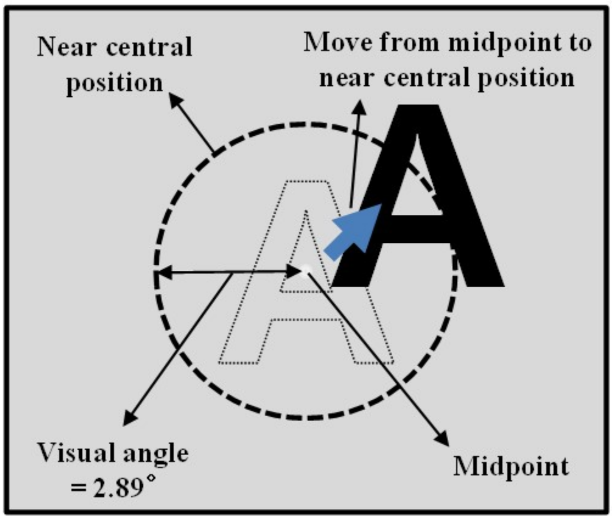

Figure 4: Motion stimulus during one presentation of the M-RSVP sequence.

B. Experimental stimuli and paradigm: Two different RSVP spellers were employed: the S-RSVP without motion stimulus, the M-RSVP with motion stimulus. We used 36 character symbols (i. e. the 26 letters of the English alphabet (A-Z), nine numerals (1-9), and the hyphen "-" used to separate different words). These characters were divided into the same six color groups in the spirit of [6] as follows: Red: A, G, M, S, Y, and 4; Blue: B, H, N, T, Z, and 5; Green: C, I, O, U, and 6; Orange: D, J, P, V, 1, and 7; Magenta: E, K, Q, W, 2, and 8; and Black: F, L, R, X, 3, and 9, as shown in Fig. 3. Thus, the target stimulus can be detected for the user by only using direction and color (e.g., the 2 o'clock direction consisted of the G, H, I, J, K, and L characters with red, blue, green, orange, magenta, and black, respectively).
The RSVP sequence (consisting of 36 symbols) was randomly shuffled before the presentation. We used a stimulus onset asynchrony (SOA) of 133 ms without an inter-sequence interval. The screen background was a static gray color [5]. The participants fixated on a point in the center of the monitor. The participants were asked to direct their attention toward the target and silently count whenever they found it. M-RSVP characters were divided into six directions (i.e. 12, 2, 4, 6, 8, and 10 o'clock). The measured visual angle of the disk area of the M-RSVP speller was 2.89 $\circ$ for all the subjects. In this design, the motion stimulation was entirely presented in foveal regions, as shown in Fig. 4 [6].

C. EEG Acquisition: During the experiments for all conditions, EEG data was recorded at a 1000 Hz sampling rate and 63 electrodes were attached using the international 10-20 system along with BRAINAMP amplifiers and an actiCap active electrode (Brain Products, Germany). The Fp1-2, AF3-4, Fz, F1-10, FCz, FC1-6, FT7-8, Cz, C1-6, T7-8, CPz, CP1-6, P7-8, Pz, P1-10, POz, PO3-4, PO7-10, Oz, and O1-2 electrodes were used. The EOG was recorded under the subject's left eye [22]. The reference was located on the ridge of the participant's nose, and the ground was located at AFz. The impedances of all electrodes were kept under 10 kΩ. The experiment paradigm was implemented in Psychtoolbox (http://psychtoolbox.org/). The participants were seated in a comfortable chair at a distance of about 80 cm from the screen and asked to fixate on a point at the center of the monitor. The participants were asked to direct their attention toward the target and silently count whenever they found it without movement (e. g. without head or eye movements). There were two sessions, a training session and an off-line test session. In the training session, participants had to copy-spell the predefined word "KNY5G2X7CUPF" (12 characters). In the test session, participants had to spell the predefined word "BSQH-DRT94WJEM36I1" (18 characters) for off-line classification. These predefined words are quite balanced combinations of the six color for equitable evaluation. For all speller conditions, the sequences flashed one-by-one for 36 symbols and the participants focused (and counted) when the target symbol flashed. A break of 3 s was given between sequences (i. e. countdown), as shown in Fig. 2. The participants were able to take a rest during that time. The participants paid attention to 10 sequences of target symbols, which consisted of one-by-one flashes of 36 symbols. In this study, the data analyzes were conducted off-line and this experiment had no feedback.

D. Data analysis: For pre-processing, all EEG data was downsampled to 100 Hz and bandpass filtered at 0.5-30 Hz with a Chebyshev filter in off-line analysis. We used the BBCI toolbox (http://bbci.de/toolbox) for data analysis and classification was performed using MATLAB (MathWorks, Natick, MA, USA). The EEG data contained physiological artifacts (e.g., eye and head movements). We computed an independent component analysis for all 63 EEG electrodes using a temporal decorrelation source separation algorithm [5]. We computed the correlations of the independent components with related EOG channels (Fp1, Fp2, F9, F10, and under left eye) and determined a conservative threshold (more than two standard deviations) for rejecting ICs as EOG-contaminated data [4]. We then rejected artifacts based on a min-max criterion (i. e. a min-max voltage difference $> 75\mu V$) [5]. For classification, the data was epoched from -233 to 800 ms based on the stimulus onset in all conditions. We selected a pre-stimulus interval (-233 to 0 ms) for baseline correction. For off-line classification analysis, the most discriminative intervals were subject-dependent from 100 to 800 ms. The five selected discriminative intervals were selected using a well-established heuristic method using signed r-squared values ($sgn - r^2$) [5]. We obtained five feature in each channel. So, we can used a feature dimension of 315 (63 electrode channels x 5 time windows). We used a regularized linear discriminant analysis with shrinkage of the covariance matrix for off-line classification [5]. The performance calculated classification accuracy (chance level

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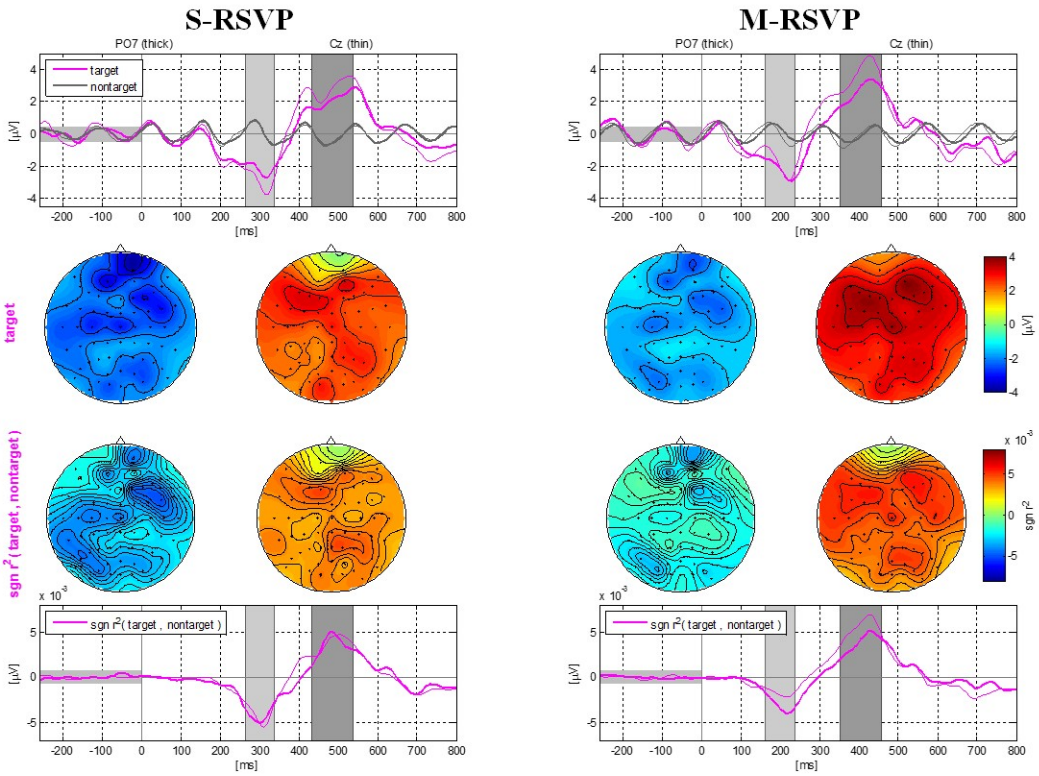

Figure 5: Grand average ERPs for the targets and non-targets in S-RSVP (first column), M-RSVP (second column). The light gray and dark gray shadows represent the N200 (S-RSVP: 265-335 ms and M-RSVP: 165-235 ms) and P300 (S-RSVP: 435-535 ms and M-RSVP: 355-455 ms) signals, respectively.

= 1/36 (2.78) %). Finally, user-intended character was determined by selecting maximum classifier output value that was averaged across the sequences.

RESULTS

The ERPs of the oddball paradigm (i.e. the target and non-target tasks) were similar with other results reported in the literature [4]. The most obvious ERP components were the N200 and P300 amplitudes from 150-350 ms and 350-550 ms based on the stimulus onset, respectively (Fig. 5). The N200 of the target and non-target tasks was a distinguishable channel located around PO7 [5]. The P300 of the target and non-target tasks was a distinguishable channel located around Cz [5]. In this study, the ERPs showed N200 and P300 components for each PO7 and Cz (Fig. 5).

We obtained the average ERP response as well as the $sgn - r^2$ values between target and non-target (Fig. 5). For all conditions, we used the PO7 and Cz electrode for the N200 and P300 components, respectively. In the S-RSVP condition, the ERP response appeared the N200 (amplitude: -2.711 μV and latency: 315 ms) and P300 (amplitude: 3.593 μV and latency: 530 ms). In the M-RSVP condition, the ERP response appeared the N200 (amplitude: -2.902 μV and latency: 225 ms) and P300 (amplitude: 4.848 μV and latency: 425 ms). Table 1 shows the classification accuracies of each subject and their mean accuracies for the 1^{st}, 6^{th}, and 10^{th} stimulus sequences. The M-RSVP condition achieved higher accuracy than the S-RSVP condition on all sequences. In addition, a Wilcoxon signed-rank test for the classification accuracy of M-RSVP conditions was significantly higher than S-RSVP condition on the 6^{th}, 8^{th}, 9^{th}, and 10^{th} sequences ($p < 0.05$), but no significant differences were found between the accuracies of S-RSVP and M-RSVP on the other sequences (i.e., 1^{st}, 2^{nd}, 3^{rd}, 4^{th}, 5^{th}, and 7^{th} sequence).

DISCUSSION

In this study, we implemented two RSVP BCI speller to achieve gaze-independence. We obtained (using 10 off-line stimulus sequences) mean classification accuracies of 73.61±22.57% and 92.36±11.09% respectively for the S-RSVP and M-RSVP conditions. We demonstrated that the M-RSVP speller system achieved easier target recognition and higher accuracy than the S-RSVP speller. Fig. 5 shows the differences in amplitude and latency between the S-RSVP and M-RSVP conditions. Also, the last line of Fig. 5 shows the $sgn - r^2$ values in the S-RSVP and M-RSVP. The M-RSVP has higher $sgn - r^2$ value than the S-RSVP condition. Moreover,

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Table 1: The classification accuracy for each subject.

	First sequence		Six sequence		Last sequence	
	S-RSVP(%)	M-RSVP(%)	S-RSVP(%)	M-RSVP(%)	S-RSVP(%)	M-RSVP(%)
Sub. 1	45.00	29.44	95.00	79.44	100	94.44
Sub. 2	25.00	38.89	70.00	86.11	88.89	100.0
Sub. 3	39.44	20.55	76.67	93.33	88.89	100.0
Sub. 4	22.78	11.11	36.11	83.89	38.89	94.44
Sub. 5	29.44	57.22	57.22	87.78	61.11	94.44
Sub. 6	38.89	93.33	93.33	94.44	94.44	100.0
Sub. 7	20.55	57.22	57.22	83.33	66.67	88.89
Sub. 8	11.11	39.44	39.44	45.56	50.00	66.67
Mean±SD	29.03±11.40	33.75±11.17	65.62±22.26	81.74±15.46	73.61±22.57	92.36±11.09

The M-RSVP has shorter latency then the S-RSVP condition. The high $sgn-r^2$ value and short latency have respect to higher target/non-target discrimination. The ERP latency could be affected by stimulus evaluation and response production [4]. And the different cognitive task conditions could be reflected in the latency and amplitude characteristics of ERPs (i. e., shorter latencies and larger amplitudes corresponded with the easier task). In this study, we can see the M-RSVP latency shorter than the S-RSVP. Therefore, the M-RSVP is easier task than S-RSVP. As a result, the M-RSVP performance is higher than that of S-RSVP. In addition, the standard deviations of classification accuracies over all subjects are shown to be more stable for M-RSVP than S-RSVP (Table 1). Further investigations are necessary in order to compare between the latency distributions across trials in S- and M-RSVP, as well as on amplitude distributions.

All the gaze-independent visual spellers that present the stimuli in the near central location were successfully implemented. The M-RSVP uses the main characteristic of RSVP. This paradigm, which presents all the stimuli in a nearly central position, is mainly processed by the foveal region of the retina. However, the motion stimuli could be affected by slight eye movements in healthy participants. Unfortunately, we did not directly evaluate saccades analytically using an eye tracker. Therefore, we indirectly showed that little eye movement was induced during the experiment using EOGs. In order to further investigate whether saccade or micro-saccade has influenced the performance, we analyzed the relationship between saccades and brain signals using gamma-band EEG responses [7-8]; the spectrogram analysis results verified that no significant EOG interferences.

We were only able to successfully improve the accuracy of the gaze-independent speller using motion RSVP. In future studies, we will include an attempt to improve BCI performance with spectral features using non-linear regression techniques.

CONCLUSION

In the present study, a novel BCI paradigm that combines the RSVP paradigm with motion stimuli was proposed and compared with the S-RSVP speller. We were able to successfully design stimulus for the ERP pattern using M-RSVP. We improved the accuracy of the RSVP-based gaze-independent speller system using the motion stimuli conditions. Thus, this study demonstrates that it is beneficial for designers to adopt motion stimuli in RSVP-based BCI spellers for practical applications. Consequentially, we suggest an M-RSVP system for practical gaze-independent applications.

ACKNOWLEDGEMENTS

This research was supported by the MSIP(Ministry of Science, ICT and Future Planning), Korea, under the “SW Starlab” (IITP-2015-1107) supervised by the IITP(Institute for Information & communications Technology Promotion).

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