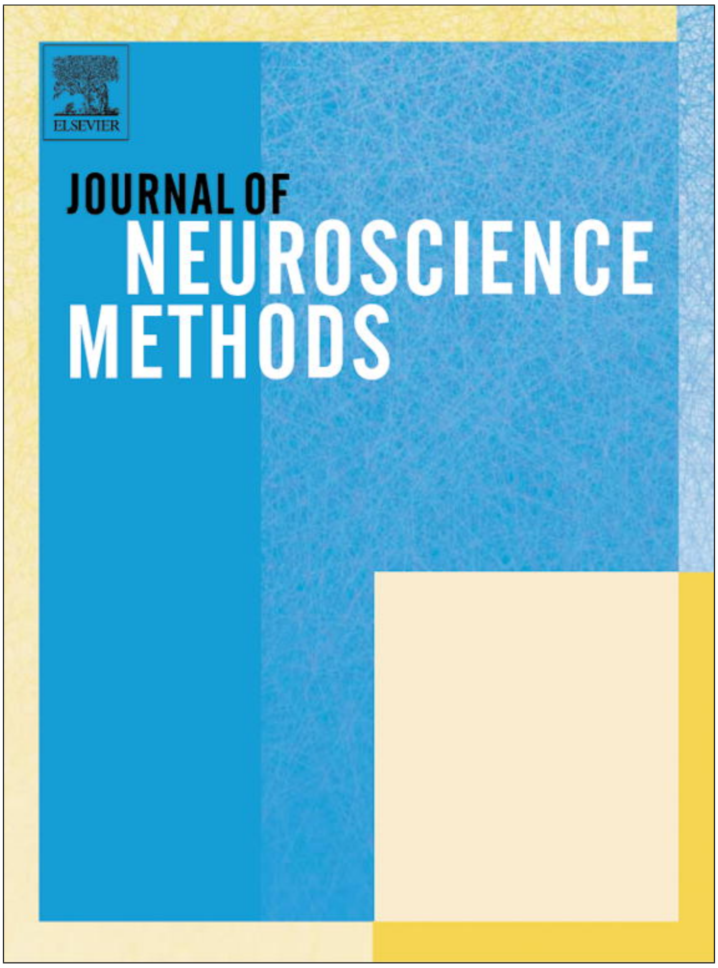
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Development of an SSVEP-based BCI spelling system adopting a QWERTY-style LED keyboard

Han-Jeong Hwang[a,1], Jeong-Hwan Lim[a,1], Young-Jin Jung[a], Han Choi[a,c], Sang Woo Lee[b], Chang-Hwan Im[a,*]

[a] Department of Biomedical Engineering, Hanyang University, Seoul 133-791, Republic of Korea
[b] Department of Biomedical Engineering, Yonsei University, Wonju 220-710, Republic of Korea
[c] Department of Biomedical Engineering, University of Rochester, NY, USA

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ABSTRACT

In this study, we introduce a new mental spelling system based on steady-state visual evoked potential (SSVEP), adopting a QWERTY style layout keyboard with 30 LEDs flickering with different frequencies. The proposed electroencephalography (EEG)-based mental spelling system allows the users to spell one target character per each target selection, without the need for multiple step selections adopted by conventional SSVEP-based mental spelling systems. Through preliminary offline experiments and online experiments, we confirmed that human SSVEPs elicited by visual flickering stimuli with a frequency resolution of 0.1 Hz could be classified with classification accuracy high enough to be used for a practical brain–computer interface (BCI) system. During the preliminary offline experiments performed with five participants, we optimized various factors influencing the performance of the mental spelling system, such as distances between adjacent keys, light source arrangements, stimulating frequencies, recording electrodes, and visual angles. Additional online experiments were conducted with six participants to verify the feasibility of the optimized mental spelling system. The results of the online experiments were an average typing speed of 9.39 letters per minute (LPM) with an average success rate of 87.58%, corresponding to an average information transfer rate of 40.72 bits per minute, demonstrating the high performance of the developed mental spelling system. Indeed, the average typing speed of 9.39 LPM attained in this study was one of the best LPM results among those reported in previous BCI literatures.

1. Introduction

People suffering from serious neurological disorders such as amyotrophic lateral sclerosis (ALS), brainstem stroke, and spinal cord injury have difficulties in communicating with other people. Brain–computer interface (BCI) is a non-muscular communication method that allows them to communicate with the outside world using external devices operated by their brain activities (Wolpaw et al., 2002). In past decades, a variety of BCI applications have been developed in order to improve people's quality of lives, e.g., mental typing of a keyboard (Sellers et al., 2010), controlling of a mouse cursor (Fabiani et al., 2004), navigating of a web browser (Mugler et al., 2010), operating of a wheelchair (Rebsamen et al., 2010), and so on. In particular, one of the most widely studied applications of electroencephalography (EEG)-based BCI is the BCI speller, which enables the paralyzed to express their thoughts by attending to target characters.

So far, most mental spelling systems have been implemented based on P300, which is an event related potential (ERP) elicited by infrequent, task-relevant stimuli (i.e. oddball paradigm) (Jin et al., 2010; Sellers et al., 2010; McFarland et al., 2011; Pires et al., 2011). In the P300 spelling system, characters are generally presented in a matrix array, of which the rows and columns are intensified at a pseudorandom sequence. While an individual focuses on a target character, strong P300 responses are elicited whenever either the row or the column containing the target character is intensified. Based on this principle, the P300 spelling system can detect the target character by finding the intersection of the row and column showing the strongest P300 responses.

Recently, some BCI studies have demonstrated that mental spelling systems can also be implemented based on steady-state visual evoked potential (SSVEP), which is a periodic brain response elicited by the continuous presentation of a visual stimulus flickering or reversing at a certain frequency (Cecotti, 2010; Pires et al., 2011; Volosyak, 2011). In the P300 spelling system, one target

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* Corresponding author at: Department of Biomedical Engineering, Hanyang University, 222 Wangsimni-ro, Seongdong-gu, Seoul 133-791, Republic of Korea. Tel.: +82 2 2220 2322; fax: +82 2 2296 5943.
E-mail addresses: ich@hanyang.ac.kr, changhwan.im@gmail.com (C.-H. Im).

[1] These authors contributed equally to this work.

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character can be spelled by a single command because each cell of the matrix array is directly assigned to a character. However, SSVEP spelling systems that have been introduced so far needed to generate two or more successive commands to spell one target character because the conventional ones used less number of visual stimuli than the number of target characters (Cecotti, 2010; Pires et al., 2011; Volosyak, 2011). In two recent SSVEP-based spelling systems, a target character was selected by moving a cursor location to the position of a target letter (Perego et al., 2010; Volosyak, 2011). The cursor position was moved toward one of the pre-determined directions (e.g., UP, DOWN, LEFT, and RIGHT), where visual stimuli with different flickering frequencies were located, by detecting the variations of EEG spectral powers recorded from a participant's Occipital area. The other study (Cecotti, 2010) introduced a three-step decision-tree design, in which a target character could be selected by sequentially producing three correct commands.

To the best of our knowledge, an SSVEP mental spelling system that can spell each target character at a single step, as in the P300 spelling system, has not yet been introduced. In order to implement such an SSVEP mental spelling system, the number of stimulating frequencies should be at least larger than that of displayed characters. In practical BCI applications, however, the available stimulating frequencies are generally restricted by several factors. First, not all stimulating frequencies always evoke high SSVEP responses. The frequencies that can elicit strong SSVEP responses are highly dependent upon individuals as well as various environmental factors such as color, size, and contrast of the visual stimuli (Zhu et al., 2010). Second, the use of two frequencies, F_1 and F_2, in the same experiment has to be avoided if F_1 is a multiple of F_2 or vice versa because of the harmonic SSVEP responses (Cheng et al., 2002; Bakardjian et al., 2010; Shyu et al., 2010a,b). Most importantly, in the case of using computer monitors for presenting visual stimuli, as in the most developed SSVEP spelling systems, stimulating frequencies have to be set as divisors of the monitor refreshing rate to attain accurate SSVEP responses (Yan et al., 2009; Cecotti, 2010; Zhu et al., 2010). For these reasons, the existing SSVEP spelling systems were implemented with only four or five stimulating frequencies and adopted 'multi-step selection' strategies to spell each target character (Cecotti, 2010; Pires et al., 2011; Volosyak, 2011).

The ultimate goal of this study was to develop a new SSVEP spelling system that is capable of spelling one target character per each target selection, as in the P300-based mental spellers. To this end, we implemented a modified QWERTY layout spelling system with thirty characters (26 English alphabets and 4 special symbols) using thirty light emitting diodes (LEDs) flickering at different frequencies. The frequency band of 5–9.9 Hz was selected and evenly divided with a span of 0.1 Hz. Preliminary offline experiments were conducted with five participants to test whether human SSVEP responses with that small frequency span could be classified with classification accuracy high enough to be applied to a BCI system. After optimizing the parameters of the mental spelling system based on the results of the preliminary experiments, online experiments were conducted with six participants to further demonstrate whether our mental spelling system could be utilized for a practical BCI application.

2. Method

2.1. Participants and experimental conditions

Ten healthy participants (eight males and two females, 21–27 yrs old) participated in our study. Five out of them took part in the preliminary offline study (named participants P1–P5), one of whom (participant P5) also participated in the pilot online experiment performed with the first version of the mental speller. The other five participants (all males, 24–27 yrs old, named participants P6–P10) were recruited to evaluate the performance of the second version of the mental speller and took part in the online experiments only. All participants had normal or corrected-to-normal vision, and none had a previous history of neurological, psychiatric or other severe diseases that might otherwise affect the experimental results. A detailed summary of the experimental procedures was explained to each participant, and all participants signed a written consent before the experiment. The participants received monetary reimbursement for their participation after the experiment. The study was reviewed and approved by the Institutional Review Board (IRB) of Hanyang University, Korea.

To record the EEG signals modulated by the flickering visual stimuli, three electrodes (Oz, O1, and O2) were mounted on the occipital area of the participants' scalp according to the international 10–20 system. During the EEG data acquisition, the participants sat on a comfortable armchair facing the developed mental speller, and were required not to move their bodies, especially their necks. While the participants were focusing on the characters flickering at different frequencies, EEG signals were recorded using a multi-channel EEG acquisition system (WEEG-32, Laxtha Inc., Daejeon, Korea) in a dimly lit, soundproof room. The reference and ground electrodes were placed behind the right ear and the left ear, respectively. The EEG signals were sampled at 512 Hz with a sensitivity of 7 μV. An anti-aliasing bandpass filter with cutoff frequencies of 0.7 Hz and 50 Hz was applied before the sampling.

2.2. Design of the mental speller

A modified QWERTY keyboard layout was designed to implement the proposed mental spelling system. As shown in Fig. 1, thirty keys were placed as similarly as possible to a conventional QWERTY keyboard layout. Twenty-six keys were assigned to each of the English alphabet letters and the other four keys were assigned to BACKSPACE, ENTER, PUNCTUATION, and SPACE. The area of each key except ENTER and SPACE was identically 2 cm × 2 cm. The distances between adjacent keys were 1 cm both horizontally and vertically.

After the preliminary offline and online experiments with five participants, we slightly changed the layout of the mental speller for preventing the confusion caused by peripheral vision, based on the opinions from participants of the preliminary offline experiments. In the second version of our mental speller, the distances between neighboring keys were set as 2 cm both horizontally and vertically. The other parts of the second version of the mental speller were identical to the layout of the first mental speller.

The mental keyboard system was made out of thick white papers, transparent films, LEDs, and LED controllers. We first printed out thirty keys on a white paper, and then cut out character shapes, below each of which four square-shaped multi-chip high flux LEDs (Part Number. DG-82A83C-001-5/S-3) with a luminous intensity of 6000 mcd (operating current: 20 mA; viewing angle: $2\theta = 60^\circ$; peak wavelength: 0.26/0.28 nm; emitting color: white; lens color: water) were attached. To collimate the emitted lights only to the frontal direction, each side of the LED arrays was covered by black papers. Sequentially, a transparent film was attached in front of the printed paper to diffuse the emitted light. In order to control the LEDs, we integrated an LED controller using TMS 320 F2812 DSP chip (Texas Instruments Inc.) to the mental spelling system. The flickering frequency of each key could be readily adjusted using in-house software developed by the authors (see Fig. 3 to check the integrated system in advance).

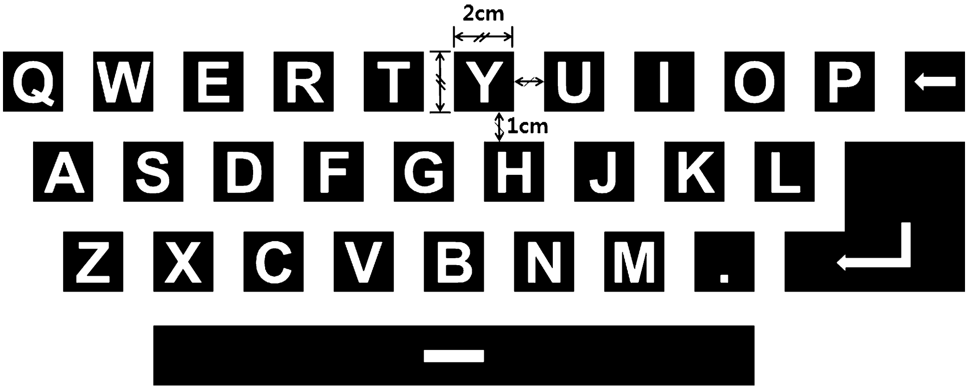

Fig. 1. The modified QWERTY keyboard layout used in the present study. Twenty-six keys were used for the letters of the English alphabet, and the other four keys were used for the special symbols: BACKSPACE, ENTER, PUNTUATION, and SPACE.

2.3. *Arrangement of stimulation frequencies*

The frequency band of 5–9.9 Hz was empirically selected and evenly divided with a span of 0.1 Hz. Thereby fifty frequencies were selected as the candidates of the stimulation frequencies. Since a specific stimulation frequency evoking strongest SSVEP responses differs from one individual to another (Lopez-Gordo et al., 2011), different combinations of thirty stimulation frequencies were used for each participant. To select the optimal combination of stimulation frequencies, we recorded EEG signals while the participants were gazing at each of fifty flickering LEDs for 10 s. After the preliminary recordings, the spectral powers were evaluated for each candidate stimulation frequency and then thirty frequencies that showed relatively stronger spectral powers were selected. For some participants (participants P6–P10) who responded all fifty stimulation frequencies fairly well, the first thirty frequencies (5–7.9 Hz with a span of 0.1 Hz) were used. Lastly, the selected thirty stimulation frequencies were assigned to each key, at which time each frequency was allocated sequentially as far from those assigned to its neighboring LEDs as possible in order to minimize the confusion caused by peripheral vision. The minimal frequency difference between adjacent keys was set to be 0.7 Hz. Fig. 2 shows an example of the stimulation frequency arrangements generated assuming 30 frequencies ranging from 5 Hz to 7.9 Hz with a span of 0.1 Hz.

2.4. *Experimental procedures*

The preliminary offline experiments were conducted with five participants using the first version of the mental speller in order to verify whether SSVEP responses with such a small frequency span could be classified and thereby used for a practical SSVEP-based BCI system. In our preliminary offline experiments, the participants were asked to focus on each character for 10 s in a random order in accordance with the verbal instruction of the experiment leader. This process was repeated twice to obtain two sets of thirty SSVEP epochs. To investigate the influence of visual angles, representing the angle that a viewed object subtends at the eye, on the performance of the spelling system, EEG signals were acquired at two different distances (44 and 60 cm) between the participants' nasion and the mental speller. Since the total width of the first version mental speller was 32 cm, 44 cm distance is proper for a visual angle of 40° and 60 cm distance for a visual angle of 30°.

One of the five participants (P5) also took part in the pilot online experiment using the first version of mental speller on the next day of the preliminary experiment. The other four participants (P1–P4) who participated in the preliminary offline experiments refused to participate in the online experiments because our laboratory moved to another city far away from the original place during this study. Two electrodes (Oz and O2) and a visual angle of 40° were used in the online experiment based on the results of offline analysis (see Table 1 to check the offline experimental results in advance). We tested fifteen English words (68 characters). In case of error, the participant could correct the misspelled character using the 'BACKSPACE' key. The result was presented to the participant using both visual and auditory information in real time (see the Supplementary Movie file). We tested three different time periods required to spell one character (5, 6, and 7 s) to investigate the changes in the performance of the mental spelling system. Fig. 3 shows a screen shot of the pilot online experiment where the participant (P5) was trying to spell 'X' to completely spell the given English word, 'TAXI'.

To further confirm the feasibility of our spelling system, additional online experiments were conducted with the second version mental speller that had longer distance between adjacent keys than the first version mental speller. We assessed the performance of the second version mental speller with newly recruited five

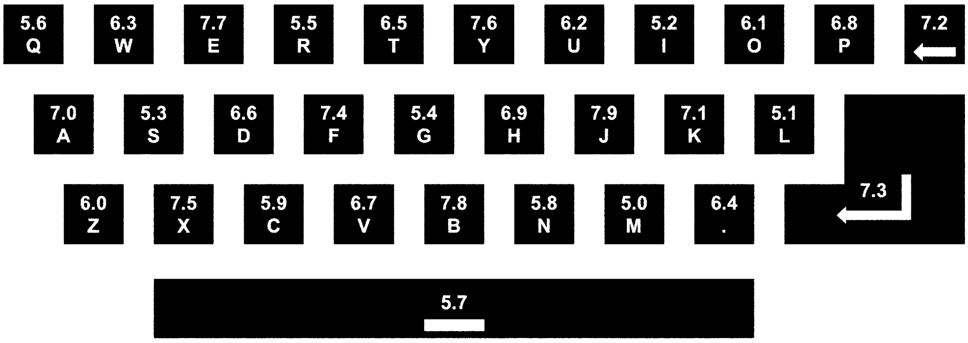

Fig. 2. An example of the stimulation frequency arrangements generated assuming 30 frequencies ranging from 5 Hz to 7.9 Hz with a span of 0.1 Hz.

Table 1
Classification accuracy for each participant with respect to different visual angles and electrode combinations. The highest classification accuracy of each participant is printed in bold.

Subjects	Visual angle	Classification accuracy (%)						
		Oz	O1	O2	Oz, O1	Oz, O2	O1, O2	Oz, O1, O2
P1	30°	**91.66**	81.66	73.33	85	88.33	85	86.67
	40°	**81.66**	58.33	55	73.33	75	63.66	71.67
P2	30°	31.67	18.33	**63.33**	25	46.66	46.66	40
	40°	26.66	13.33	**56.67**	21.66	43.33	41.67	36.67
P3	30°	15	33.33	**71.67**	23.33	41.67	53.33	41.67
	40°	16.67	23.33	**71.67**	20	55	53.33	33.67
P4	30°	70	63.34	50	**73.34**	68.34	66.67	**73.34**
	40°	63.34	56.67	48.34	**65**	65	60	**65**
P5	30°	80	65	76.67	75	**83.34**	75	75
	40°	83.34	76.67	**86.67**	80	**86.67**	83.33	85

volunteers who did not take part in preliminary experiments. Before the online experiments, optimal electrode positions were selected independently for each participant (Oz and O1 for participants P6, P7, P8 and P9; Oz, O1 and O2 for participant P10) based on the offline analyses of preliminary EEG recordings performed right before the online experiments. The detailed procedures for selecting optimal electrode combination will be presented in the next section. The distance between the participants and the mental speller was empirically set as 50 cm because our preliminary offline study demonstrated that the influence of visual angle on the speller performance was not significant. Before the online experiments, the participants were given 30 min training time in order to get accustomed to the spelling system. During the training period, no feedback was provided. Each participant was asked to spell the 15 English words (68 characters) used in the previous online experiment. The time period required to spell one character was set as 6 s. Since one participant (P6) spelled all given 68 characters without any errors, we further tested shorter time periods (4 s and 5 s) for the participant. The movies of the online experiments can be found in the attached Supplementary Movie file, in which three participants (P5, P7, and P8) were spelling the given English words.

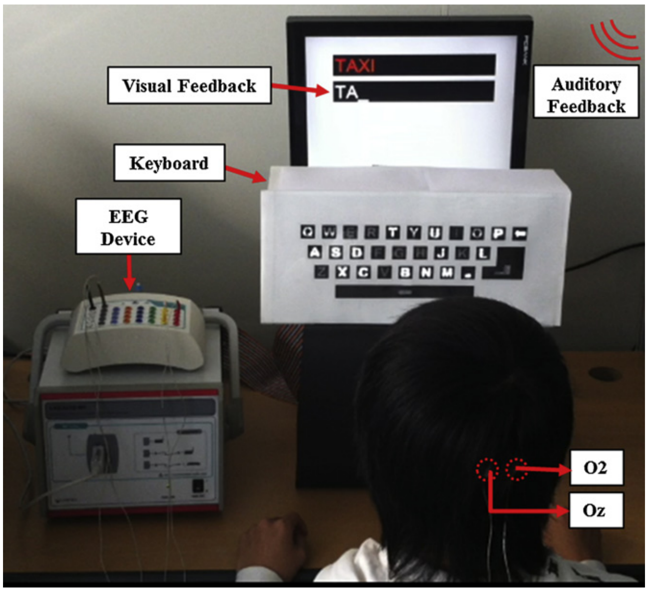

Fig. 3. A snapshot of the online experiment (please watch the attached Supplementary Movie file or watch on YouTube at http://www.youtube.com/watch?v=uunf3FDfEno). The participant was trying to spell the given English word by successively gazing at the target characters.

2.5. EEG data analysis

To use the SSVEP responses as feature vectors, the spectral densities of the recorded EEG data were estimated using the fast Fourier transform (FFT) (Cheng et al., 2002; Mukesh et al., 2006; Wang et al., 2010) with a frequency resolution of 0.1 Hz. Since we used various time periods (4, 5, 6, and 7 s), proper numbers of zeros were added to the end of the EEG data to keep a frequency resolution to be 0.1 Hz.

In the preliminary offline analyses, the SSVEP amplitudes at stimulation frequencies, H1 (unit: μV^2), and those at the second harmonic frequencies (2× stimulation frequency), H2, were evaluated at every electrode position for each trial. Then, the feature vectors were constructed by the arithmetic sum of H1 and H2 because harmonic frequency components can enhance the classification accuracy (Muller-Putz et al., 2005). For the classification, we used a simple classification algorithm, which found a frequency with the largest H1 + H2.

In order to determine the optimal electrode combination for each participant, we evaluated the classification accuracies for all possible combinations of three recording electrodes (O1, Oz, O2, mean of O1 + Oz, mean of O1 + O2, mean of Oz + O2, and mean of O1 + Oz + O2) with a fixed analysis window size of 10 s. Based on the results, the optimal electrode combination was determined for each participant as ones showing the highest classification accuracy, which were used for the online experiments.

In the online experiments, we used the same classification method used in the offline analysis. To assess the online performance of the spelling system, we calculated the classification accuracy, the information transfer rate (ITR), and the number of decoded letters per minute (LPM). The ITR and LPM have been widely used in many BCI studies to quantify the speeds of the developed BCI systems (Cecotti, 2010; Perego et al., 2010; Pires et al., 2011; Volosyak, 2011).

3. Results

3.1. Results of preliminary offline experiments

Table 1 presents the classification accuracy for each participant with respect to different visual angles and electrode combinations. The average classification accuracies of 76.67% and 72.33% were obtained for the visual angles at 40° and 30°, when the optimal electrode combination yielding best classification accuracy was taken into account. Since we found that the influence of visual angles on the speller performance was not very significant ($p = 0.625$, Wilcoxon signed-rank sum test), we did not customize the visual angles for each participant in the online experiment. Certainly, the individual customization of visual angles could enhance the performance of our speller, but we could not customize that factor because we had to reduce the overall time for the experiments considering the participants' fatigue. Through the offline experiments, we confirmed that the electrode combination should be customized for each individual, as frequently reported in previous SSVEP studies (Yijun et al., 2004; Friman et al., 2007; Meng et al., 2011). Therefore, in the online experiments, optimal electrode combination was determined independently for each participant based on the offline analyses of the preliminary SSVEP recordings. Considering that the chance level was just 3.33% (1/30), we could confirm the possibility of using our mental spelling system for a practical BCI system.

3.2. Online experimental results

Table 2 shows an example of the online experimental results (participant P5), where the full typing sequences are presented. The classification accuracy was slightly increased as the time period was increased (5 s: 84.69%, 6 s: 86.17%, and 7 s: 89.53%). However, it should be noted that both LPM and ITR were increased as the time period got shorter (5 s: 10.16 letters/min and 42.55 bits/min, 6 s: 8.62 letters/min and 36.55 letters/min, 7 s: 7.64 letters/min and 33.55 bits/min). The results of the participant P6 showed similar tendencies with the participant P5 (see Table 3). These results suggest that the trade-off between both indices (LPM and ITR) and the typing accuracy should be carefully considered to implement a practical BCI spelling system.

All results of the online experiments were summarized in Table 3, where only the results of the participant P5 were obtained using the first version mental speller (please watch the attached Supplementary Movie file). The average accuracy, ITR, and LPT were 87.58%, 40.72 bits/min, and 9.39 letters/min, respectively. The LPM of 9.39 letters/min obtained in this study was comparable with the best results previously reported in BCI literatures (Perego et al., 2010; Volosyak, 2011). Notably, the classification accuracy of the participant P6 was 100% for the time period of 6 s, and the highest LPM was almost 12 letters/min, for 4 and 5 s. The experimental results demonstrated that our proposed SSVEP mental spelling system could be used as a practical BCI mental speller.

4. Discussion

Most BCI spelling systems have been implemented based on the P300 paradigm since the first P300 speller was introduced by Farwell and Donchin (1988). Recently, some BCI studies introduced SSVEP-based mental spelling systems (Cecotti, 2010; Perego et al., 2010; Volosyak, 2011). Contrary to P300 spelling systems, generally using the matrix layout, a variety of speller layouts were proposed to implement SSVEP spelling systems; all of them used the less number of visual stimuli than the number of target characters. In this study, we first introduced an SSVEP spelling system that had the same number of visual stimuli as the number of target characters, thereby allowing the users to spell one target character per each target selection. From the results of the offline and online experiments, we demonstrated the feasibility of the proposed mental spelling system.

The ITR has been used as a representative index for evaluating the performance of BCI systems. However, since it is possible to achieve a high ITR by simply increasing the number of detectable targets, the performance of BCI systems should not be evaluated solely by ITR (Volosyak, 2011). For this reason, a recent BCI study introduced a new evaluation index called command transfer interval (CTI) to quantify the mean time required for a single command (Shyu et al., 2010a). On the other hand, in mental spelling applications, LPM is generally estimated along with ITR to assess how many characters a user can spell per minute. In this study, we obtained the average LPM of 9.39 through the online experiments. Two recent BCI studies regarding mental speller applications (Perego et al., 2010; Volosyak, 2011) showed average LPMs of 7.45 and 10.75, which were the state-of-the-art results previously reported in literatures. Based on this comparison, we could confirm that our proposed spelling system is one of the high-performance mental spelling systems. We will continue to try to enhance the overall performance of our mental speller by introducing new feature selection/classification algorithms and signal processing methods. Please note that we did not apply any specific signal processing algorithms to increase the signal to noise ratio of the recorded SSVEP.

The biggest difference between our mental spelling system and those proposed in other SSVEP studies (Cecotti, 2010; Perego et al., 2010; Volosyak, 2011) lies on the number of required commands to spell one target character. Therefore, two kinds of BCI spelling systems have their own pros and cons. The previous SSVEP mental spelling systems have an advantage in that it is easy to produce a single command because they use few numbers of visual stimuli (4 or 5) and each visual stimulus is placed far from the other visual stimuli. Another advantage of these SSVEP-based spelling systems is that high classification accuracy could be attained with a shorter time window for classification. In the conventional spellers, however, target selection process was relatively complicated as the users had to produce sequential commands to select a target character. On the contrary, the proposed mental spelling system has an advantage in that the users can spell each target character with just a single command as each visual stimulus is directly assigned to each character just like the P300-based spellers. The weakness of our spelling system is the disturbance caused by peripheral vision which sometimes makes misspellings. Indeed, the overall accuracy of the system was enhanced by widening the inter-key distances in the second version mental speller. Thus, in our future studies, we will further optimize the distances between adjacent keys or develop a training system that can help the users to focus better on the target stimuli.

A multi-LED-based SSVEP BCI system was first introduced in Gao et al.'s study (Gao et al., 2003). The SSVEP-based BCI system consisted of 48 LEDs with a frequency resolution of about 0.2 Hz and was successfully applied to a TV remote controller. The Gao et al.'s study was very meaningful in that they showed the possibility of simultaneous use of a fairly large number of visual stimuli with high frequency resolution as high as 0.2 Hz in implementing an SSVEP-based BCI system. Nevertheless, their study did not consider various factors that might affect the performance of the SSVEP-based BCI spelling system, e.g., distance between adjacent keys, light source arrangements, visual angles, and so on. In our study, we implemented a multi-LED-based SSVEP BCI spelling system after optimizing those factors through preliminary offline experiments and demonstrated human SSVEPs with 0.1 Hz frequency resolution could be used to materialize a practical SSVEP-based BCI spelling system. A recent study introduced a high-speed SSVEP BCI system that also had the same number of visual stimuli as the number of targets, and thereby could produce one complete command per each target selection (Bin et al., 2011). Their study used code modulation visual evoked potential (C-VEP). The average ITR reported in the study was 108 bits/min, which is obviously one of the best results reported in the EEG-based BCI literatures to date. Unlike the conventional SSVEP-based BCI systems, the C-VEP BCI system requires a training stage to construct the reference templates prior to the main experiment. It is because a target is identified by selecting one that maximizes the correlation coefficient. Therefore, as the authors of the study also mentioned in their article, the system performance could be affected by the constructed reference templates especially when the number of targets is increased (Bin et al., 2011). In the case of the BCI systems based on the template matching, the

Table 2
The results of the pilot online experiment with respect to different time periods. The time listed in the first row of the table is the time given to the participant to spell each character. If the selection was wrong, the subject could delete the misspelled letter by attending on the 'BACKSPACE' key denoted as '←' in the table.

Word	5 s		6 s		7 s	
	Input results (wrong underlined)	Correct/ total	Input results (wrong underlined)	Correct/ total	Input results (wrong underlined)	Correct/total
WOMEN	WU←P←OMEM←N	8/11	WOMEN	5/5	WOMEN	5/5
DESK	DESQ←K	5/6	DES←SK	5/6	DES←SK	5/6
WATER	WATER	5/5	WATER	5/5	WAG←TER	6/7
HAND	HAND	4/4	HAND	4/4	HAND	4/4
MEMORY	L←L←MEMORY	8/10	MEMORY	6/6	MEMORY	6/6
ZONE	ZONE	4/4	ZONY←E	5/6	ZSR←←ONE	6/8
BABY	U←BAW←R←BD←Y	8/12	BABX←Z←Y	6/8	BABY	4/4
FACE	FACE	4/4	R←FACE	5/6	FAC←CE	5/6
TAXI	TAXL←I	5/6	TAXI	4/4	TAXI	4/4
JUNE	JUNE	4/4	JUR←NE	5/6	M←JUNE	5/6
QUICK	QUICK	5/5	QUICZ←M←K	7/9	QO←UICK	6/7
VIDEO	VIDE_←O	6/7	VIA←N←DEO	7/9	VIU←DEO	6/7
GOLF	GOLF	4/4	GOLG←F	5/6	GOLF	4/4
HOUR	T←HOUG←R	6/8	HOUR	4/4	HOUR	4/4
PENCIL	PY←ENCIL	7/8	PENM←CZ←IL	8/10	PENI←CIL	7/8
Total		83/98		81/94		77/86
Accuracy (%)		84.69		86.17		89.53
ITR (bits/min)		42.55		36.55		33.55
LPM (letters/min)		10.16		8.62		7.64

database templates need to be updated as the reference templates could vary in time. On the contrary, for a conventional SSVEP-based BCI, once a participant responds to visual stimuli flickering at different frequencies, high system performance can be maintained for a relatively long time, as demonstrated in many SSVEP-based BCI studies (Cheng et al., 2002; Bakardjian et al., 2010; Cecotti, 2010; Perego et al., 2010; Volosyak, 2011). Since our SSVEP-based BCI speller also does not require any reference templates, a practical mental spelling system with little set-up time can be readily implemented.

It has been revealed through many SSVEP studies that human SSVEPs can be generated in a wide frequency band ranging from 1 to 90 Hz (Herrmann, 2001; Asano et al., 2009; Vialatte et al., 2009, 2010). However, there is a little literature exploring the frequency resolution of SSVEPs that the human brain can discriminate. The minimum frequency resolution of SSVEPs investigated so far was approximately 0.2 Hz (Gao et al., 2003). In the present study, we used flickering frequencies with a span of 0.1 Hz and demonstrated that SSVEPs with that frequency resolution could be utilized for a practical BCI system. It is important to investigate the frequency resolution of SSVEPs that the human brain can recognize, because this can allow BCI researchers to have more choices in the stimulation frequency selection, which is an interesting topic needed to be investigated in future studies.

One of the main advantages of the SSVEP-based mental spellers over the conventional P300-based spellers is that the keyboard layouts of the SSVEP-based spellers can be readily changed without a loss of efficiency. In our spelling system, we adopted a modified QWERTY keyboard layout based on the previous non-BCI studies reporting that the QWERTY layout is more effective in visually finding target characters than unfamiliar keyboard layouts such as the matrix layout generally used in P300 spelling systems (MacKenzie et al., 1999; Zhai and Kristensson, 2008; Bi et al., 2010). Since the main cause of disabilities in most disabled individuals is acquired factors such as disabilities due to traffic accidents and severe brain diseases (Elwan, 1999), the use of familiar keyboard layouts would help them get readily accustomed to the mental spelling system. However, there are still some other factors to be considered in terms of speller layout design that need to be investigated in future studies. The QWERTY layout was originally devised for solving the mechanical problem that characters mounted on mental arms would frequently clash and jam. On the contrary, since BCI users select target characters using their eyes, mental spellers are not subject to any mechanical problem. Thus, it would be an interesting future topic to arrange character locations to be more suitable for mental spelling systems. For example, commonly used letters can be placed around the center of the speller (Volosyak, 2011) and/or some frequently used pairs of letters can

Table 3
The results of all online experiments. The results of the participant P5 was attained with the first version of the mental speller, while those of the other participants (P6, P7, P8, P9, and P10) were attained with the second version of the mental speller. Two participants (P5 and P6) were tested with three different time periods.

Participants	Time period (s)	Correct/total	Accuracy (%)	ITR (bits/min)	LPM (letters/min)
P5	5	83/98	84.69	42.55	10.16
	6	81/94	86.17	36.55	8.62
	7	77/86	89.53	33.55	7.64
P6	4	91/114	79.82	48.02	11.97
	5	69/70	98.57	56.75	11.83
	6	68/68	100	49.07	10
P7	6	78/88	88.64	38.44	8.86
P8	6	84/100	84	34.95	8.40
P9	6	90/112	80.36	32.38	8.04
P10	6	84/100	84	34.95	8.40
Mean			87.58	40.72	9.39
S.D.			6.9	8.12	1.54

be closely located, i.e. ‘th’, ‘st’, and ‘ea’, in order to reduce visual scan time.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.jneumeth.2012.04.011.

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