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Eliciting dual-frequency SSVEP using a hybrid SSVEP-P300 BCI

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HIGHLIGHTS

- We propose a hybrid BCI speller that generates both dual-frequency SSVEP and P300.
- The hybrid speller employs harmonic flickering frequencies for different stimuli.
- The hybrid speller improves SSVEP recognition and reduces stimulation time.
- The hybrid speller outperforms conventional SSVEP and P300 spellers.

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ABSTRACT

Background: Steady-state visual-evoked potential (SSVEP)-based brain–computer interfaces (BCIs) generate weak SSVEP with a monitor and cannot use harmonic frequencies, whereas P300-based BCIs need multiple stimulation sequences. These issues can decrease the information transfer rate (ITR).
New method: In this paper, we introduce a novel hybrid SSVEP-P300 speller that generates dual-frequency SSVEP, allowing it to overcome the abovementioned limitations and improve the performance. The hybrid speller consists of nine panels flickering at different frequencies. Each panel contains four different characters that appear in a random sequence. The flickering panel and the periodically updating character evoke the dual-frequency SSVEP, while the oddball stimulus of the target character evokes the P300. A canonical correlation analysis (CCA) and a step-wise linear discriminant analysis (SWLDA) classified SSVEP and P300, respectively. Ten subjects participated in offline and online experiments, in which accuracy and ITR were compared with those of conventional SSVEP and P300 spellers.
Results: The offline analysis revealed not only the P300 potential but also SSVEP with peaks at subharmonic frequencies, demonstrating that the proposed speller elicited dual-frequency SSVEP. This dual-frequency stimulation improved SSVEP recognition, increased the number of targets by employing harmonic frequencies, reduced the stimulation time for P300, and consequently improved ITR as compared to the conventional spellers.
Comparison with existing methods: The new method reduces the stimulation time and allows harmonic frequencies to be employed for different stimuli.
Conclusions: The results indicate that this study provides a promising approach to make the BCI speller more reliable and efficient.

1. Introduction

A brain–computer interface (BCI) enables a user to communicate with his/her environment without limb movement by translating brain activity. The primary goal of the BCI is to help severely disabled people interact with other people or assistive devices. Most BCI studies are based on electroencephalograms (EEGs) because EEG-based BCIs are non-invasive, provide brain signals with relative ease, and have a high temporal resolution. Various EEG signals are used for BCI systems, such as sensori-motor rhythm (SMR) (Morash et al., 2008), event-related potential (ERP) (Farwell and Donchin, 1988; Lew et al., 2012), and steady-state evoked potential (SSEP) (Bin et al., 2009; Snyder, 1992). In particular, steady-state visual-evoked potential (SSVEP) and P300 potential have been widely used for high performance and a relatively large number of commands.

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SSVEP is generated in the occipital region when a subject focuses on a target flickering at a constant frequency. Because SSVEP has spectral peaks at the harmonics of the stimulation frequency (Herrmann, 2001), targets flicker at non-harmonic frequencies in SSVEP-based BCIs. SSVEP-based BCIs are fast and reliable, and need little subject training (Wang et al., 2006). However, when a monitor is used for providing both stimulation and feedback without an additional device, the number of targets is limited by the monitor's refresh rate (Volosyak et al., 2009). A recent study developed a dynamically optimized SSVEP speller producing 36 stimuli with only six flickering frequencies in frequency-limited condition (Yin et al., 2015). Another study reported a 45-target monitor-based SSVEP-BCI system in which brightness of a stimulus varied sinusoidally (Chen et al., 2014). However, in those system, harmonic frequencies still could not be used for different stimuli. Furthermore, the SSVEP peak is weaker than that evoked by light-emitting diodes (LEDs) (Wu et al., 2008). These limitations reduce the information transfer rate (ITR).

The P300 potential is elicited approximately 300 ms after a subject spots an infrequent target (Polich, 2012). The oddball paradigm is commonly used for P300-based BCIs, which presents an infrequent target in the background of frequent standard stimuli. Usually, P300-based BCIs could have many targets, which can increase ITR in proportion to the number of targets. However, P300-based BCIs need repetitive stimulation sequences to average ERPs, which increases the stimulation time and reduces ITR (Farwell and Donchin, 1988).

Complementary strategies that combine P300 and SSVEP offer a more reliable and faster BCI speller. A hybrid BCI system designed for practical use in asynchronous control has been described (Li et al., 2013b). The system employed P300 and SSVEP as a brain switch to control a real wheelchair; nonetheless, the speed of the BCI was not improved. A visual parallel-BCI speller incorporating P300 and SSVEP-blocking (SSVEP-B) features has been suggested as a way to improve the speller's accuracy and ITR (Xu et al., 2014, 2013). However, this system entails that the SSVEP stimulation be suspended for a certain period to generate the P300 potential, and this time gap can attenuate the SSVEP. Furthermore, harmonic frequencies cannot be used for creating more targets. The limited number of flickering frequencies may increase the number of flashes in a sequence and the stimulation time for P300 and decrease ITR. A hybrid BCI spelling system has been developed that divides a conventional P300 speller into six subgroups, where each group flickers at different frequencies (Yin et al., 2013). The hybrid system combined the individual features of P300 and SSVEP to reduce errors occurring in the same row or column relative to the target. The same research team has proposed another hybrid SSVEP-P300 BCI speller to decrease the flash number for P300 to half and increased the accuracy and ITR compared to the SSVEP and P300 spellers (Yin et al., 2014). However, these systems do not solve the frequency-limitation problem of the SSVEP-based BCI system.

Dual-frequency SSVEP is evoked by a visual stimulus that flickers at two different frequencies simultaneously, thereby showing spectral peaks in a linear combination of the two stimulation frequencies (Shyu et al., 2010). Dual-frequency SSVEP-based BCIs can create more commands by combining several frequencies in frequency-limited settings, such as the utilization of a monitor (Hwang et al., 2013). In the case of dual-frequency stimulation consisting of two harmonic frequencies, a corresponding SSVEP concentrates the power at one of the frequencies (Srihari Mukesh et al., 2006). Most dual-frequency stimulators generate light intensity variation as a sinusoidal or square wave. However, neither periodic shape variation nor a combination of shape and intensity variations has been used.

In this study, we propose a novel hybrid BCI speller that generates dual-frequency SSVEPs by periodically presenting characters while simultaneously flickering. The hybrid stimulus consists of a stimulation-frequency pair for SSVEP and P300. Thus, harmonic flickering frequencies can be used for different stimuli with relatively prime stimulation frequencies for P300. Two of the hybrid stimuli employ harmonic SSVEP frequencies that confirm the ability of the hybrid speller to recognize each of them. Furthermore, the simultaneous stimulation by the proposed speller reduces the time required for stimulation, which results in a swift decision. The benefits of dual-frequency SSVEP in the hybrid speller, including enhanced SSVEPs and the use of harmonic flickering frequencies for different stimuli, were compared with those of the use of single-frequency SSVEP in a conventional SSVEP speller in terms of accuracy and ITR.

2. Materials and methods

2.1. Hybrid speller

The hybrid speller was designed to generate P300 potential and SSVEP simultaneously without interference. In particular, a black-and-white flickering stimulus includes four different characters, which appear periodically in a random sequence. The flickering stimulus and periodic change of the character evokes dual-frequency SSVEP, while the oddball stimulus of the target character evokes P300. The dual-frequency SSVEP peaks at a linear combination of the flickering frequency (SSVEP stimulation frequency) and the frequency of characters appearing (P300 stimulation frequency) rather than the harmonics of the flickering frequency. This approach enables the use of the harmonic SSVEP frequencies for different stimuli in conjunction with relatively prime P300 stimulation frequencies.

The four different characters appear in different colors and places for improved recognition and performance (Fig. 1a). Thus, nine stimuli consist of 36 characters (A–Z, 1–9, and Backspace) arranged in sequence (Fig. 1b). Each stimulus flickers in black (OFF) and white (ON) with a different flickering period (SSVEP stimulation period; Table 1) to evoke SSVEPs. The duty rate remains at 0.8. When the stimulus is ON, one of the four characters appears randomly. The period in the ON state during which a character appears (P300 stimulation period) varies with the stimulus (Table 1). For example, a character among A to D appears at every two ON states. Fig. 2 describes the hybrid speller paradigm for frames 1–60. The stimulation frequency is estimated as the *refresh rate/stimulation period* (in this study, *120/stimulation period*). P300 stimuli (i.e., characters) are presented on the basis of the SSVEP stimulus; thus, the P300 stimulation frequency is sub-harmonic of the SSVEP stimulation frequency.

Each stimulus has a different SSVEP and P300 stimulation period; thus, each stimulus has different P300 stimulation parameters, such as flash duration, stimulus onset asynchrony (SOA: onset-to-onset time), and sequence stimulation time (Table 1). In particular, because the stimulation time of a sequence varies with the stimulus, stimulations finish at different times.

$$\text{Stimulation time (s)} = \frac{\text{SSVEP period} \times \text{P300 period}}{\text{frame rate}} .\text{the number of characters} \quad (1)$$

However, the SSVEP response to a stimulus with a short stimulation time has a disadvantage in the SSVEP analysis as compared to that with a long stimulation time. To equalize the SSVEP stimulation time, a stimulus keeps flickering without showing characters after its P300 stimulation time until the last stimulus finishes. The SSVEP response was segmented and analyzed on the basis of the

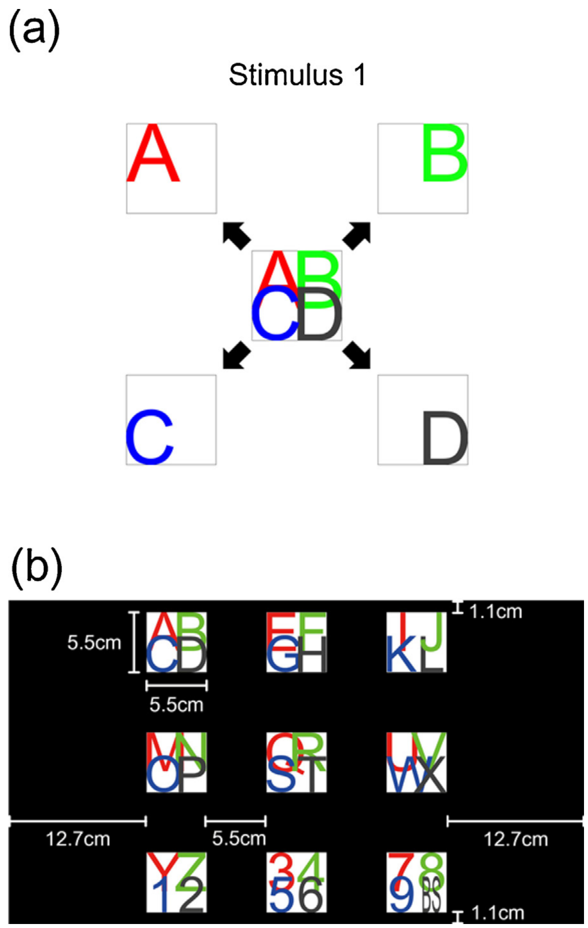

Fig. 1. Proposed hybrid speller: (a) composition of the hybrid stimulus and (b) hybrid speller.

longest stimulation time (i.e., 0.933 s × # sequence, stimulation time of Stimulus 9).

2.2. Experimental settings

Ten graduate students (male:female, 8:2; age range, 26.7 ± 2.6 years) participated in the experiments with informed consent. EEG signals were acquired using a g.USBamp (g.tec, Austria) with a sampling rate of 600 Hz. Every channel was high-pass-filtered at 0.1 Hz, low-pass-filtered at 60 Hz, and notch-filtered at 60 Hz. Electrodes were placed at 14 channels following the international 10–20 system, namely F3, Fz, F4, Cz, P7, P3, Pz, P4, P8, PO7, PO8, O1, Oz, and O2, on the subjects, grounded at Fpz, and referenced at A1. In the P300 recognition step, a stepwise linear discriminant analysis (SWLDA) automatically chooses channels on the basis of their statistical significance. In the SSVEP recognition step, three electrode configurations were compared in an offline analysis:

Channel Set 1: All 14 channels
Channel Set 2: Oz, PO7, PO8, O1, and O2
Channel Set 3: Oz, PO7, PO8, O1, O2, Pz, P3, P4, P7, and P8

The configuration with the highest accuracy was subsequently used in the online experiments.

The hybrid speller consisted of nine stimuli flickering at different frequencies (Table 1). Two pairs of stimuli flickered at harmonic frequencies: Stimuli 1 (120/10 Hz) and 6 (120/5 Hz), and Stimuli 2 (120/7 Hz) and 9 (120/14 Hz). Conventional SSVEP and P300 spellers were employed with equivalent settings to compare and assess the practicality of the hybrid speller. However, because single-frequency SSVEP-based BCI systems cannot accurately classify SSVEP responses to stimuli that flicker at harmonic frequencies, only seven stimuli were used for the SSVEP speller in the study (Stimuli 3–9; Fig. 3a). The stimuli were represented by a colored number from 3 to 9, where the colors were the same as those of the hybrid stimuli. Both the hybrid speller and the SSVEP speller were implemented using Matlab/Simulink (Mathworks, USA) and Psychophysics Toolbox extensions (Brainard, 1997; Pelli, 1997). The P300 speller was implemented using BCI2000 (Schalk et al., 2004), which consisted of 36 characters, as did the hybrid speller (Fig. 3b). The SOA and the flash duration of the P300 speller were determined as an average of those produced by the hybrid speller (SOA of 200 ms and flash duration of 80 ms) because the correlation between the BCI performance and the SOA or the flash duration is still controversial (Farwell and Donchin, 1988; Li et al., 2013a; Sellers et al., 2006). The stimulator for the spellers was a 24-in. LED monitor (ASUS, VG248QE; resolution: 1920 × 1080) with a refresh rate of 120 Hz.

2.3. Experimental procedure

All experiments were performed in a general laboratory under common illumination conditions on two or three separate days according to a subject's schedule. However, the experiments with the same speller were conducted on the same day.

For the hybrid or P300 speller, a participant was instructed to focus on a target character and to count the number of times it appeared or flashed. In offline experiments, a trial consisted of ten sequences. Therefore, the P300 stimulus of the hybrid speller appeared ten times during a trial, and the stimulus of the P300 speller flashed twenty times. The subject was exposed to every character in a random order. For the SSVEP speller, the trial stimulation took 9.3 s, which is in accordance with the longest ten-sequence-stimulation time of the hybrid speller (Stimulus 9). A

Table 1
Stimulation parameters of the hybrid speller.

Stimulus	SSVEP stimulation period	SSVEP stimulation frequency (Hz)	P300 stimulation period	P300 stimulation frequency (Hz)	Flash duration (ms)	SOA (ms)	Stimulation time of a sequence (ms)
1	10	12.0	2	6.0	66.7	166.7	667
2	7	17.1	3	5.7	46.7	175.0	700
3	11	10.9	2	5.5	73.3	183.3	733
4	23	5.2	1	5.2	153.3	191.7	767
5	12	10.0	2	5.0	80.0	200.0	800
6	5	24.0	5	4.8	33.3	208.3	833
7	13	9.2	2	4.6	86.7	216.7	867
8	9	13.3	3	4.4	60.0	225.0	900
9	14	8.6	2	4.3	93.3	233.3	933

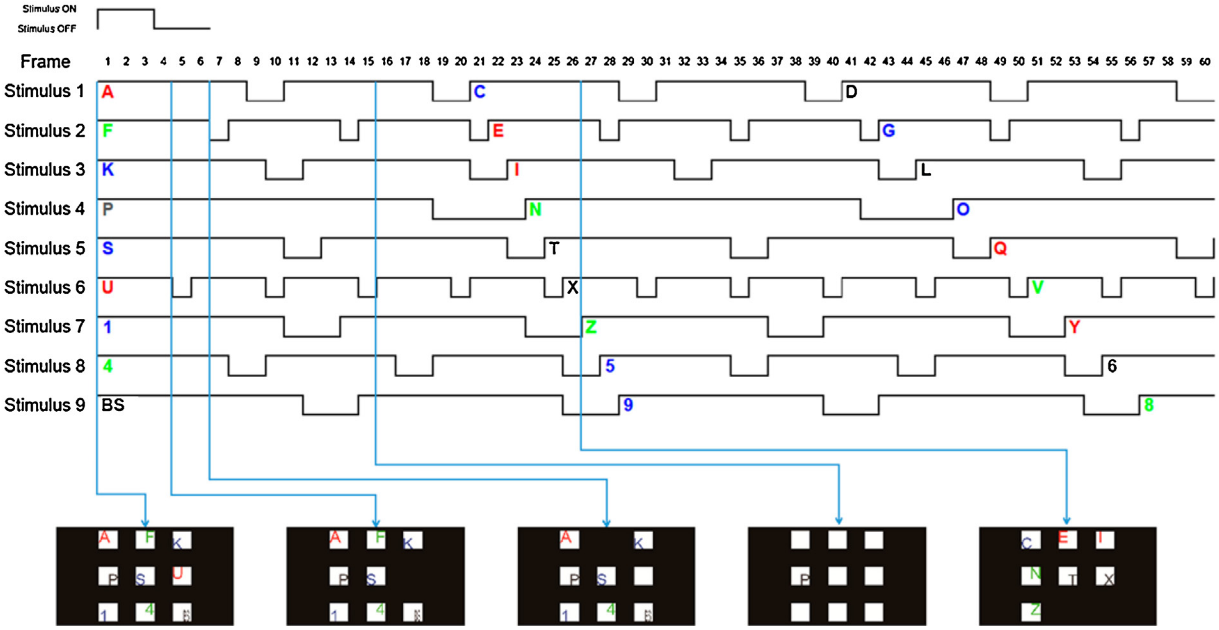

Fig. 2. Paradigm of the hybrid speller.

subject focused on one of the seven stimuli during this time, which was repeated 36 times.

In the online experiments, the sequence number was different for each speller: the hybrid and P300 spellers had a trial with sequences equal to the optimal number of sequences; the SSVEP speller flickered for the stimulation time that corresponded to the optimal number of sequences. The optimal number of sequences was determined as the number of sequences with the highest ITR in the offline experiments. The hybrid and P300 speller task was to type the subject's name and his/her phone number once in a run.

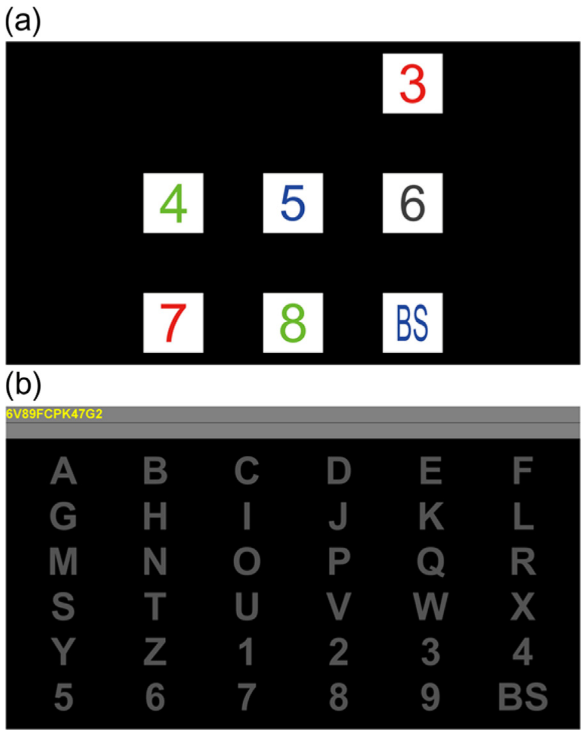

Fig. 3. Conventional spellers used in this study: (a) SSVEP speller and (b) P300 speller.

The task for the SSVEP speller was to type a sequence of numbers consisting of six numbers (3–8). Stimulus 9 of the SSVEP speller functioned as "Backspace (BS)" in the online analysis. The classification result was shown on the screen. The task length remained equal for all the spellers, and the average task length for the subjects was 20.9 characters (range: 18–25). Subjects repeated the task twice. All spellers had BS; thus, a subject could correct an error by erasing it and typing a new character. We regarded a run as failed if a subject made more than five consecutive errors for the same target or if the subject was frustrated with repeated errors. Between trials, a period of 5 s was allowed for feedback and a break.

2.4. Signal processing

SSVEP and P300 recognition steps were performed in parallel for the hybrid speller. For SSVEP recognition, the EEG signals were band-pass-filtered at [2 50] Hz and segmented starting from the stimulus onset to the end of the longest stimulation, whose length was *sequence number* × 0.93 s. The SSVEP response was classified using a canonical correlation analysis (CCA), which showed high accuracy for both single- and dual-frequency SSVEP recognition (Bin et al., 2009; Chang and Park, 2013). CCA finds a pair of weight vectors (W_x and W_y) for multichannel EEG (X) and reference signal (Y) by maximizing the correlation between two canonical variants $x = X^T W_x$ and $y = Y^T W_y$ (Bin et al., 2009):

$$\max_{W_x, W_y} \rho(x, y) = \frac{E[x^T y]}{\sqrt{E[x^T x] E[y^T y]}} = \frac{E[W_x^T X Y^T W_y]}{\sqrt{E[W_x^T X X^T W_x] E[W_y^T Y Y^T W_y]}} \tag{2}$$

Dual-frequency SSVEPs can have multiple peaks at linear combinations of stimulation frequencies, but a distinct peak frequency or amplitude varies between individuals (Chang et al., 2014). Therefore, the existing classification methods for single-frequency SSVEPs should be equipped to handle the variation. In our previous study, CCA with a modified reference signal showed the best performance with dual-frequency SSVEPs (Chang and Park, 2013).

Therefore, in this study, the reference signal for the hybrid speller (Y_{hybrid}) consisted of the sine and cosine of up to the third harmonics of the SSVEP stimulation frequency (f_{SSVEP}) and the P300 stimulation frequency (f_{P300}):

$$Y_{\text{hybrid}_i} = \begin{pmatrix} \sin\left(2\pi f_{\text{SSVEP}_i} t\right) \\ \cos\left(2\pi f_{\text{SSVEP}_i} t\right) \\ \vdots \\ \sin\left(6\pi f_{\text{SSVEP}_i} t\right) \\ \cos\left(6\pi f_{\text{SSVEP}_i} t\right) \\ \sin\left(2\pi f_{\text{P300}_i} t\right) \\ \cos\left(2\pi f_{\text{P300}_i} t\right) \\ \vdots \\ \sin\left(6\pi f_{\text{P300}_i} t\right) \\ \cos\left(6\pi f_{\text{P300}_i} t\right) \end{pmatrix}, \quad i = 1, 2, 3, \ldots, 9. \tag{3}$$

Finally, nine correlations (ρ_i) between the transformed SSVEP response and the reference signals were calculated and compared.

In the P300 recognition steps, 800-ms-long EEG segments (480 samples) were extracted starting from the onset of each P300 stimulus for each channel. These segments were then down-sampled to 30 Hz (16 samples) by using a moving average filter. The dimension-reduced segments of all channels were concatenated to yield a single feature vector (x) as [# channels × 16 samples]. Then, SWLDA was performed to choose 30 statistically significant features and compute the feature weights vector ω (Krusienski et al., 2008). The classifier was trained by a leave-one-out cross validation technique. For the online experiment, the feature weight vector was computed using all the data from the offline experiment. Lastly, the scores of each P300 stimulus were calculated as the sum of the inner product of the feature weight vector and the feature vector.

Taken together, a target on which a subject focused was classified as follows:

$$(l, m) = arg_{i,j}\left[\max(\rho_i), \max\left[\sum_{k=1}^{K}(\omega . x_{jk})\right]\right], \quad i \in [1, \ldots, 9], j \in [1, \ldots, 4] \tag{4}$$

where i and j denote the numbers of the SSVEP and P300 stimuli of the hybrid speller, respectively; k represents the sequence number, and K is equal to 10 for the offline analysis and the optimal number of sequences for the online analysis. Consequently, the target was regarded as the mth character (P300 stimulus) of the lth stimulus group (SSVEP stimulus).

For the SSVEP speller, the EEG segments were extracted and analyzed using CCA with a reference signal consisting of up to the third harmonics. The EEG response to a P300 speller was processed with the same P300 recognition steps as those used for the hybrid speller.

2.5. Statistical comparison of the EEG responses

Segmented SSVEP and P300 responses were statistically compared in the frequency and time domains, respectively ($\alpha = 0.05$). First, the grand average periodograms of the SSVEP were calculated for subjects with respect to the stimulus and the speller. Then, 8th-order SSVEP SNRs were calculated at each stimulation frequency (Vialatte et al., 2010; Wang et al., 2006) and were statistically compared between spellers:

$$\text{SNR}(f) = \frac{n \times P(f)}{\sum_{n/2}^{k=1}[P(f + k\Delta f) + P(f - k\Delta f)]} \tag{5}$$

where f denotes frequency, P represents the power of the signal, n refers to the order of 8, and Δf indicates the frequency step. Two-way repeated-measure analysis of variance (RM-ANOVA) was employed to compare SSVEP SNRs with the speller and the stimulation-frequency factors. Post hoc testing was conducted using a paired t-test with Bonferroni correction.

Grand average ERPs over subjects were calculated and plotted using EEGLAB (Delorme and Makeig, 2004). Pairs of target and non-target ERPs at different electrodes (Fz, Cz, and Pz) and target ERP pairs of different spellers were compared statistically by using a paired t-test with Bonferroni correction. Moreover, the P300 amplitude and latency at each electrode were statistically compared between spellers using two-way RM-ANOVA (speller × channel). The P300 amplitude was estimated as the amplitude difference between the peak amplitude within 300–600 ms and the pre-stimulus baseline at −200 to 0 ms. P300 latency was estimated as the time from stimulus onset to the peak amplitude between 300 ms and 600 ms (Polich, 2012).

2.6. BCI performance

In addition to accuracy, Wolpaw's ITR is the most common BCI metric that incorporates time (Yuan et al., 2013). The ITR was calculated using the time taken for feedback and a break as follows:

$$B = \log_2 N + P\log_2 P + (1 - P)\log_2\left[\frac{1 - P}{N - 1}\right] \text{(bits/symbol)}, \tag{6}$$

$$T = \begin{cases} \dfrac{ST.N_s + ITI}{60} & \text{for hybrid and conventional SSVEP spellers} \\ \dfrac{SOA.N_s.12 + ITI}{60} & \text{for the conventional P300 speller} \end{cases} \tag{7}$$

$$\text{ITR} = \frac{B}{T}\text{(bpm)} \tag{8}$$

where N denotes the number of stimuli (36 for the hybrid and P300 spellers, and 7 for the SSVEP speller) and P represents the accuracy. ST, N_s, and ITI indicate the stimulation time, the sequence number, and the inter-trial interval (5 s), respectively. The equations of T for the hybrid and SSVEP spellers were the same because the SSVEP recognition of the spellers was based on the same stimulation time of a sequence (i.e., 0.933 s).

The BCI performance values were compared with SPSS Statistics 20 (IBM, USA) using two-way RM-ANOVA (speller × sequence number; $\alpha = 0.05$). Significant differences between pairs were found using a paired t-test with Bonferroni correction.

3. Results

3.1. EEG response to the hybrid speller

The EEG response to the hybrid stimuli peaked at the P300 and SSVEP stimulation frequencies (Fig. 4). Other peaks appeared at the harmonics of the P300 stimulation frequency. Furthermore, compared with the SSVEP stimuli, the hybrid stimuli evoked stronger SSVEPs with significantly higher SSVEP SNR by a factor of 2.24 at the SSVEP stimulation frequency (Fig. 5; $F = 8.897$, $p = 0.015$). The post hoc analysis revealed that the SNR difference was significant for Stimuli 3 and 4 ($t = 4.752$ and $p < 0.001$ for Stimulus 3; $t = -3.266$ and $p = 0.010$ for Stimulus 4).

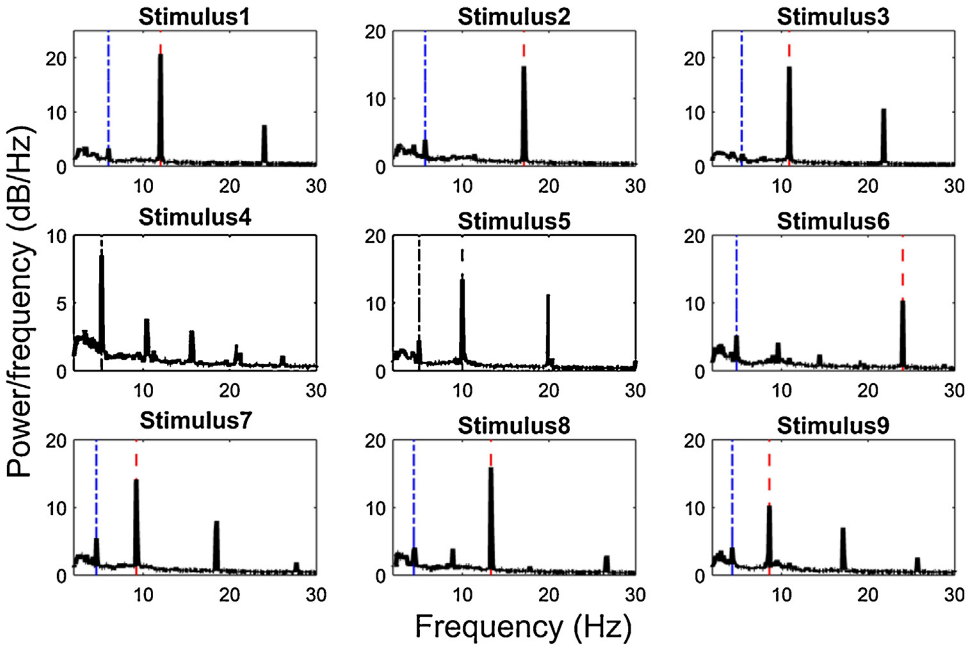

Fig. 4. Grand average power spectrum of the SSVEP response to each hybrid stimulus at Oz. The dash-dot line represents the P300 stimulation frequency, and the dashed line represents the SSVEP stimulation frequency for each stimulus. The dash-dot and dashed lines of stimulus 4 are overlapped because SSVEP and P300 frequencies are the same.

The hybrid speller also generated P300 components in the frontal, central, and parietal regions. In Fig. 6a, the grand average ERPs at Fz, Cz, and Pz show apparent positive peaks approximately 450 ms after the P300 stimulus. These positive waves are significantly different from those of the non-target responses ($p < 0.05$). However, the target response at Oz does not show a positive peak and was not significantly different from the non-target response. The P300 latency values showed a significant difference between the spellers ($F = 9.049$, $p = 0.015$; Fig. 6); the positive peak of the hybrid speller (455 ± 17 ms) occurred 66 ms later than that of the P300 speller (389 ± 15 ms). However, the P300 latency did not differ between channels ($F = 2.259$, $p = 0.133$) and showed no interaction between the speller and channels ($F = 0.440$, $p = 0.651$). P300 amplitudes were not significantly different between the hybrid and P300 spellers (hybrid speller: 3.093 ± 0.279 μV, P300 speller: 2.790 ± 0.405 μV; $F = 1.098$, $p = 0.322$) and the channels ($F = 2.393$, $p = 0.120$). There was no interaction between the speller and the channel ($F = 0.923$, $p = 0.415$).

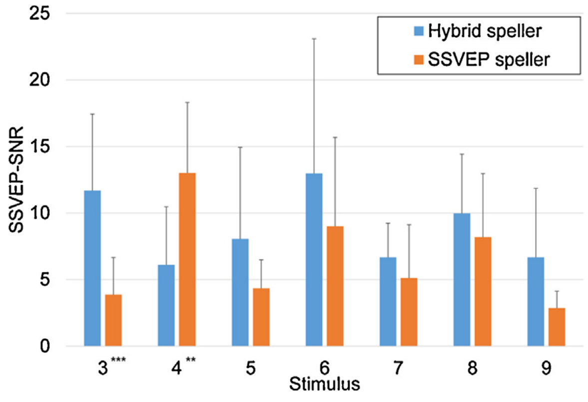

Fig. 5. Average SSVEP SNR of the hybrid and the SSVEP speller for each stimulus ($^{**}p < 0.01$, $^{***}p < 0.001$).

3.2. *Offline analysis*

An optimized channel set improved the SSVEP recognition rate (Fig. 7) by 0.017 ± 0.057 for the hybrid speller ($t = 2.977$, $p = 0.004$) and 0.069 ± 0.092 on average for the SSVEP speller ($t = 7.491$, $p < 0.001$). Almost every subject had the highest accuracy with Channel Set 2 for both spellers, which corresponds to the occipital region, which is well known as the place of origin for SSVEP (Vialatte et al., 2010). However, subjects 4, 5, 7, and 10 (S4, S5, S7, and S10, respectively) showed the best performance with Channel Set 3 for the hybrid speller, while S4 and S10 showed the highest accuracy with Channel Set 1 for the SSVEP speller. The channel set that produced the highest accuracy was employed in the online analysis.

The average accuracy over all the sequences of the SSVEP speller (0.855 ± 0.024) was higher than that for the other spellers (hybrid speller: 0.819 ± 0.027, P300 speller: 0.831 ± 0.030; Fig. 8a), although the difference was not significant ($F = 0.736$, $p = 0.493$). The average ITR was significantly different between spellers ($F = 51.294$, $p < 0.001$) and sequence numbers ($F = 48.211$, $p < 0.001$), and the interaction between the two factors also existed ($F = 22.103$, $p < 0.001$; Fig. 8b). In particular, the hybrid speller (22.290 ± 1.274 bpm) outperformed the others (11.843 ± 0.743 bpm for the SSVEP speller; 13.251 ± 0.938 bpm for the P300 speller; $p < 0.001$). More importantly, the ITR of the hybrid speller was consistently significantly higher than that of the other spellers for sequence numbers of 3 and above ($p < 0.003$).

3.3. *Online analysis*

The optimal number of sequences for each speller differed depending on the subject, as shown in Table 2. The average optimal number of sequences was significantly different between the spellers ($F = 6.766$, $p = 0.006$), which seems consistent with ITR trends in the offline analysis (Fig. 8b).

Table 2 shows the accuracy and ITR values for each subject with the different spellers. Each value indicates an average of two runs.

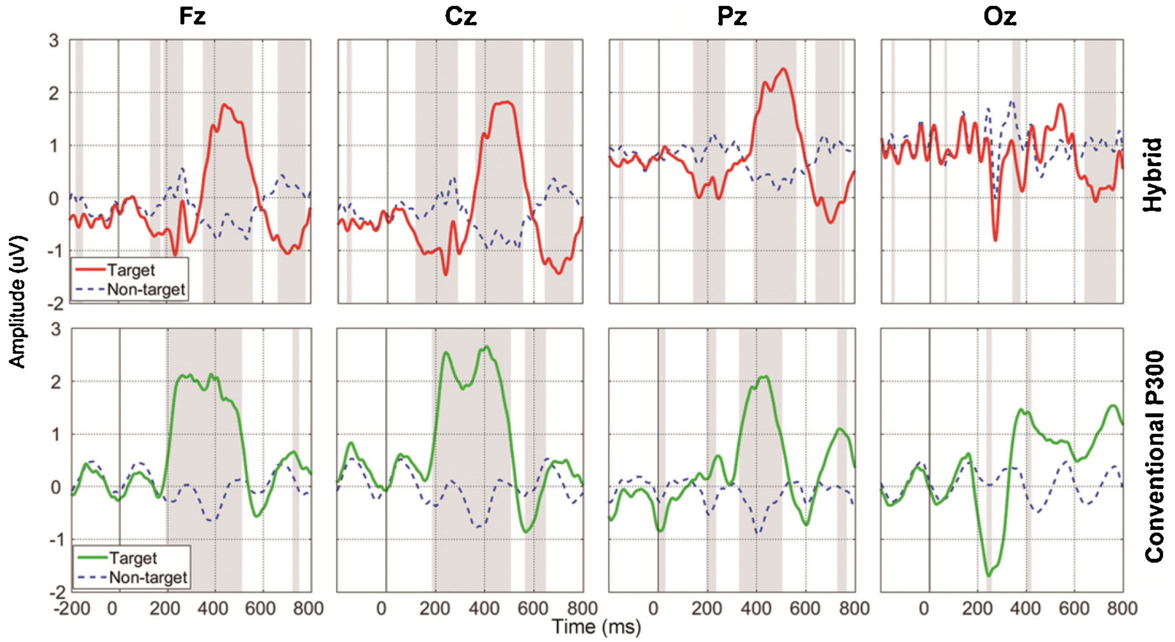

Fig. 6. Grand average ERP waveforms for different channels. Solid and dashed lines, respectively, represent the target and non-target waveforms of the hybrid speller (top) and the P300 speller (bottom). The gray-shaded regions indicate a significant difference between the two waveforms with $p < 0.05$ (paired t-test).

S3 could not complete the first run on the hybrid speller; S5 could not complete the second run on the P300 speller or either run on the hybrid speller; and S7 and S10 could not complete either run on the SSVEP speller, yielding very low ITR (Table 2). The average accuracy was not significantly different between the spellers ($F = 0.330$, $p = 0.624$). However, the ITR was significantly different between the spellers ($F = 37.159$, $p < 0.001$). In the post hoc test, the hybrid speller showed a significantly higher ITR than the others by more than 11 bpm ($p < 0.002$).

4. Discussion

4.1. Dual-frequency SSVEP

In this paper, we propose a hybrid BCI speller that flickers at the SSVEP stimulation frequency and presents characters at the P300 stimulation frequency simultaneously. The EEG response to the stimulus shows not only P300 but also the spectral peaks at the sub-harmonic of the SSVEP frequency, which demonstrates that the hybrid speller generates dual-frequency SSVEP. The response to a single-frequency stimulation typically peaks at the fundamental frequency and at the second harmonic. A few rare stimulation frequencies evoke SSVEPs at the second sub-harmonic around the α-band (Herrmann, 2001). However, hybrid speller-evoked SSVEPs exhibit peaks at a third, or some other, sub-harmonic of the SSVEP

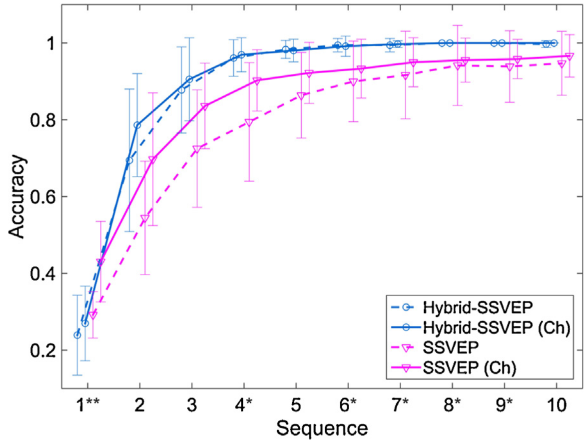

Fig. 7. SSVEP recognition rate of the SSVEP and hybrid stimuli with or without channel selection in the offline analysis (*$p < 0.05$; **$p < 0.01$). The solid lines indicate the SSVEP recognition rate with channel selection.

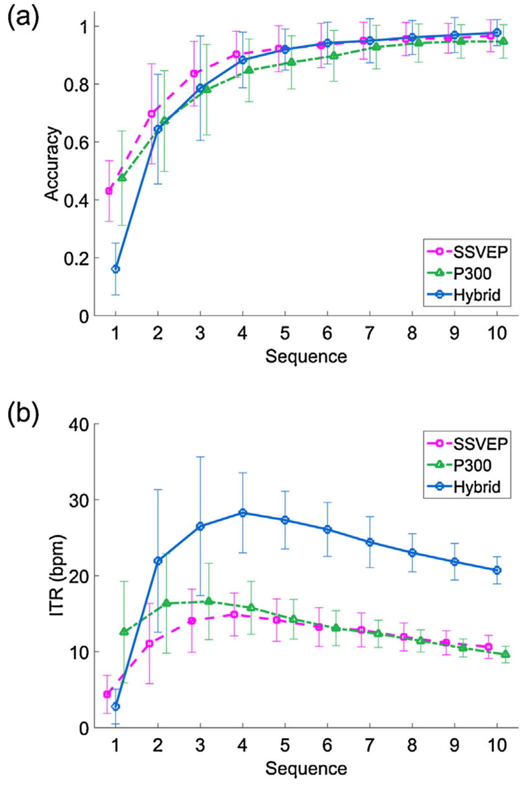

Fig. 8. BCI performance of the hybrid, SSVEP, and P300 spellers in the offline analysis: (a) average accuracy and (b) average ITR across subjects.

Table 2
Results of online experiments in terms of accuracy and ITR with optimal sequence number (SN).

Subject	Hybrid			SSVEP			P300		
	Optimal SN	Accuracy	ITR	Optimal SN	Accuracy	ITR	Optimal SN	Accuracy	ITR
S1	3	0.93	34.2	8	0.94	11.4	2	0.98	30.0
S2	3	0.96	36.7	3	0.96	19.3	4	0.94	18.7
S3	3	0.83	28.3	4	1.00	19.3	3	0.98	24.2
S4	6	1.00	29.3	9	0.96	11.0	3	0.96	23.5
S5	3	0.70	21.3	6	0.94	13.1	2	0.62	16.3
S6	4	0.98	33.9	7	0.95	12.6	4	0.88	16.5
S7	3	1.00	39.8	6	0.56	3.9	5	0.87	14.0
S8	3	0.96	36.6	4	0.98	18.1	3	0.94	22.2
S9	5	0.96	29.4	6	0.98	14.8	4	0.98	20.2
S10	6	0.98	28.1	4	0.64	6.6	5	0.85	13.5
Average	3.9	0.93	31.8	5.7	0.89	13.0	3.5	0.90	19.9

stimulation frequency. Considering that the P300 stimulation frequency is a sub-harmonic of the SSVEP stimulation frequency, the peak frequencies can be regarded as a linear combination of the SSVEP and P300 frequencies. The spectral peaks at the linear combination of the stimulation frequencies indicate that the hybrid speller evokes dual-frequency SSVEPs; this is in agreement with the results of previous studies (Chang and Park, 2013; Srihari Mukesh et al., 2006)).

It is interesting that the EEG response to the hybrid stimulus is the dual-frequency SSVEP. Usually, a visual stimulus for SSVEP flickers at a constant frequency in a constant shape (e.g., black and white squares or checkerboard). Even a visual stimulus that generates dual-frequency SSVEPs consists of two LEDs flickering at different frequencies without a shape change (Shyu et al., 2010). However, notwithstanding the fact that the shape (i.e., the character presented on a hybrid stimulus) changes randomly, a combination of light intensity and shape variations generated dual-frequency SSVEPs successfully.

The dual-frequency stimulation shows some advantages; first, it enhances SSVEPs and improves SSVEP recognition. Second, the use of harmonic frequencies as flickering frequencies increases the number of targets. Third, the simultaneous light intensity and shape variation eliminates unnecessary suspension to generate two types of EEG responses and reduces the stimulation time. All of these effects of dual-frequency stimulation contribute to the improvement of ITR.

4.1.1. *Improvement in SSVEP recognition*

The dual-frequency stimulation of the hybrid speller enhances the SSVEP SNR and creates features at the harmonics (Fig. 5), apparently resulting in more accurate SSVEP recognition. Fig. 7 shows the average SSVEP recognition rate of the hybrid speller and the average accuracy of the SSVEP speller in the offline analysis. The SSVEP recognition rate of the hybrid speller is consistently higher than that of the SSVEP speller except when the sequence number is 1 (Fig. 7).

The hybrid speller enhanced the SSVEPs in every frequency range including the relatively high frequencies (24 Hz). In the online experiments with the SSVEP speller, two subjects (S7 and S10) failed to complete the whole task, yielding very low ITR. They made almost every error when they tried to type “6” (Stimulus 6). In the offline analysis, their error rate for Stimulus 6 reached 87.5% (7/8). The average SSVEP SNR at the corresponding stimulation frequency (3.250 ± 0.472) was lower than that corresponding to the other stimuli (6.234 ± 4.503). Furthermore, the average SNR for Stimulus 6 of the subjects (3.250 ± 0.472) was lower than that of the other subjects (10.447 ± 6.740). This weak SSVEP would be expected to result in low performance by the SSVEP speller, and the weak response to Stimulus 6 might result from the relatively high SSVEP frequency. Nevertheless, the phenomenon was scarcely observed with the hybrid speller. The two subjects completed the tasks with almost 100% accuracy, and the average SNR of Stimulus 6 (11.140 ± 4.237) was considerably higher than that for the SSVEP speller. We inferred that the dual-frequency stimulation of the hybrid speller enhanced the SSVEPs to Stimulus 6 as well as the other stimuli; therefore, the SSVEP to Stimulus 6 was better recognized with the hybrid speller.

4.1.2. *Use of harmonic frequencies*

The hybrid speller augments the number of available targets by successfully employing harmonic frequencies for different stimuli. In an SSVEP-based BCI system, stimulation frequencies should be adjusted according to the refresh rate of the monitor (Volosyak et al., 2009), and harmonic frequencies cannot be used for different stimuli. However, the hybrid speller overcame the problem by employing relatively prime P300 stimulation frequencies, which generated harmonics at non-overlapping frequencies, even with harmonic SSVEP frequencies. The hybrid speller succeeded in classifying the two stimuli by using the non-overlapping harmonic frequencies and achieved a high SSVEP recognition rate.

4.1.3. *Reduction in stimulation time*

The hybrid speller reduces the stimulation time compared with a previous hybrid or P300 speller. The combination of intensity and shape variation generates both SSVEP and P300 at the same time; thus, the proposed speller does not require separate stimulation times, as was not the case with a previous hybrid speller (Xu et al., 2013). Fig. 9 illustrates the representative target responses to Stimulus 2 of S10 at Fz, Cz, Pz, and Oz (average of 200 ms before and 800 ms after the appearance of a target character) along with the

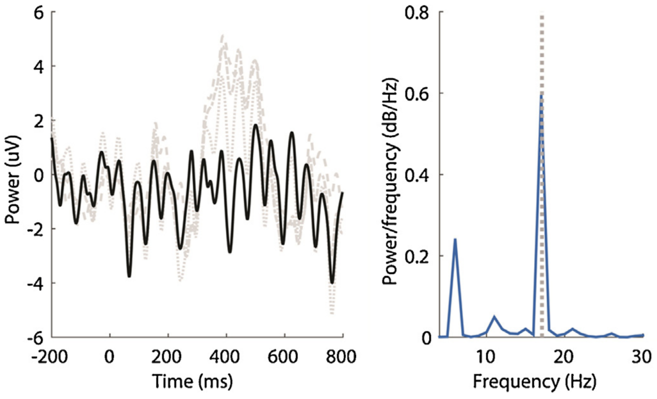

Fig. 9. Average target response to Stimulus 2 for S10 at Fz (dashed gray line), Cz (dash-dot gray line), Pz (dotted gray line), and Oz (solid black line). The right panel illustrates the power spectrum of the target response at Oz, and the dashed line indicates the corresponding SSVEP stimulation frequency.

response spectrum at Oz. Interestingly, a seamless periodic oscillation is observed at Oz, while the P300 component dominates at Fz, Cz, and Pz, as shown in Fig. 6. The peak frequency of the periodic oscillation at Oz corresponds to the SSVEP stimulation frequency. In addition, the proposed speller reduces the stimulation time compared with the P300 speller by grouping four characters into one stimulus. This strategy results in reducing the number of flashes in a sequence from twelve flashes in the P300 speller (six rows and six columns) to four in the hybrid speller (four P300 stimuli). Simultaneous stimulation and the reduced number of flashes allow the hybrid speller to have a considerably shorter stimulation time (0.93 s) even with a longer stimulus duration and ISI than the P300 speller (stimulation time: 2.4 s).

4.2. ITR comparison with conventional spellers

The characteristics of dual-frequency stimulation in the proposed speller increased the number of targets and reduced the stimulation time; all of these effects contributed to an ITR improvement, shown by Eqs. (6)–(8). In the offline analysis, the ITR of the hybrid speller was considerably larger than that of the other spellers except when the sequence number was 1. In particular, sequence numbers higher than 3 are more likely to be used in practical BCI applications with higher-than-minimum acceptable accuracy (70%) (Kübler et al., 2001; Kleih et al., 2010). These results suggest that the hybrid speller is more beneficial in practical use than the conventional spellers. The same conclusion is drawn from the results of the online analysis, in which the hybrid speller showed the best accuracy and ITR. For the hybrid and P300 spellers, the subject-specific parameter (ω) and the channel set in the offline/online tasks and the subject-specific optimal sequence number in the online tasks were employed.

Speller attributes such as the stimulus design and stimulation parameters are different, which makes it difficult to compare the performance of spellers. However, the different attributes reflect and highlight the superiority of the speller proposed in this paper. First, the hybrid speller consists of two more SSVEP stimuli than an SSVEP speller. This difference comes from the ability of the hybrid speller to employ harmonic frequencies for different stimuli, which is an important advantage that results in a positive effect on ITR. Second, the flash duration and the SOA of the P300 stimuli on the hybrid speller vary, and the segmentation performed for the final classification is based on the longest SOA. In contrast, the stimulation parameters of the P300 speller are set to the median of those of the hybrid speller rather than the longest or the shortest ones. This method avoids any unascertained effects of the stimulation parameters on the BCI performance. However, the hybrid speller showed a higher ITR than did the P300 speller despite the longer stimulation time and the shorter distance between characters in a group. Only P300 latency was different between the spellers (Fig. 6), and it is presumed to be because of different task complexity; that is, the more densely located characters and the higher degree of noise (white and black squares) in the proposed speller may impede the target recognition and thereby result in a longer P300 latency.

4.3. ITR comparison with previous studies

The BCI performance in this study was lower than that observed in previous studies because of the long ITI. A period of 5 s was given to the subjects to rest their eyes and to prepare for the next task. An ITI of 5 s is relatively long considering the stimulation time (9.33 s) and the fact that the ITR is inversely proportional to the time taken, as seen in Eqs. (6)–(8). Therefore, the long interval inevitably results in considerable decreases in the ITR. However, some recent studies take approximately 2 s, and some studies do not even consider the ITI in the ITR calculation. Table 3 shows the estimated ITR values from the online analysis for ITIs of 2 s. As the ITI is reduced, the estimated ITR substantially increases by about 20 bpm. The estimated ITR is higher than or equivalent to that of a recently proposed hybrid speller (Xu et al., 2014, 2013). In addition, the estimated practical ITR (PITR) with 2-s ITI (48.2 ± 12.7 bpm) is also equivalent to that of a previous study (Yin et al., 2014).

Table 3
Estimated ITR (bpm) in online analysis with different inter-trial intervals.

	Inter-trial interval	
	5 s	2 s
Average	31.8	49.4
SD	5.9	10.8
Max	39.8	64.6
Min	19.6	31.8

4.4. Limitations

A limitation of the present study is the different stimulation times of the stimuli. When the number of sequences remains constant, a stimulus with a short stimulation time finishes its stimulation earlier than that with a longer stimulation time. We let the stimulus flicker black and white without showing characters after the simulation is completed, but this strategy appears to be time inefficient. Therefore, in the future, we will rearrange the stimulus shapes (i.e., characters) so that all stimuli finish their stimulations at similar times. Another consideration is the visual fatigue caused by the complex stimulation method. The proposed speller presents colorful characters non-uniformly in various directions, which may increase visual fatigue. Thus, modifications in speller design are needed to reduce eye fatigue while maintaining performance.

5. Conclusion

The proposed hybrid speller was designed so that a flickering SSVEP stimulus would simultaneously provide a P300 stimulus. The simultaneous stimulation evoked dual-frequency SSVEP, which enhanced SSVEPs and significantly improved the performance of some subjects (S7 and S10). Furthermore, it allowed for harmonic frequencies to be employed as flickering frequencies for different stimuli. These results make up for the weak points of SSVEP-based BCIs with a monitor, such as weak SSVEP and unavailable harmonic frequencies. Further, the hybrid speller reduced the number of flashes from twelve (RC paradigm) to four (the hybrid speller), thereby reducing the stimulation time and improving ITR compared to a P300 speller. In the online analysis, the ITR of the hybrid speller was considerably greater than that of the conventional SSVEP and P300 spellers with accuracy of more than 90%. In conclusion, the hybrid speller overcomes the weaknesses of SSVEP- and P300-based BCIs by using a dual-frequency stimulus, yielding a more reliable and more time-efficient speller.

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