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Research Report

A new dual-frequency stimulation method to increase the number of visual stimuli for multi-class SSVEP-based brain–computer interface (BCI)

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ABSTRACT

In the present study, we introduce a new dual-frequency stimulation method that can produce more visual stimuli with limited number of stimulation frequencies for use in multiclass steady-state visual evoked potential (SSVEP)-based brain–computer interface (BCI) systems. Methods for increasing the number of visual stimuli are necessary, particularly for the implementation of multi-class SSVEP-based BCI, as available stimulation frequencies are generally limited when visual stimuli are presented through a computer monitor. The new stimulation was based on a conventional black–white checkerboard pattern; however, unlike the conventional approach, ten visual stimuli eliciting distinct SSVEP responses at different frequencies could be generated by combining four different stimulation frequencies. Through the offline experiments conducted with eleven participants, we confirmed that all ten visual stimuli could evoke distinct and discriminable single SSVEP peaks, of which the signal-to-noise ratios were high enough to be used for practical SSVEP-based BCI systems. In order to demonstrate the possibility of the practical use of the proposed method, a mental keypad system was implemented and online experiments were conducted with additional ten participants. We achieved an average information transfer rate of 33.26 bits/min and an average accuracy of 87.23%, and all ten participants succeeded in calling their mobile phones using our online BCI system.

1. Introduction

Brain–computer interface (BCI) is a novel mode of communication that can help paralyzed individuals operate external devices or communicate with others using their brain signals (Wolpaw et al., 2002). Diverse types of experimental paradigms and tasks have been used to realize electroencephalography (EEG)-based BCI systems, e.g., steady-state visual evoked potential (SSVEP) (Bakardjian et al., 2010; Cheng et al., 2002; Volosyak, 2011), mu rhythm (Blankertz et al., 2007; Hwang et al., 2009; Pfurtscheller et al., 2006), slow cortical potential (SCP) (Birbaumer et al., 1999), and event-related p300 (Hoffmann et al., 2008; Sellers et al., 2010). Among them, SSVEP-based BCI systems have advantages over the other paradigms in that they

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provide a high information transfer rate (ITR), require relatively few electrodes, and generally do not need any training, compared to the requirements of other BCI systems (Vialatte et al., 2010; Zhu et al., 2010; Volosyak, 2011).

SSVEP is a periodic brain electrical response induced by the repetitive presentation of a visual stimulus, flickering or reversing at a certain frequency ranging from 1 Hz to 60 Hz (Zhu et al., 2010). Although SSVEP can be elicited by a broad range of frequencies, the available frequencies in practical BCI applications are often restricted by several factors. First, all available stimulation frequencies do not always evoke high SSVEP responses. The frequencies that elicit strong SSVEP responses are highly dependent upon the participants, as well as various properties of the visual stimuli, such as color, size, and contrast (Zhu et al., 2010). Second, the use of two frequencies, F_1 and F_2, in the same experiment has been typically avoided when F_1 is a multiple of F_2 or vice versa because of the harmonic SSVEP responses (Bakardjian et al., 2010; Cheng et al., 2002; Shyu et al., 2010); simultaneous use of those frequencies could significantly decrease the performance of SSVEP-based BCI systems. Third, the frequencies in the alpha band (8–13 Hz) should be carefully selected because its use has been attributed to a considerable number of false positives (Cheng et al., 2002; Zhu et al., 2010). Fourth, it is rare but sometimes possible that some visual stimuli with flickering frequencies in the 15–25 Hz frequency band may provoke epileptic seizures (Fisher et al., 2005). Most importantly, when using a monitor as a rendering device, stimulation frequencies have to be set as sub-harmonics of the monitor refresh rate (usually 60 Hz) to attain accurate SSVEP responses (Yan et al., 2009; Zhu et al., 2010). Therefore, one of the challenging issues in SSVEP-based BCI studies is to make the best use of available frequencies, particularly when using the computer monitor to implement a multi-class SSVEP-based BCI system.

Recently, a few methods based on dual-frequency stimulation have been studied for the production of more distracters than the number of stimulation frequencies (Mukesh et al., 2006; Shyu et al., 2010; Yan et al., 2009). For example, one study showed that a single visual stimulus modulated with two different frequencies, F_1 and F_2, could elicit SSVEP responses at F_1, F_2, F_1+F_2, and their harmonics (Mukesh et al., 2006). Based on this phenomenon, three different types of visual stimuli could be generated using two flickering frequencies F_1 and F_2 (first stimulus modulated with a single frequency F_1, second stimulus modulated with F_2, and third stimulus modulated with both F_1 and F_2). This study demonstrated the possibility of increasing the number of selections using fewer numbers of frequencies; however, unfortunately, the concept was not expanded to more than two frequencies.

More recently, two other studies used two closely-spaced visual stimuli each flickering at different frequencies (Shyu et al., 2010; Yan et al., 2009). Although these studies used different rendering devices and different strategies for extracting SSVEP features, they used a common stimulation strategy. In both studies, participants were asked to focus their eyes on the middle of the two flickering points, and the SSVEP responses at two main frequencies were used as the main feature vectors for classification (Shyu et al., 2010; Yan et al., 2009). However, it was observed in both previous studies (Shyu et al., 2010; Yan et al., 2009) as well as in preliminary experiments of our study that the spectral powers at two stimulation frequencies were not consistent with respect to time, which was because the participants shifted their attention from the middle of the visual stimuli to one of the two stimuli (Gao et al., 2000; Yan et al., 2009). Indeed, in Yan et al.'s (2009) study, two out of eight participants had difficulty in maintaining their concentration on the middle of two visual stimuli, and thereby they did not show high classification accuracy. Consequently, this type of visual stimuli could cause a number of false positives and requires more complicated classification algorithms to enhance the detection accuracy.

The goal of the present study was to provide an efficient dual-frequency stimulation method that can address the 'attention-shift' problems of the conventional dual-frequency stimulation methods. To this end, a pattern-reversal checkerboard stimulus consisting of black and white squares was modulated with two stimulation frequencies. In the offline study, EEG signals were recorded from 11 participants while they were staring at the new checkerboard pattern stimuli modulated with two frequencies. The power spectral analysis was applied to the recorded EEG data and SSVEP signal-to-noise ratios (SNRs) were evaluated to verify the feasibility of the proposed dual-frequency stimulation method. For the online experiment, we implemented a mental keypad system consisting of twelve visual stimuli generated by the proposed dual-frequency stimulation method, and evaluated the performance of the mental keypad system with ten additional participants.

2. Results

2.1. *Offline experimental results*

2.1.1. *The conventional dual-frequency stimulation method*

Before the main experiments, a conventional dual-frequency stimulation method was replicated to demonstrate the limitation of the conventional dual-frequency stimulation approach. In order to observe the SSVEP responses evoked by the conventional dual-frequency stimulation method, two flashing squares, each of which subtended a visual angle of 1.43° both vertically and horizontally, were placed in a row, with a 0.5 cm inter-stimulus distance, on a gray background. Fig. 1 shows the conventional dual-frequency visual stimulus used in this study. Each square flashed with white (ON) and black (OFF) colors at given stimulating frequencies, respectively. Six dual-frequency visual stimuli were generated by combining four different flickering frequencies (Shyu et al., 2010). The selected four stimulation frequencies were 6 Hz, 6.66 Hz, 7.5 Hz, and 8.57 Hz, which corresponded to the frequencies of classical pattern reversal checkerboard stimuli used in our offline studies.

Fig. 2(a)–(d) shows the representative examples of the time–frequency spectral power maps acquired while a participant (P1) was focusing on the conventional dual-frequency visual stimuli for 30 s. In those examples, it was observed that the frequency evoking a strong SSVEP response was time-varying. For example, in the first example (Fig. 2(a)), the participant directed his attention to the right side stimulus (6.66 Hz) and then switched his attention to the left side stimulus (6 Hz). In this example, we could observe a short period during which two distinct SSVEP peaks were observed at both the main frequencies, but the period lasted only for about eight seconds. In the second example (Fig. 2(b)), the participant first directed his attention more toward the right side stimulus (7.5 Hz) and then switched his attention to left side stimulus (6.66 Hz). After a few seconds, he again switched his attention to the right side stimulus. In this case, no multiple SSVEP peaks were observed during any time periods. In the other examples (Fig. 2(c) and (d)), we also observed that the participant could not continuously maintain attention to both stimuli. Indeed, we confirmed that about half of the participants had difficulty in consistently maintaining their concentration on both visual stimuli flickering at different frequencies, as also described in the previous dual-frequency SSVEP studies (Shyu et al., 2010; Gao et al., 2000; Yan et al., 2009). Considering that the conventional dual-frequency stimulation methods require two sufficiently large SSVEP responses at two main frequencies for the discrimination of participants' intentions, it is obvious that this type of visual stimuli would need more complicated classification algorithms than the conventional 'single-frequency' visual stimuli to reduce possible false positives.

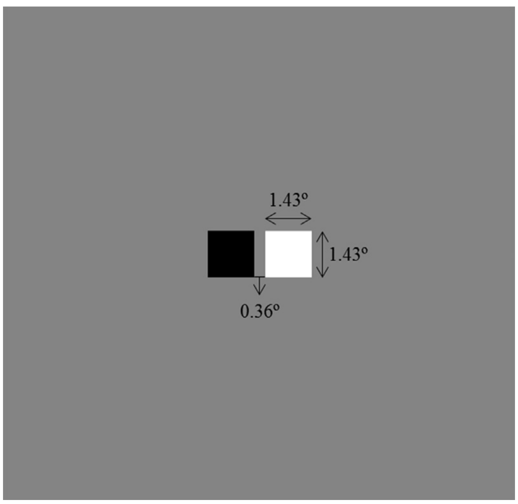


Fig. 1 – A conventional dual-frequency visual stimulus tested in this study. Two squares flickered with different frequencies, i.e., 6–6.66 Hz, 6–7.5 Hz, 6–8.57 Hz, 6.66–7.5 Hz, 6.66–8.57 Hz, and 7.5–8.57 Hz.

2.1.2. *The proposed new dual-frequency stimulation method*

To overcome the 'attention-shift' problem confirmed in the present study and the previous studies (Shyu et al., 2010; Gao et al., 2000; Yan et al., 2009), a novel dual-frequency stimulation method was proposed by modifying a traditional pattern reversal checkerboard stimulus. The traditional checkerboard stimulus colored in black and white actually consists of two sets of arrayed squares, denoted as 'Pattern 1' stimulus and 'Pattern 2' stimulus shown in Fig. 3(a) and (b), respectively. Each pattern stimulus changes its color (black and white) at a certain frequency, which is defined as the number of full cycles per second. On the other hand, when those two patterns are combined into a single pattern reversal stimulus, it is known that the pattern reversal stimulus elicits a strong SSVEP response at a frequency corresponding to the number

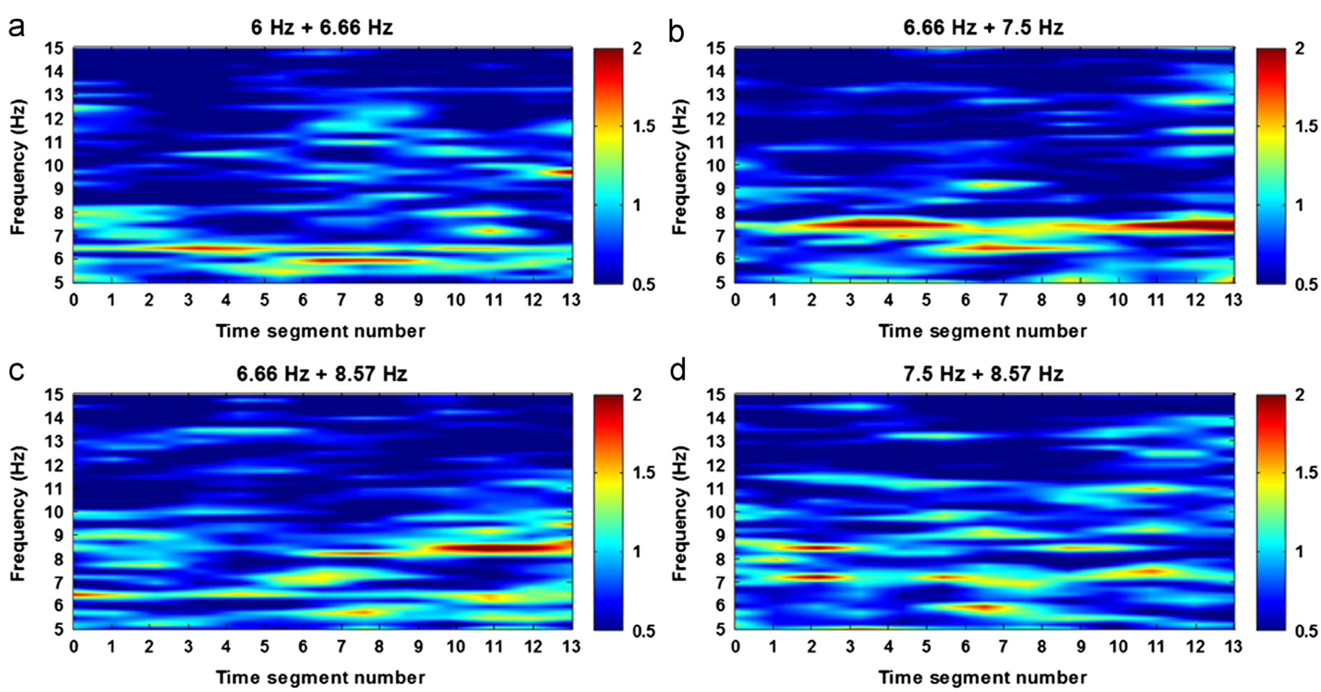


Fig. 2 – Time–frequency pattern maps of a participant (P1) demonstrating time-varying amplitudes of two fundamental frequencies: (a) SSVEP responses when 6.66 Hz and 7.5 Hz were used as stimulating frequencies, (b) SSVEP responses when 6 Hz and 6.66 Hz were used as stimulating frequencies, (c) SSVEP responses when 6.66 Hz and 8.57 Hz were used as stimulating frequencies, and (d) SSVEP responses when 7.5 Hz and 8.57 Hz were used as stimulating frequencies. Units: μV^2.

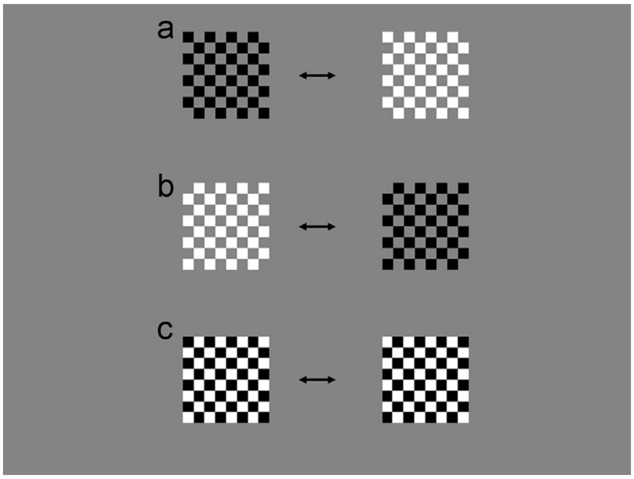


Fig. 3 – Schematic diagram to elucidate traditional and modified pattern reversal checkerboard pattern stimuli: (a) 'Pattern 1' stimulus flickering at F_1 frequency, (b) 'Pattern 2' stimulus flickering at F_2 frequency, (c) a checkerboard pattern stimulus reversing at F_1+F_2 frequency. For the conventional checkerboard pattern stimulus, the stimulation frequencies of the 'Pattern 1' and 'Pattern 2' stimuli are identical ($F_1=F_2$), while the two frequencies can have different values in the proposed dual-frequency stimuli.

of half cycles per second, which can be regarded as a sum of frequencies of 'Pattern 1' and 'Pattern 2'. That is, when the two patterns with 180° phase difference have a common alternating frequency of F_1, a strong SSVEP response is evoked at a frequency of $2\times F_1$ ($=F_1+F_1$). Inspired by this observation, we tried to slightly modify the traditional pattern-reversal checkerboard stimulus by giving different modulation frequencies to 'Pattern 1' and 'Pattern 2' stimuli, and investigated the SSVEP responses elicited by the modified checkerboard stimulus. Unlike the previous dual-frequency stimulation strategies using two separately-placed visual stimuli, since the proposed dual-frequency stimulation method uses a single visual stimulus mixed with two different patterns ('Pattern 1' and 'Pattern 2'), the 'attention-shift' problem can be solved. The detailed information about the proposed dual-frequency stimulation method can be found in Section 4.2. To verify the feasibility of the proposed dual-frequency stimulation method, offline experiments were conducted with eleven participants. For the offline experiments, we used four different stimulation frequencies (3, 3.33, 3.75 and 4.285 Hz), and generated ten dual-frequency checkerboard stimuli each modulated with 3–3 Hz, 3–3.33 Hz, 3–3.75 Hz, 3–4.285 Hz, 3.33–3.33 Hz, 3.33–3.75 Hz, 3.33–4.285 Hz, 3.75–3.75 Hz, 3.75–4.285 Hz and 4.285–4.285 Hz. Every stimulus was presented to each participant for 30 s with an inter-stimulus interval of 30 s.

Fig. 4 shows the time–frequency spectral power maps acquired while a participant (P1) was staring at the proposed dual-frequency checkerboard stimuli. Fig. 5 shows the spectral powers averaged over the entire 30-s epoch shown in Fig. 4. It was clearly observed from both figures that the SSVEP peaks were evoked at different single frequencies for each different visual stimulus, demonstrating that ten discriminable distracters could be successfully generated using only four different frequencies. All SSVEP peaks appeared at the sum of two stimulating frequencies and kept consistency with respect to time. Unlike the conventional dual-frequency stimulation methods that used multiple SSVEP peaks appearing at multiple frequencies (Mukesh et al., 2006; Shyu et al., 2010; Gao et al., 2000; Yan et al., 2009), it is noteworthy that a single strong SSVEP response consistent with respect to time was observed for each modified checkerboard visual stimulus. This unique characteristic would be secure of significant advantage over the conventional dual-frequency stimulation methods because the SSVEP responses of the 10 visual stimuli are not overlapped with each other and thus can be readily discriminated with a simple classification strategy used for the 'single-frequency' SSVEP-based BCI.

In order to determine whether or not the evoked SSVEP responses could be applied to practical SSVEP-based BCI systems, the SNRs of the SSVEP responses were calculated. To estimate the SNR values, we first calculated SSVEP amplitudes at the sum of two stimulating frequencies for each dual-frequency stimulus and the averaged SSVEP amplitudes of 8 adjacent frequencies. Fig. 6 presents the SSVEP amplitudes averaged over all 11 participants for each dual-frequency checkerboard stimulus. We could confirm from the figure that all the SSVEP amplitudes at the sum of two stimulating frequencies were significantly higher than the averaged SSVEP amplitudes of 8 adjacent frequencies. The SNR values were obtained by dividing the SSVEP amplitude at the sum of two frequencies by the mean SSVEP amplitude of 8 adjacent frequencies. Fig. 7 shows the mean SNR values averaged over all 11 participants for each SSVEP response. The SNRs more than 1.5 imply that the SSVEP responses at the sum of two stimulating frequencies were more than at least 1.5 times higher than the averaged SSVEP responses of 8 adjacent frequencies. In the SSVEP-based BCI studies, the SSVEP SNR value is an important factor to evaluate the feasibility of visual stimuli because the SSVEP responses with high SNR values can facilitate simple extraction of BCI features and thus enhance the overall classification accuracy (Zhu et al., 2010). The SSVEP SNR values acquired in this study were high enough to be applied to a practical SSVEP-based BCI system, considering those reported in previous SSVEP-based BCI studies (Materka and Byczuk, 2006; Vialatte et al., 2009), although direct comparisons were rather difficult due to differences in the independent variables.

2.2. *Online experimental results*

To confirm whether the proposed dual-frequency stimulation method could be utilized for a multi-class SSVEP-based BCI system, we conducted online experiments with ten participants who did not take part in the offline experiments. In the online experiments, two traditional pattern-reversal checkerboard stimuli (5–5 Hz and 6–6 Hz) were added to the above ten checkerboard stimuli used in the offline experiments to implement a mental keypad consisting of twelve keys. The twelve visual stimuli were arranged in a 3-by-4 array, each of which was assigned to numbers 0 to 9, 'BACKSPACE', and 'CALL' buttons, respectively (see Fig. 8 and Table 2). During

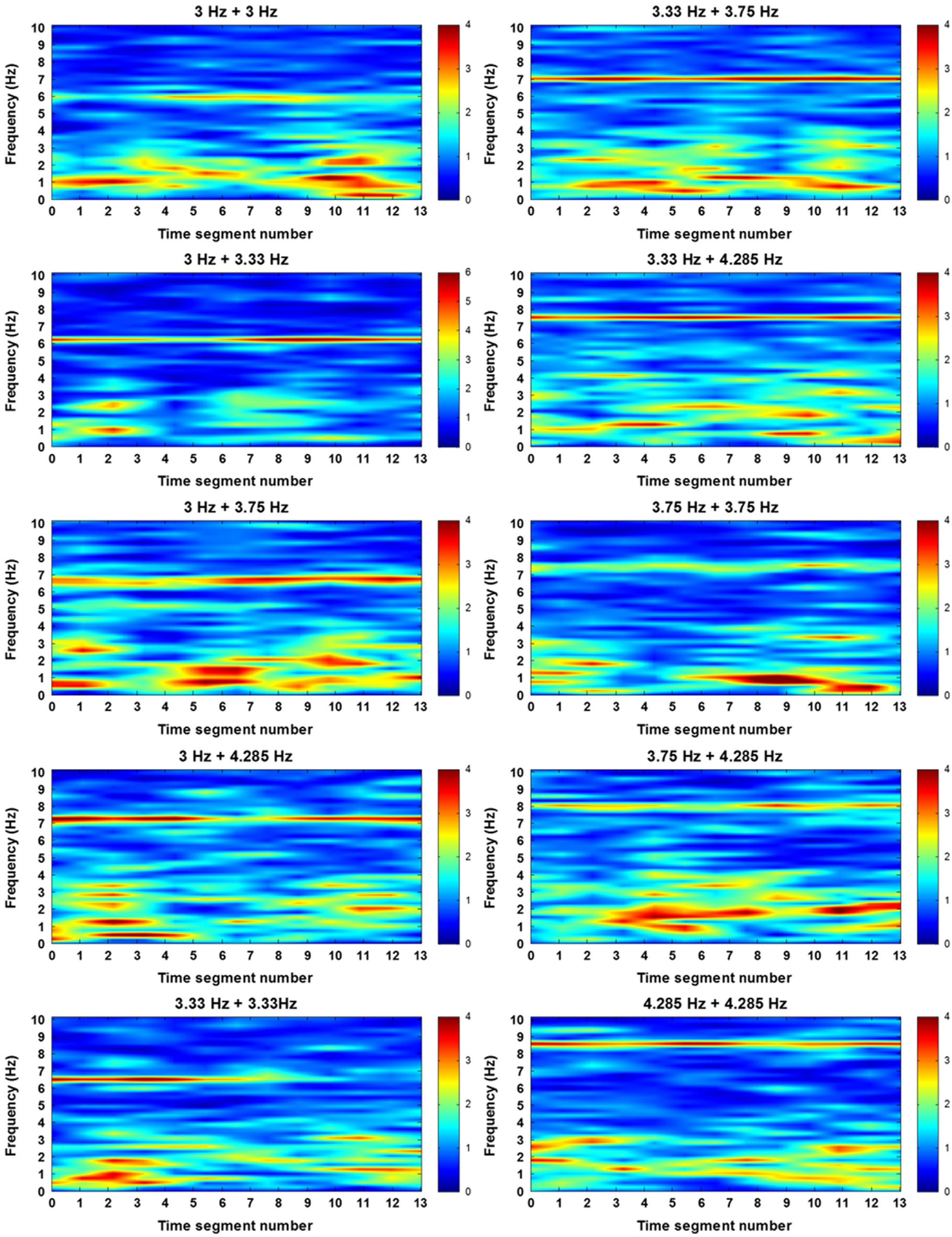


Fig. 4 – Time–frequency pattern maps of a participant (P1) acquired while he was staring at the ten different visual stimuli generated by combining four different frequencies (3 Hz, 3.33 Hz, 3.75 Hz, and 4.285 Hz). Units: μV^2.

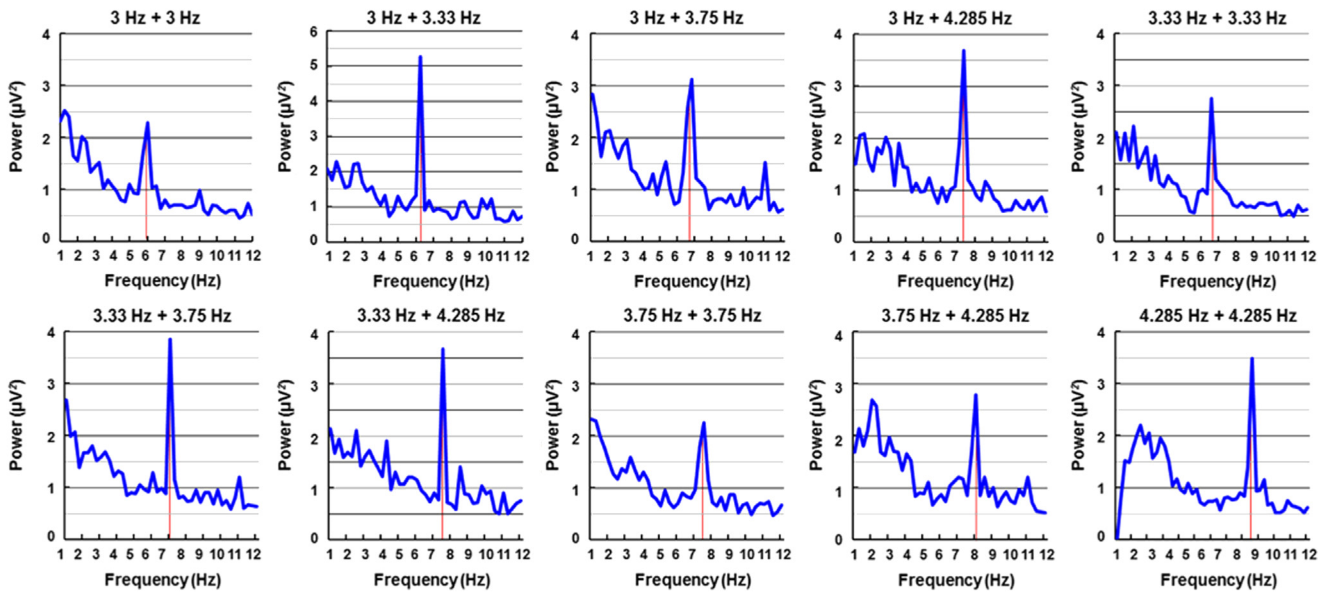


Fig. 5 – Spectral powers averaged over the 30-s epoch shown in Fig. 4. Four different frequencies (3, 3.33, 3.75, and 4.285 Hz) were used to generate ten visual stimuli. Distinct SSVEP peaks were observed at the sum of two fundamental frequencies for every stimulus. Note that the range of the *y*-axis for the 3 Hz+3.33 Hz result is from 0 to 6, while the others range from 0 to 4.

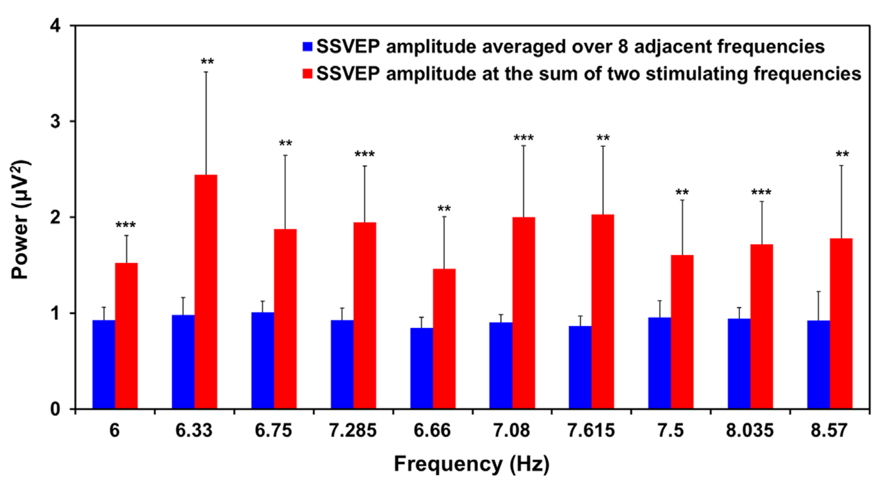


Fig. 6 – SSVEP amplitudes at the sum of two stimulation frequencies and the averaged SSVEP amplitudes of 8 adjacent frequencies for ten different visual stimuli (*$p<0.05$, $p<0.01$,*** $p<0.001$, two tailed paired *t*-test).**

the online experiments, the 3-by-4 stimuli matrix shown in Fig. 8 was presented to the participants, and they were asked to input ten sets of 5-digit numbers for evaluating the performance of the mental keypad system.

The results of the online BCI experiments are summarized in Table 1. The average information transfer rate (ITR) over ten participants were 33.26 bits/min with an average success rate of 87.23%. All participants showed sufficiently high classification accuracy (>80%), which can be used for practical communications (70% according to Perelmouter and Birbaumer) (Perelmouter and Birbaumer, 2000). The Efficiency values also showed positive values in all participants. Note that when the Efficiency of a BCI system is zero, the performance (accuracy or ITR) of the BCI system is meaningless because practical communication using the system is not actually possible (Quitadamo et al., 2012).

To further demonstrate the practicality of the mental keypad system, we asked participants to call their own mobile phones using internet-based telephone application software (Skype^{TM}, Microsoft, US). The number selected using the mental keypad system was automatically transferred to the dial pad of the Skype^{TM} using a virtual keyboard. As the results of the experiments, all participants succeeded in calling their mobile phones using the developed mental keypad system

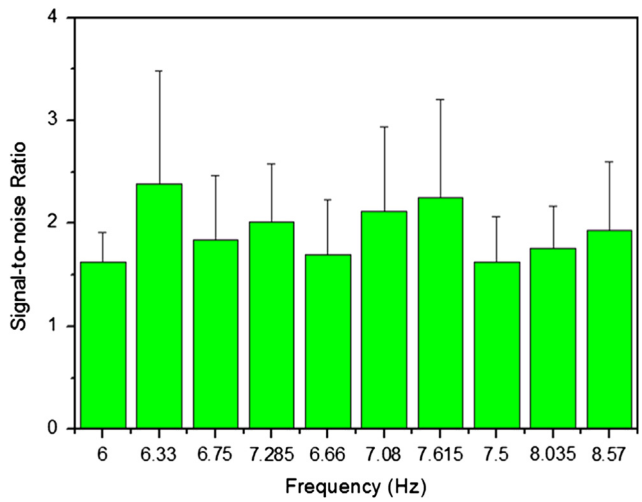


Fig. 7 – The mean signal-to-noise ratio (SNR) of evoked SSVEP responses averaged over all participants.

combined with Skype[TM] (see the Supplementary movie file).

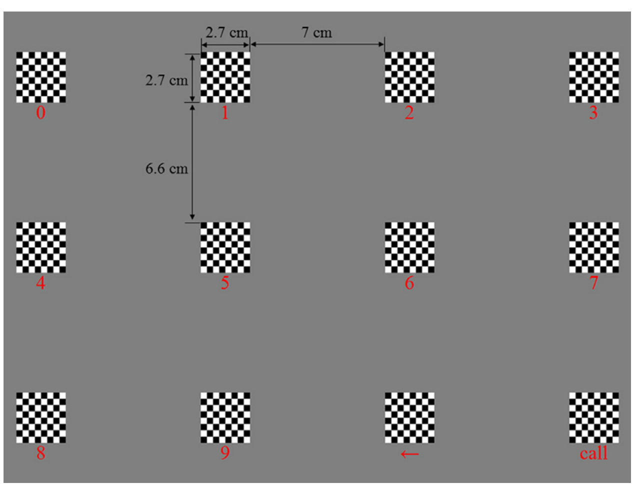


Fig. 8 – The user interface of the implemented online mental keypad system, which adopted our dual-frequency stimulation method.

Our experimental results demonstrated that the proposed dual-frequency stimulation method can be utilized for a practical multi-class SSVEP-based BCI system.

3. Discussion

Most previous SSVEP-based BCI studies have used a single stimulation frequency to encode each selection. So far, only a few BCI studies have proposed dual-frequency stimulation methods in order to increase the number of visual stimuli with limited stimulation frequencies (Mukesh et al., 2006; Shyu et al., 2010; Yan et al., 2009). In the conventional approaches, one of the two SSVEP peaks was frequently weakened or sometimes disappeared due to the shift of attention, as shown in the previous studies (Shyu et al., 2010; Gao et al., 2000; Yan et al., 2009) as well as in the present study. In this study, to address this issue, we proposed a new dual-frequency stimulation method by modifying the traditional pattern reversal checkerboard stimulus. The proposed stimulation method was no longer subject to the attention shift problem because two different pattern stimuli are mixed into a single visual stimulus. Through the offline and online experiments, we demonstrated the feasibility and practicality of the proposed stimulation method.

As briefly introduced before, the results of a previous study (Shyu et al., 2010) demonstrated that six targets could be successfully generated using four different frequencies. This paradigm can be generalized such that N different frequencies can generate ${}_NC_2$ visual stimuli. Similarly, another study showed that a half-field stimulation method can generate N^2 targets by combining N different frequencies (Yan et al., 2009). Also, Mukesh et al. showed the possibility that N stimulation frequencies can produce ${}_NC_2+N$ discriminable visual stimuli by controlling the alternation timing of the traditional checkerboard pattern stimulus. These studies will be discussed one by one later. Based on the results in Figs. 4–7, we readily expect that ${}_NC_2+N$ selections could be obtained by combining N frequencies in our proposed stimulation method. When we compare our results with those of the previous studies, the proposed dual-frequency stimulation

Table 1 – Results of the online experiments.

Participants	Time period (s)	Correct/total	Accuracy (%)	ITR (bits/min)	Efficiency
P12	4	67/72	93.06	44.72	0.072
P13	6	73/84	86.90	25.72	0.044
P14	4	68/74	91.89	43.48	0.070
P15	6	79/96	82.29	22.99	0.039
P16	4	70/78	89.74	41.29	0.063
P17	5	80/98	81.63	27.14	0.050
P18	4	67/72	93.06	44.72	0.063
P19	6	74/86	86.05	25.19	0.058
P20	5	80/98	81.63	27.14	0.037
P21	5	74/86	86.05	30.23	0.056
Mean			87.23	33.26	0.056
S.D.			4.55	9.08	0.012

Table 2 – The stimulation frequencies used for each visual stimulus.

Command	Alternating frequencies		Expected SSVEP peak frequency (Hz)
	Pattern 1, F_1 (Hz)	Pattern 2, F_2 (Hz)	
0	3	3.33	6.33
1	3	3	6
2	3	3.75	6.75
3	3.33	3.33	6.66
4	3.75	3.75	7.5
5	3.33	3.75	7.08
6	4.285	4.285	8.57
7	3	4.285	7.285
8	3.75	4.285	8.035
9	5	5	10
BACKSPACE	3.33	4.285	7.545
CALL	6	6	12

method may not be the best solution to make the best use of available stimulation frequencies. However, our stimulation method was not only free from the attention shift problem but also could evoke a distinct SSVEP peak for each stimulus, thereby making it possible to reliably classify the users' intentions.

The ITR is a representative metric that has been frequently used to evaluate the performance of a BCI system. However, the use of ITR has recently been met with criticisms because a BCI system even having a classification accuracy lower than the chance level (e.g., 50% for 2-class classification) can have a high ITR (Quitadamo et al., 2012) and a high ITR can be achieved by simply increasing the number of detectable targets (Volosyak, 2011). Recently, Quitadamo et al. (2012) introduced a new BCI metric, called Efficiency, which can predict whether or not the developed BCI system can be used for practical communications. They provided some examples demonstrating that a high ITR could be attained even when the Efficiency suggests that the BCI system cannot be used for the practical communications (Efficiency=0). Therefore, the ITR and classification accuracy may be meaningful only when the Efficiency of the BCI system has a positive value. Our online BCI system not only reported positive Efficiency values in all participants, but also showed high average ITR (33.26 bits/min), suggesting that our BCI system adopting the modified pattern-reversal checkerboard stimuli can be successfully used in various real world scenarios.

Mukesh et al. introduced a dual-frequency stimulation method based on the pattern-reversal checkerboard stimulus (Mukesh et al., 2006). Although our dual-frequency stimulation method is also based on the checkerboard stimulus, the method of presenting visual stimuli and the resultant SSVEP responses were totally different from those of Mukesh et al.'s (2006) study. We mixed two different pattern stimuli flickering at independent frequencies, while Mukesh et al. controlled the alternation timing of the checkerboard pattern stimulus. The SSVEP response elicited by this stimulation method had a number of spectral peaks at F_1, F_2, F_1+F_2, $2F_2$, F_1+$2F_2$, $2F_1$+$2F_2$, $3F_2$, and so on. To take the full advantage from this stimulation method, a more complex classification algorithm should be adopted for accurate target identification. However, unfortunately, they did not attempt to classify SSVEP responses evoked by different visual stimuli, and only reported the relative amplitude values of the evoked SSVEP responses. Contrary to Mukesh et al.'s (2006) study, our results showed distinct SSVEP peaks at the sum of two stimulation frequencies, which would obviously simplify the classification processes as shown in this study. More importantly, we demonstrated the feasibility and practicality of the proposed dual-frequency stimulation method through both offline and online experiments, while Mukesh et al.'s study only showed the possibility of increasing the number of targets with limited stimulation frequencies via offline analyses.

Another dual-frequency stimulation method was introduced using half-field stimulation patterns (Yan et al., 2009). In this study, nine targets were simultaneously presented on a screen, each of which consisted of closely-spaced two rectangles each flickering at independent frequencies. The average ITR of 33.74 bits/min with classification accuracy of 75.94% was attained in the experiments performed with eight participants. However, two out of them had difficulty concentrating on the middle of two visual stimuli, and thereby they could not show acceptable ITR and accuracy (s6: 40% and 6.8 bits/min, s8: 51.1% and 12.1 bits/min). To overcome this limitation, we proposed a new dual-frequency stimulation method that used a single visual stimulus consisting of two different patterns. The accuracy averaged over ten participants (87.23%) was significantly higher than that obtained in Yan et al.'s (2009) study, but the average ITR (33.26 bits/min) was comparable with that in Yan et al.'s (2009) study. Notably, unlike the results of Yan et al.'s (2009) study, all ten participants showed high classification accuracy over at least 80%, demonstrating the reliability of our method.

Shyu et al. also proposed a dual-frequency stimulation method using light emitting diodes (LEDs) (Shyu et al., 2010). In this study, six targets were generated by combining four different flickering frequencies, each of which consisted of a pair of LEDs flickering at different frequencies. SSVEP spectral peaks induced by each pair of dual-frequency LEDs were mainly observed at two stimulation frequencies (F_1 and F_2)

and a symmetric harmonic frequency ($2F_2$–F_1). Similar to the results of our preliminary experiments conducted to demonstrate the limitation of the previous dual-frequency stimulation methods, the SSVEP peaks were fluctuated with respect to time, and one of them was sometimes attenuated or disappeared. As we mentioned above, unlike our proposed dual-frequency stimulation method, this type of stimulation method requires more complicated classification strategies because two large SSVEP responses at two main stimulation frequencies are needed for accurate target detection. More importantly, since Shyu et al. only showed the results of the SSVEP responses evoked by their dual-frequency stimulation method, further experiments are needed to confirm the practicality of their proposed method.

In addition to the use of dual-frequency stimulation approaches, other stimulation strategies have been introduced to increase the number of selections with a limited number of stimulation frequencies (Jia et al., 2011; Zhang et al., 2012). One of them was based on mixed coding of frequency and phase (Jia et al., 2011). Fifteen visual stimuli could be generated using three different flickering frequencies by modifying the phase information of each stimulus. This study showed a high average ITR (66.5 ± 18 bits/min) from ten subjects, but the ITR was estimated only from simulated online tests. As discussed in Pires et al.'s (2011) study, since the online accuracy and online ITR should be used to evaluate the performance of developed BCI systems, it is difficult to directly compare the resultant ITR value of the simulated tests with that of our online experimental study. In addition, the use of phase information not only increases the experimental set-up time to find a reference phase of each stimulus, but also requires more complicated classification method than the conventional frequency coding. Recently, Zhang et al. (2012) introduced a novel stimulation method based on multiple frequencies sequential coding (MFSC). Four different stimuli could be generated using two frequencies by changing the presentation sequences of two successive stimuli (F_1–F_1, F_2–F_1, F_1–F_2, and F_2–F_2). The average ITRs were 24.28 bits/min and 22.87 bits/min for the cycle periods of 3 s and 4 s, respectively. Theoretically, the MFSC method can obtain more targets than our proposed stimulation method with the same number of stimulation frequencies (N^2 for the MFSC method and ${}_NC_2+N$ for our method, when N stimulation frequencies are used). However, since the cycle period increases in proportion to the number of stimulation frequencies, longer detection time is needed for the increased number of frequencies, which may degrade the overall ITR value. The average ITR of 33.26 bits/min obtained from our online experiments was higher than that obtained from the offline experiments in Zhang et al.'s (2012) study.

The online BCI keypad system implemented in our study was a synchronous BCI system that produced one output within every pre-defined time period. In order to materialize an asynchronous BCI system, the idle state should also be considered. The use of a threshold value would be one of the promising methods for adding the idle state to our BCI system (Bakardjian et al., 2010; Cheng et al., 2002; Panicker et al., 2011; Volosyak, 2011). We can identify the time when the SSVEP responses exceed the pre-defined threshold value, at which time we can make the BCI system operate. To improve the practicality of our BCI system, we are planning to develop an asynchronous BCI system in our future study.

4. Experimental procedures

4.1. *Participants and experimental conditions*

Twenty-one participants (eighteen males and three females) aged between 21 and 27 years took part in the present study. Eleven out of them (all males) participated in the offline experiments and the other ten participants (seven males and three females) took part in the online experiments. Since our laboratory moved to another city far away from the original place during this research, we could not recruit participants who participated in the offline experiments again for the online experiments. Thus, we newly recruited ten participants for the online experiments. All participants had normal or corrected-to-normal vision and none of them had a previous history of neurological, psychiatric, or other severe disease known to adversely affect EEG recording. A comprehensive summary of the experimental procedures and protocols was explained to each participant before the experiment. They signed a consent form and received monetary reimbursement for their participation. The offline study was approved by the Institutional Review Board (IRB) committee of Yonsei University, and the online study was approved by the IRB committee of Hanyang University.

All visual stimuli used in this study were generated using Cogent 2000 and Cogent Graphics, a system developed for helping researchers design visual stimuli for psychophysical studies (http://www.vislab.ucl.ac.uk/cogent.php). A 17-in. LCD monitor configured with a resolution of 1024 × 768 pixels was used for the presentation of the stimuli, and the refresh rate of the monitor was set at 60 Hz. During the entire experiment, the participants were seated in a comfortable armchair facing the 17-in. LCD monitor in a dimly lit, soundproof room. They were asked to remain still and concentrate their attention on the presented visual stimuli. EEG signals were recorded using a multi-channel EEG acquisition system (WEEG-32, Laxtha Inc., Daejeon, Korea) from only one electrode (Oz) attached to the participants' scalps in the offline experiments. In the online experiments, three electrodes were mounted at O1, O2, and Oz positions. The EEG channels were referenced to an electrode behind the right mastoid, and a ground electrode was placed behind the left mastoid. The EEG signal was band-pass filtered with an anti-aliasing filter with cutoff frequencies of 0.7 Hz and 46 Hz and was sampled at 512 Hz. We used different electrode configurations for the offline and online experiments. Since the aim of the offline experiments was to confirm the feasibility of the proposed stimulation method, we used only one electrode attached at Oz position. On the other hand, in the online experiments, the size of the visual stimulus was reduced to display a number of targets simultaneously, and the time staring at one target was significantly decreased as compared to the offline experiments. It is obvious that SSVEP responses obtained in the online experiments would be less clear and discriminable than those in the offline experiments. Also, SSVEP responses evoked even by the same visual stimuli vary from one individual to another. Therefore, we used two additional electrodes (O1 and O2) to implement a reliable online BCI system. The detailed information for the size of the visual stimulus and the time period will be presented in the next sections.

4.2. *Visual stimulation*

In the offline experiments, the checkerboard pattern consisted of 8-by-8 arrayed squares and was 5 cm wide and 5 cm tall, resulting in a visual angle of approximately 3.58° by 3.58° (a viewing distance of 80 cm) (Fig. 3(c)). Ten checkerboard stimuli were generated by combining four different frequencies: 3, 3.33, 3.75, and 4.285 Hz, all of which were subharmonics of the monitor refresh rate (60 Hz). The first four checkerboard stimuli were generated by setting an identical flickering frequency for each ‘Pattern 1’ and ‘Pattern 2’ stimulus, i.e., 3–3 Hz, 3.33–3.33 Hz, 3.75–3.75 Hz, and 4.285–4.285 Hz. These four stimuli were identical to the traditional pattern-reversal checkerboard stimuli that elicit SSVEP peaks at 6 Hz, 6.66 Hz, 7.5 Hz, and 8.57 Hz, respectively. The other six stimuli were generated by combining two different frequencies, i.e., 3–3.33 Hz, 3–3.75 Hz, 3–4.285 Hz, 3.33–3.75 Hz, 3.33–4.285 Hz, and 3.75–4.285 Hz. We chose the four frequencies (3, 3.33, 3.75, and 4.285 Hz) in order to make the resultant SSVEP peaks appear at frequencies outside alpha and beta bands.

Fig. 9 shows an example of temporal sequences of a modified checkerboard pattern stimulus modulated with two different frequencies (6 Hz for ‘Pattern 1’ and 7.5 Hz for ‘Pattern 2’) and its SSVEP response. As shown in Fig. 9(c), the stimulus has four different patterns with respect to time. In the beginning of the stimulus presentation, ‘Pattern 1’ and ‘Pattern 2’ stimuli have different colors as shown in Fig. 9(a) and (b), and thus the dual-frequency stimulus mixed with ‘Pattern 1’ and ‘Pattern 2’ has an identical pattern to the conventional checkerboard pattern. Since the reversing frequencies of two patterns are different, ‘white-only’ and ‘black-only’ patterns can also be generated as shown in Fig. 9(c). Fig. 9(d) shows the SSVEP response of a participant evoked by the new dual-frequency checkerboard stimulus, where a distinct SSVEP peak was observed at the sum of two stimulation frequencies (13.5 Hz) rather than each modulation frequency.

For the online experiments, the size of each checkerboard pattern was reduced to 2.7 cm × 2.7 cm to display twelve visual stimuli simultaneously in a screen as shown in Fig. 8, and the distance between the adjacent buttons was set to 7 cm horizontally and 6.6 cm vertically (see the Supplementary movie file to check how each visual stimulus was presented). The visual angle of each stimulus was 1.93° by 1.93°, and that between the adjacent visual stimuli was 5.01° horizontally and 4.72° vertically. The identical twelve visual stimuli were also used in the mobile phone calling experiments.

4.3. *Experimental procedures*

To verify the feasibility and practicality of the proposed dual-frequency stimulation method, we conducted both online and offline experiments. In the offline experiments, the modified checkerboard pattern was placed on the center of a gray (RGB: 132, 132, 132) background and was presented to each participant for 30 s with an inter-stimulus interval of 30 s. In the online experiments, the 3-by-4 stimuli matrix

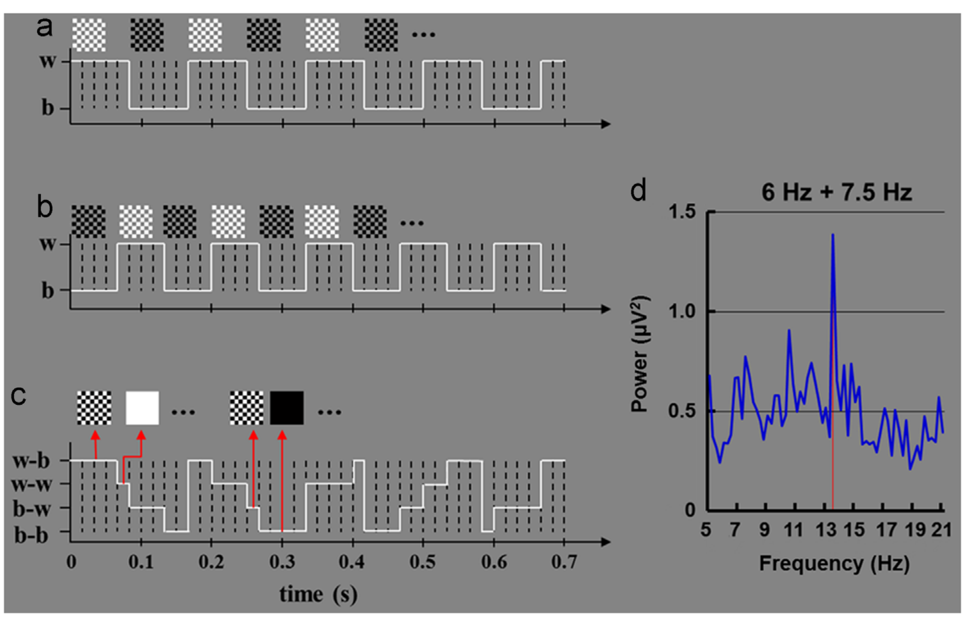
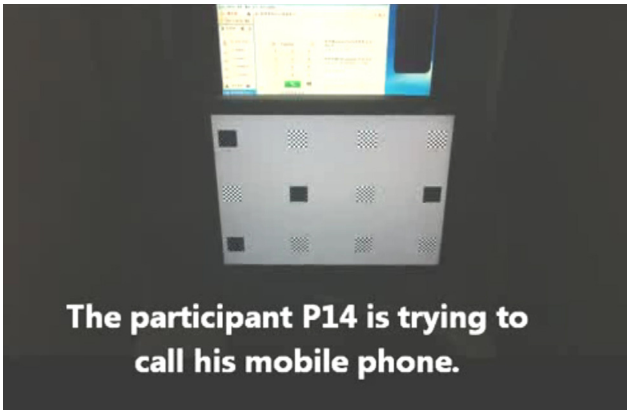


Fig. 9 – An example of temporal sequences of a modified checkerboard pattern stimulus modulated with two different frequencies and its SSVEP response: (a) sequence of a ‘Pattern 1’ stimulus with a flickering frequency of 6 Hz, (b) sequence of a ‘Pattern 2’ stimulus with a flickering frequency of 7.5 Hz, (c) sequence of the proposed dual-frequency stimulation, and (d) SSVEP response of a participant elicited by the proposed dual-frequency stimulation. The characters, ‘w’ and ‘b’, on the y-axis indicate ‘white’ and ‘black’, respectively.



Video S1 . A video clip is available online. Supplementary material related to this article can be found online at http://dx.doi.org/10.1016/j.brainres.2013.03.050.

shown in Fig. 8 was presented to the participants and we asked them to input ten sets of 5-digit numbers ('01 234', '56 789', '45 126', '89 501', '23 768', '89 673', '37 540', '41 237', '65 980', and '04 912'). Each number was presented equally five times. The results were presented to the participant using both visual and auditory feedbacks in real time (see the Supplementary movie file). In case of error, the participant could correct the misspelled number using the 'BACKSPACE' button. To delete a misspelled number, the participant should first attend to the 'BACKSPACE' button for a given time period, and then attend to the target button again for the next time period. Three different time periods (4, 5, and 6 s) were tested for each participant under the same experimental condition. To determine one of the three time periods for each participant, preliminary experiments were performed right before the main online experiments. In the preliminary experiments, the time period for one target detection was first set as 5 s, and the participant was asked to sequentially input all numbers (0–9) and 'BACKSPACE' once. If the target detection accuracy was higher than 70%, the time period was reduced by 1 s because it is generally accepted that the classification accuracy more than 70% can be used for practical communication (Perelmouter and Birbaumer, 2000). If the accuracy was less than 70%, the time period was increased by 1 s.

In the mobile phone calling experiments, the participants were asked to call their own mobile phones using the developed keypad system combined with the SKYPE^{TM}. When the participant correctly typed his/her own phone number (11-digit numbers in Korean mobile telephone service) and selected the 'CALL' button, the Skype^{TM} connected the participant's mobile phone. The movies of the online experiments can also be found in the attached Supplementary movie file, in which three participants (P14, P16 and P18) were typing designated numbers and one participant (P14) was making a phone call.

4.4. *EEG data analysis*

In the offline analysis, to observe the SSVEP responses, each of the recorded 30-s EEG epochs was divided into 4-s time windows with 50% overlap, resulting in 14 successive sub-epochs for each trial. The power spectrum of each sub-epoch was evaluated using fast Fourier transform (FFT) implemented in Matlab ver. 7.7 (MathWorks, Inc., USA). For each epoch, time–frequency spectral power maps as well as the average of 14 power spectra were computed. The SNRs of the SSVEP responses were also calculated for each dual-frequency checkerboard visual stimulus. Traditionally, the SNR has been defined as the ratio of spectral power at a stimulation frequency relative to the mean spectral power at its n adjacent frequencies (Vialatte et al., 2010; Zhu et al., 2010). In this study, $n=8$ adjacent frequencies were used for the calculation of the SNR values. Note that there has been no consensus in determining the number of adjacent frequencies, which varied from 6 to 16 in previous SSVEP studies (Wang et al., 2004, 2005; Vialatte et al., 2009).

In the online experiments, we also used FFT to detect SSVEP responses in real time. Since the frequency resolutions of the 12 candidate frequencies were not identical as presented in Table 2, we applied different window sizes for each candidate frequency using zero-padding. For example, when the time period for one target detection was 4 s, three different FFT windows (4, 6, 7 s) were used to calculate the spectral powers at the 12 candidate frequencies as accurately as possible. The window size of 4 s was used to evaluate SSVEP responses at 6, 6.75, 7 (for 7.08 Hz), 7.5, 8 (for 8.035 Hz), 10 and 12 Hz. The window size of 6 s (1024 zeros were added) was used to calculate SSVEP responses at 6.33 and 6.66 Hz, and that of 7 s (1536 zeros were added) was used to estimate spectral powers at 8.5714 (for 8.57 Hz), 7.2857 (for 7.285 Hz), and 7.5714 Hz (for 7.545 Hz). Likewise, appropriate numbers of zeros were also added to the recorded signals in the cases of the time periods of 5 and 6 s. For the classification, the arithmetic sums of SSVEP responses recorded from three electrodes (Oz, O1, and O2) were evaluated for the 12 candidate frequencies, and then a frequency with the largest SSVEP amplitude was selected among them (we did not use any specific classifiers). Finally, the BCI system produced the corresponding number of the chosen frequency per every time period.

To assess the online performance of the implemented mental keypad system, we evaluated the information transfer rate (ITR) as well as the classification accuracy. To calculate the ITR of the proposed BCI system, we used the ITR estimation method proposed by Wolpaw et al. (1998), of which the assumptions coincided best with our developed BCI system (Kronegg et al., 2005). When estimating the classification accuracy, if the 'BACKSPACE' button was intentionally selected by the participant to delete an unwanted number, we considered that the participant's intention was classified correctly. On the other hand, the 'BACKSPACE' button could be wrongly selected by the mental keypad system. This case was regarded as incorrect classification. As all online experiments were conducted in the 'copy spelling' mode, the developed BCI system could accurately recognize whether or not the 'BACKSPACE' button was intentionally selected by the participant.

We also evaluated a recently introduced index, called Efficiency, to confirm whether or not the developed mental keypad system can be used for a practical communication (Quitadamo et al., 2012). According to Quitadamo et al.'s study, a BCI system can be practically used for communications only when the Efficiency has a positive value. When the Efficiency of a system is zero, the system cannot be used for a practical communication regardless of its ITR and classification accuracy (Quitadamo et al., 2012).

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