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An amplitude-modulated visual stimulation for reducing eye fatigue in SSVEP-based brain–computer interfaces

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HIGHLIGHTS

- Amplitude-modulated visual stimuli elicit integer and non-integer harmonic steady-state visual evoked potentials (SSVEPs) including both low- and high-frequency bands.
- Amplitude-modulated visual stimuli cause low eye fatigue in a manner similar to a high-frequency stimuli.
- The accuracy of the SSVEP response to an amplitude-modulated stimulus (AM-SSVEP) was equivalent to that of the low-frequency SSVEP.

ABSTRACT

Objective: A high-frequency steady-state visual evoked potential (SSVEP) has been suggested for the reduction of eye fatigue for SSVEP-based brain–computer interfaces (BCIs). However, the poor performance of high-frequency SSVEP requires a novel stimulus of better performance even with low eye fatigue. As an alternative to the high-frequency SSVEP, we explore the SSVEP response to an amplitude-modulated stimulus (AM-SSVEP) to verify its availability for brain–computer interfaces (BCIs).
Methods: An amplitude-modulated stimulus was generated as the product of two sine waves at a carrier frequency (f_c) and a modulating frequency (f_m). The carrier frequency was higher than 40 Hz to reduce eye fatigue, and the modulating frequency ranged around the α-band (9–12 Hz) to utilize low-frequency harmonic information. Four targets were used in combinations of three different modulating frequencies and two different carrier frequencies in the offline experiment, and two additional targets were added with one additional modulating and one carrier frequency in online experiments.
Results: In the AM-SSVEP spectra, seven harmonic components were identified at $2f_c$, $2f_m$, $f_c \pm f_m$, $f_c \pm 3f_m$, and $2f_c - 4f_m$. Using an optimized combination of the harmonic frequencies, online experiments demonstrated that the accuracy of the AM-SSVEP was equivalent to that of the low-frequency SSVEP. Furthermore, subject evaluation indicated that an AM stimulus caused lower eye fatigue and less sensing of flickering than a low-frequency stimulus, in a manner similar to a high-frequency stimulus.
Conclusions: The actual stimulus frequencies of AM-SSVEPs are in the high-frequency band, resulting in reduced eye fatigue. Furthermore, AM-SSVEPs can utilize both fundamental stimulus frequencies and non-integer harmonic frequencies including low frequencies for SSVEP recognition. The feasibility of AM-SSVEP with high BCI performance and low eye fatigue was confirmed through offline and online experiments.
Significance: AM-SSVEPs combine the advantages of both low- and high-frequency SSVEPs – high power and low eye fatigue, respectively. AM-SSVEP-based BCI systems exploit these advantages, making them promising for application in practical BCI systems.

1. Introduction

A brain–computer interface (BCI) system decodes a user's intent to facilitate communication between the user and the environment

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using his/her own brain activity. In terms of the measurement methods for brain activity, BCIs can be divided into invasive and noninvasive BCIs (Lebedev and Nicolelis, 2006). In particular, noninvasive BCIs are primarily based on scalp electroencephalograms (EEGs) due to their low-cost and noninvasive characteristics. EEG-based BCI systems employ many electrophysiological responses such as sensorimotor rhythms (SMRs), P300, steady-state visual evoked potentials (SSVEPs), slow cortical potentials (SCPs) (Graimann et al., 2010), or combined responses (Pfurtscheller et al., 2010).

Among the signals mentioned above, SSVEP-based BCI systems have recently attracted growing interest because they require less training, offer a higher information transfer rate (ITR), and usually involve a simple system configuration with less electrodes than other EEG-based BCI systems (Graimann et al., 2010; Pasqualotto et al., 2012). The SSVEP is evoked by a visual stimulus flickering at a constant frequency (Vialatte et al., 2010), which peaks at the flickering frequency, its harmonic, and its sub-harmonic frequencies ranging from 1 to 100 Hz (Herrmann and Human, 2001). The broad frequency range – low- and medium-frequency bands (<30 Hz) and high-frequency bands above 30 Hz – facilitates an increase in the number of targets through the addition of visual stimuli with different flickering frequencies. The target that a user attends can be deduced as the one with the same peak frequencies (fundamental or its harmonic frequencies) as the user's SSVEP. SSVEP-based BCI applications have been proposed for communication with the environment, such as an SSVEP speller (Cecotti, 2010), control of a hospital bed nursing system (Shyu et al., 2013), or hand orthosis for tetraplegic patients (Ortner et al., 2011).

SSVEPs in the low-frequency band have a larger amplitude response than those in the medium- and high-frequency ranges; in particular, SSVEPs at $\sim$15 Hz exhibit the largest amplitude (Wang et al., 2006). Therefore, many SSVEP-BCI systems employ the low-frequency band at stimulation frequencies between 8 and 15 Hz (Ortner et al., 2011; Wang et al., 2011; Wilson and Palaniappan, 2011). However, low-frequency flickering stimuli are annoying (Fang-Cheng et al., 2012) and can cause epileptic seizures. In particular, frequencies within the range of 15–20 Hz pose the greatest risk of seizures. Other frequencies also pose a potential risk of photosensitive epilepsy; however, the percentage of patients with photosensitive epilepsy decreases as the flickering frequency increases (Wilkins et al., 2010). Several recent studies have proposed higher-frequency SSVEP-based BCIs as an alternative to alleviate this risk and visual fatigue (Molina and Mihajlovic, 2010; Muller et al., 2011; Volosyak et al., 2011). However, more people were unable to complete BCI tasks with high-frequency SSVEPs because of their poor performance than those with low-frequency SSVEPs: 84 subjects succeeded in using low-frequency SSVEP-based BCIs, whereas only 56 subjects succeeded with high-frequency SSVEP-based BCIs. Furthermore, high-frequency SSVEPs resulted in significantly lower accuracy and ITR (Volosyak et al., 2011). Even within a high-frequency band, the detection accuracy decreased by 8.6% as the stimulation frequency increased from 30 to 45 Hz (Molina and Mihajlovic, 2010). Other efforts to reduce visual fatigue created a half-field stimulation pattern without direct attention to a stimulus (Zheng et al., 2009) or a high duty-cycle flicker with an α-band flashing frequency (Lee et al., 2011). However, these stimuli also flicker at a low frequency; thus, visual discomfort (annoyance and fatigue) and the risk of seizure caused by a low-frequency flicker cannot be completely eliminated. Therefore, a new approach is required to achieve both sufficiently high BCI performance as well as low eye fatigue and low risk of epileptic seizure.

Amplitude modulation (AM) techniques have been widely used in electronic communication, mostly for radio carrier waves. An amplitude-modulated signal is presented as the amplitude variation of a carrier signal in accordance with the amplitude and frequency variations of the modulating signal. In particular, double-sideband suppressed carrier (DSB) signals suppress the carrier to reduce the consumption of power. While a general amplitude modulation signal simultaneously contains spectral peaks at the carrier frequency and in the upper and lower sidebands, a DSB signal contains peaks only at the frequencies in the sidebands (Frenzel, 2007). If the brightness of a visual stimulus varies as a DSB-AM sine wave, the maximum and minimum brightness of a stimulus flickering at the carrier frequency will change sinusoidally at the modulating frequency. With the carrier frequency in the high-frequency band and the modulating frequency in the low-frequency band, a DSB-AM stimulus can convey high- and low-frequency information simultaneously. If a brain responds to both types of information, the SSVEP response to an amplitude-modulated stimulus (AM-SSVEP) would contain peaks in a wide frequency range from low to high frequencies. Then, the AM stimulus would encompass the advantages of both low-frequency SSVEPs, such as high amplitude and low BCI illiteracy, and high-frequency SSVEPs, such as less eye fatigue and a decreased risk of epileptic seizure.

Several research groups have introduced various types of combined frequency stimulation methods analogous to AM stimulus. However, harmonic components elicited by multi-frequency stimuli were not analyzed and utilized for BCI systems. Moreover, the eye fatigue problem caused by low-frequency flickering stimuli was not considered. Bieger and Molina (2010) suggested multi-frequency stimulation generated by the sum or average of multiple pure frequency stimulations. These authors assumed that such stimulation would elicit SSVEPs at linear combinations of the stimulus frequencies but did not demonstrate their theory. Teng et al. (2010) investigated EEG responses to multi-frequency sine stimulation at two or three frequencies. However, they only examined which stimulus frequency was dominant in a SSVEP according to different frequency combinations without BCI application. The analysis on the resulting SSVEP peaks was limited to the main stimulus frequencies and not the harmonic frequencies, unlike the present study. In addition, the stimulus frequencies tested were below 20 Hz, which is sufficient to cause considerable eye fatigue. Lopez-Gordo et al. (2010) used AM stimuli similar to those used in this study; however, all of the stimuli had the same carrier and modulation frequencies of 16 and 1 Hz, respectively; the only difference was the phase shift. The acquired EEG signals were AM demodulated before a SSVEP recognition step. Therefore, the visual response evoked by AM visual stimulation was not considered in the SSVEP analysis, and advantages obtained from using the multi-frequency stimulation could not be expected in their approach. Shyu et al. (2010) reported that a dual-frequency SSVEP can be evoked through a stimulus consisting of two LEDs flickering at different frequencies. The approach has the advantage of generating more stimuli with the limited number of available flickering frequencies using the combination of the frequencies. When a subject was exposed to the stimulus flickering at both f_1 and f_2, the symmetric harmonic frequencies (i.e., peak frequencies of dual-frequency SSVEP) were f_1, f_2, $2f_1 - f_2$, and $2f_2 - f_1$. However, their findings were not applied to BCI systems.

In this study, we investigated the characteristics of the SSVEP response to an AM stimulus and validated its usability and the reduction in eye fatigue in SSVEP-based BCI systems. We employed multi-frequency AM stimulation with different combinations of carrier and modulation frequencies. Each combination elicited different harmonic frequencies from the low- to high-frequency range; we employed the harmonic information in SSVEP recognition to improve BCI performance. The visual stimulus was generated according to the DSB signal with a set of high carrier frequencies exceeding 40 Hz and low modulating frequencies of