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Frequency-modulated steady-state visual evoked potentials: A new stimulation method for brain–computer interfaces

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HIGHLIGHTS

- We were able to evoke SSVEPs with a frequency-modulated flickering LED.
- FM SSVEP's amplitude does not differ from sinusoidally evoked SSVEP amplitude.
- Subjective flicker perceptibility decreases with increasing carrier frequency.

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ABSTRACT

Background: Steady-state visual evoked potentials (SSVEPs) are widely used for brain–computer interfaces. However, users experience fatigue due to exposure to flickering stimuli. High-frequency stimulation has been proposed to reduce this problem. We adapt frequency-modulated (FM) stimulation from the auditory domain, where it is commonly used to evoke steady-state responses, and compare the EEG as well as behavioral flicker perceptibility ratings.
New method: We evoke SSVEPs with a green light-emitting diode (LED) driven by FM signals.
Results: FM-SSVEPs with different carrier and modulation frequencies can reliably be evoked with spectral peaks at the lower FM sideband. Subjective perceptibility ratings decrease with increasing FM carrier frequencies, while the peak amplitude and signal-to-noise ratio (SNR) remain the same.
Comparison with existing method: There are neither amplitude nor SNR differences between SSVEPs evoked rectangularly, sinusoidally or via FM. Perceptibility ratings were lower for FM-SSVEPs with carrier frequencies of 20 Hz and above than for sinusoidally evoked SSVEPs.
Conclusions: FM-SSVEPs seem to be beneficial for BCI usage. Reduced flicker perceptibility in FM-SSVEPs suggests reduced fatigue, which leads to an enhanced user experience and performance.

1. Introduction

Repetitive presentation of a stimulus leads to a synchronization of neural firing in sensory cortex neurons at the respective stimulus-presentation frequency. For different sensory modalities, this phenomenon can be measured as distinct oscillations in the electroencephalogram (EEG). In the auditory domain such oscillations are known as so called auditory steady-state responses (ASSRs; Ross et al., 2000) and in the visual domain they are known as steady-state visual evoked potentials (SSVEPs; Silberstein, 1995). Steady state responses can be evoked with a wide range of stimulation frequencies in both domains, but especially strong responses to particular resonance frequencies (Herrmann, 2001; Zaehle et al., 2010) as well as to attended stimuli (Müller et al., 1998; Ross et al., 2004) have been shown. SSVEPs will be frequency- and phase-locked to the stimulus (Regan, 1989) and can be evoked using many different flickering stimuli (e.g. Halbleib et al., 2012; Martens & Hübner, 2013). Due to their high signal-to-noise ratio (SNR) in the frequency domain, SSVEPs can be reliably recorded within a few

Abbreviations: EEG, electroencephalogram; SSVEP, steady-state visual evoked potential; BCI, brain-–computer interface; LED, light-emitting diode; FM, frequency-modulation; AM, amplitude-modulation; SNR, signal-to-noise ratio; ITR, information transfer rate; FFT, fast Fourier transform; ERP, event-related potential; IAF, individual alpha frequency; ASSR, auditory steady-state response; CFF, critical flicker fusion frequency; FDR, false discovery rate.

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seconds of stimulation. Therefore they are very promising stimuli for brain–computer-interfaces (BCIs) and many studies have reported the successful integration of flickering stimuli into their BCI systems (see Vialatte et al., 2010 for a review). Presenting stimuli on a computer screen limits the number of available stimulation frequencies because they depend on the respective refresh-rate of the screen used, but one can overcome such limitations with the use of light emitting diodes (LEDs) as stimuli. Moreover LED stimulation devices can easily and cheaply get specifically designed for their respective task without any spatial limitations. Hwang et al. (2012) for example, built a keyboard out of thirty individually flickering LEDs that was successfully implemented as a mental spelling system with a high information transfer rate (ITR), which is a commonly used performance measure for BCI systems. The high ITR in combination with the 30 simultaneous commands shows the progress of SSVEP-BCI system during the last years, since Vialatte et al. (2010) reviewed SSVEP-based systems with 'only' up to 13 simultaneous commands (Cheng et al., 2002).

While stimulation parameters such as frequency, stimulus proximity and number of stimuli were tested and analyzed in detail (e.g. Ng et al., 2012) because they influence SSVEP power and SNR which are crucial factors when planning BCI systems, we believe, that potential BCI systems, especially for clinical application, should also further integrate the users perspective. On the one hand, more simultaneous commands broaden the range of possible applications, on the other hand, BCI users might be overwhelmed by the attentional demand of many independently flickering stimuli and experience fatigue during the stimulation process. Increasing levels of fatigue after SSVEP stimulation have been shown with subjective and physiological measures (Cao et al., 2014). One way to cope with such a problem might be to reduce the perceptibility of each individual stimulus so that it is easier for the user to ignore certain stimuli which are not important for a certain command. Low frequency flickering stimuli have been shown to be more perceptible and more annoying than faster flickering stimuli (Lin et al., 2012). This is consistent with the fact that subjects perceive a constant dim light instead of a flickering LED when the stimulation rate exerts a critical flicker fusion frequency (CFF; e.g. 30 Hz in Herrmann, 2001), which depends on parameters like stimulus brightness, color, size, its position in the visual field and others (Levin et al., 2011). SSVEPs can still be recorded at higher frequencies, but with increasing stimulation frequency their respective power decreases (Kuś et al., 2013). Consequently, BCI accuracy drops with increasing flicker frequency (Volosyak et al., 2011).

Recently, Chang et al. (2014) proposed amplitude-modulated (AM) stimulation for the visual domain in order to reduce eye fatigue and the risk of epileptic seizures. Their study revealed similar BCI performance of low constant-frequency SSVEPs and higher frequency AM-SSVEPs while subjects reported less eye fatigue and a reduced sense of flickering with AM stimulation. This suggests that also frequency-modulated (FM) stimulation, which is frequently used in ASSR-research (Picton et al., 2003), might be another compromise between stimulation based on high carrier frequencies and recording low frequency spectra, because FM signals have sidebands at the distance of modulation and carrier frequency in their spectral decomposition. In contrast to AM signals, FM signals have a constant envelope, i.e. the amplitude of the flicker stays constant. A comparison of AM and FM signals and spectra is shown in Fig. 1. This suggests that also FM stimulation is a feasible protocol for BCI and other SSVEP studies. Apart from one study that used frequency shift keying for modulating the stimulation signal (Kimura et al., 2013), which works differently than the FM approach we introduce in Section 2.2, we are not aware of any study that evoked SSVEPs with FM signals to date.

The goal of our study therefore was to test whether we would be able to evoke SSVEPs at certain sidebands with an LED that is driven with FM signals and to analyze behavioral subjective reports on the perceptibility of different carrier/modulation frequency pairs in comparison to a constant-frequency stimulation.

2. Materials and methods

2.1. Participants

Twelve students (9 female) from the University of Oldenburg with a mean age of 23.1 years (range from 19 to 25), were paid for participating in the EEG session of this study. Thirteen additional students (9 female) with a mean age of 25.7 years (range from 24 to 30), voluntarily reported the flicker perceptibility of the different stimulation frequencies in a short experimental session without EEG recording. All participants had normal or corrected-to-normal vision and were informed about the risk of seizures in epileptics due to flicker stimulation. They reported not to have ever suffered from epilepsy and gave their written informed consent. The study was approved by the local ethics committee.

2.2. Stimuli

A green LED (diameter 0.5 cm) was mounted in a distance of 1 m from the participants' nasion, thereby covering 0.286° of the visual field. The LED was mounted on a tripod and in front of a black wall. A digital-to-analog converter (NI USB-6229 BNC, National Instruments, Austin, Texas, USA) was used to drive the LED at different frequencies, namely at 10 Hz (sinusoidally and rectangularly) and at nine additional modulated frequencies. The modulated signals were generated with MATLAB (The MathWorks Inc., Natick, MA, USA) using the following formula:

$$\text{signal} = A + FV * \sin(2 * \text{pi} * Fc * t + (M * \sin(2 * \text{pi} * Fm * t))).$$

A is the DC bias (1.9 V) at which the LED was driven. FV is the flicker voltage span (0.04 V), Fc represents the carrier frequencies (20, 30, 40, 50, 60, 70, 80, 90, 100 Hz) and Fm the corresponding modulation frequencies (10, 20, 30, 40, 50, 60, 70, 80, 90 Hz). M is the modulation index (0.5) and t is the time vector. The parenthesized values were used for the experiment. In order to make sure that the LED flickered sinusoidally between a light glimmer and its maximal possible brightness, we tested different stimulation parameters and analyzed the flicker using a photodiode connected to our EEG amplifier which lead to the given average and span values as well as to the modulation Index of 0.5 and a sampling rate of 10 kHz. The carrier/modulation frequency pairs all had a difference of 10 Hz which equals the lower sideband of the modulated signal in its frequency domain. Refer to Fig. 1A, B and D to see the types of stimulation we used to evoke SSVEPs in this study. For illustrative purposes the amplitude values used for this figure deviate from the experimental values.

2.3. Data acquisition and experimental procedure

The experiment was carried out in an electrically shielded, dark recording chamber, using Brain Vision Recorder (Brain Products GmbH, Gilching, Germany) for EEG acquisition. Sampling rate was set to 500 Hz while the amplifiers frequency passband ranged from 0.1 Hz to 250 Hz. Thirty-two electrodes, including one vertical EOG electrode below the right eye, were placed on size-appropriate EEG caps according to the international 10–20 system. One further electrode was placed on the nose as online reference. A two-minute baseline recording was done first which gave the subjects a chance to adapt to the darkness. After that, we started with