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On diversity within operators' EEG responses to LED-produced alternate stimulus in SSVEP BCI

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Abstract. This work is an attempt to identify causes of the widely observed fact that performance of Brain-Computer Interface systems based on Steady-State Visual Evoked Potentials varies between different users. The efficient LED-produced alternate stimulus systems are taken into account. The effect of stimulus color and flickering frequency on measured SSVEP response at first and second harmonics is investigated for 10 women and 11 men. The experimental setup is described, measurement procedure, signal processing and analysis algorithms are outlined. The results are presented and discussed. One of the early conclusions drawn from this extensive research is that the promising strategy of SSVEP-based BCI system optimization for best performance can be through stimulus adjustment to each individual user.

Key words: SSVEP brain-computer interface, SSVEP diversity, alternate half-field visual stimulation, information transfer rate, signal to background ratio.

1. Introduction

Electroencephalography (EEG)-based brain-computer interfaces (BCIs) are considered attractive devices that facilitate human communication with machines without making use of peripheral nerves and muscles. They are especially useful for people that are not able to make any move, e.g. subjects paralyzed after serious injuries, or professionals whose limbs are preoccupied with some demanding activities, e.g. fighter pilots. BCIs have a great potential to bring independence to severely disabled people. It is known that different mental states intentionally invoked by a user can make the brain produce characteristic EEG components. For example, thinking about a feet movement may increase electrical activity of neurons in the brain's motor cortex. An electrode placed on the scull over this region can be used to measure the increased electrical signal. If the amplitude of this EEG signal component is larger than a predefined threshold, a message of detection is generated by the interface. Such a message can have a predefined meaning, e.g. "activate the email client on the computer" or "switch on a news channel on a TV".

In general, the presence of EEG components induced by user's intention can be detected using pattern recognition techniques and then converted into predefined commands understandable to the computer. The main advantage of using the EEG is in noninvasiveness and relatively low price. On the other hand, the EEG signals are very weak and the message-carrying useful components are buried in noise. Special means have to be undertaken to increase the signal-to-noise ratio and thus increase the speed of information transfer and reduce the number of errors in commands recognition. There are several types of different components of the EEG that are used to control the interface, such as P300 potentials [1–2], event-related synchronization-desynchronization (ERS/ERD) [3] or visual evoked potentials (VEP) [4]. It is believed that BCI systems that utilize steady-state visual evoked potentials (SSVEP) provide highest speed of data transfer and require short time of training, as compared to BCI systems that are based on other electric signal components produced by the brain.

Despite the tremendous progress observed over the last two decades in the area of brain-computer interfacing, the performance of prototype BCI systems constructed by different research teams worldwide still varies significantly between their users. This fact opens important research avenues, aimed at identifying the causes of the BCI performance variation and, ultimately, at defining ways of the differences reduction by proper design, e.g. through system components adaptation to subject characteristics. The problem applies to all types of BCI; in the present work, the steady-state visual evoked potential with light-emitting-diode (LED) display used as the stimulus light source.

In the SSVEP-based BCI, the user is simultaneously presented a number of periodically flickering light sources such that each of them has a distinctive property, e.g. frequency or phase. Typically, these light sources are arranged in a virtual array of flickering shapes on a computer monitor or they are built using light emitting diodes (LEDs) excited with a periodic current to produce a modulated light [5]. Each of these sources is called a target. Suppose each target is attributed a distinct frequency. When the user focuses her/his attention on a specific target, an involuntary SSVEP response of the user visual system is produced which is an EEG periodic component at the target frequency and/or its harmonics. The SSVEP signals can be measured in the range from 1 to 100 Hz. Increasing the number of different-frequency targets leads to higher number of possible commands, but can decrease the speed of the interface and the classification accuracy. Therefore, efforts have been undertaken to increase the strength of

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the SSVEP and the signal to noise-radio by proper design of the stimulus.

An alternate half-field stimulation method combined with differential EEG signal measurement over the visual cortex (between left and occipital side of scalp) was proposed in [6] to increase the SSVEP signal to noise ratio. It indeed outperformed the best results reported before for conventional SSVEP BCI. Although the shortest times of command detection using an alternate-stimulus virtual keyboard were in the order of 1.5 second, still substantial differences in the interface performance are observed – caused by individual factors attributed to the BCI user. Initial results have shown a substantial diversity in the response of different users to the same stimulus [7–8]. This diversity not only originates in anatomical differences that can be accounted for by lead selection [9] or multi-channel signal measurement and processing [10]. There are also effects, which can be related to the properties of the stimulus – its frequency and color are considered main factors. Moreover, phenomena are observed that are lacking of a rigorous psychophysiological model, such as VEP responses at harmonics of the stimulus frequency. Behavioral investigation of the diversity effect, through a quantitative study involving a larger group of users, was then carried out. First results of this study are presented in this paper.

2. Materials and methods

2.1. Experimental setup. The experiments were carried out in a normal office room at the Institute of Electronics, Technical University of Lodz. The layout plan and photograph of the measurement stand are shown respectively in Figs. 1a and 1b. Light conditions during all experiments were the same: an office window was curtained with a light impermeable material blind and a room light was switched on. Subjects sat in a comfortable, ergonomic chair approximately 50 cm from the front of a visual stimulator (described in next section).

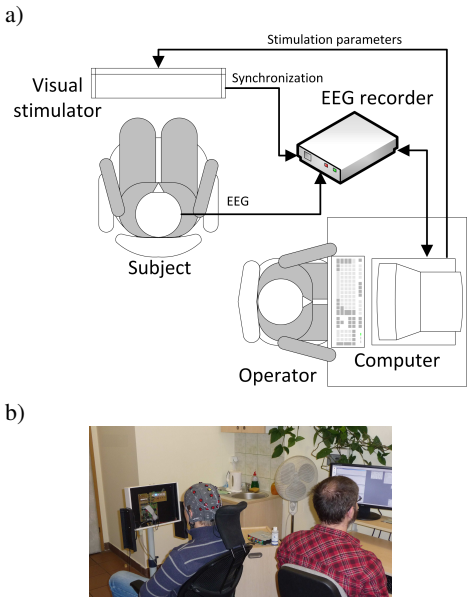


Fig. 1. Layout plan (a) and photograph (b) of the measurement stand

2.2. Visual stimulator. A universal, computer driven LED stimulator was used in the experiment. Each stimulation symbol consisted of three LEDs: two stimulation lights, with a diameter of 5 mm, positioned on the lower right and lower left quarter of the visual field of each eye retina and one fixation light, with a diameter of 3 mm, placed in the centre of visual field (Figs. 2a and 2b). Stimulation lights flashed with the same frequency, alternatively in phase [6–8].

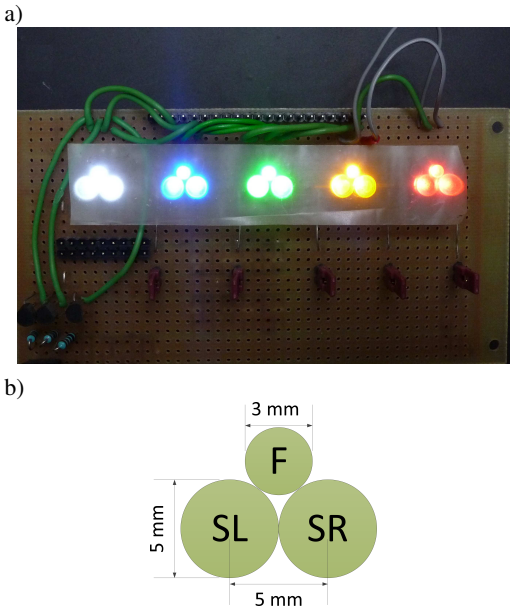


Fig. 2. A view of stimulator targets (a); a view of stimulating lights (SL, SR) and a fixation light (F) on the screen of stimulator (b)

A fixation light is used for two purposes: the subject is expected to concentrate his/her sight on it; additionally it provides feedback information about amplitudes of corresponding SSVEPs detected in the subject EEG signal (ratio of the SSVEP signal power to the power of background EEG activity).

The visual stimulator had five sets of LEDs forming stimulation symbols in five different colors: white, blue, green, yellow and red. Each set had stimulation and fixation LEDs of the same color. The luminous intensity of each LED used was approximately 1000 mcd.

2.3. EEG recording. The EEG data were recorded from the surface of the scalp via sixteen active Ag/AgCl EEG electrodes (Fig. 3). Seven electrodes were placed over the primary visual cortex (positions PO7, PO3, O1, OZ, O2, PO4 and PO8) and nine electrodes were evenly distributed over the remaining cerebral cortex (positions P3, PZ, P4, C3, CZ, C4, F3, FZ and F4). A ground electrode was placed on CPZ position. A reference electrode was placed on right ear lobe (position A2). Standard abrasive electrolytic electrode gel was applied between the electrodes and the skin to bring impedances below 5 kΩ. The impedances were controlled during the subject preparation phase.

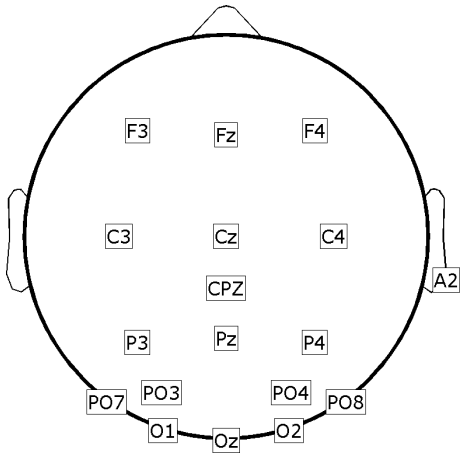


Fig. 3. A set of electrodes used in experiment

Equipment from g.tec (Guger Technologies, Graz, Austria) was used for EEG measurements: g.USBamp biosignal amplifier, g.GAMMAbox active electrode driver and g.GAMMAcap with pre-assembled electrodes. The EEG signals were band-pass filtered between 2.0–60.0 Hz with a notch filter for 50 Hz power line frequency suppression, and then amplified and sampled at 600 Hz.

EEG signals were recorded using a home-made software package – BioStudio [11] which was able to drive visual stimulator and process measured signals in order to compute biofeedback information presented to the subject via modulation of the fixation light intensity.

2.4. Subjects. Twenty one healthy subjects (ten women and eleven men, age range 16–33 years, with the average of 22.2 years and a standard deviation of 3.4 years) participated in the study. Only four subjects used any kind of BCI system previously. None of the subjects had neurological or visual disorders (glasses or contact lenses were worn when appropriate). Subjects did not receive any financial reward for participating in the study.

Before the formal participation in the experiments, the subjects filled in the questionnaire containing contact details, information about diet, mood and factors that may affect their mental and physical conditions (the length and quality of sleep, time since last meal, etc.). This information is to be used in our future studies.

2.5. Experimental paradigm. Each subject was instructed to focus his/her gaze on a fixation LED and flickering lights below it to produce SSVEPs. Each measurement lasted for several minutes and consisted of five stimulus sequences (one sequence for each color, only one stimulation symbol switched on at a time) – Fig. 4. The first sequence began a few seconds after starting of the measurement (time required for stabilization of electrode-skin connection impedance and possible adjustments of subjects' position on the chair to reduce the EMG signals). Stimulation frequencies were chosen to match the discrete Fourier transform frequencies used in the subsequent analysis (in order to minimize spectral leakage). For given frequency analysis window length of 256 samples and sampling frequency equal to 200 Hz (down-sampled during preprocessing procedure) stimulation frequencies must fulfill the equation:

$$f_{stim} = \frac{200}{256} \cdot k = \frac{k}{1.28} \text{ [Hz]}. \tag{1}$$

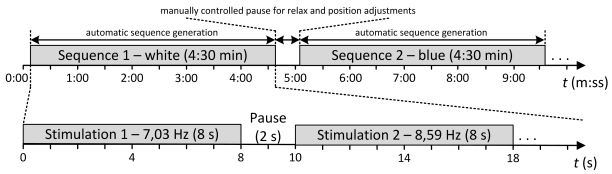


Fig. 4. Timing of each trial

Each sequence contains 27 different stimulation frequencies ($k = \langle 9,\ 11,\ 13,\ ...,\ 61 \rangle$), which results in stimulation frequency in the range of about 7–47 Hz. Such wide range of stimulation frequencies is the result of our previous research and observations.

A target stimulation event lasted eight seconds, followed by a 2-second pause before the next stimulation. Additionally a brief manually invoked pause followed each sequence (several up to tens of seconds, Fig. 4). It was intended for subject relax and position adjustments (EEG signal was still being recorded). Binary signal from visual stimulator indicating stimulation state (on/off) was recorded together with the subject EEG signal from all sixteen channels.

2.6. Data analysis. The recorded signals were analyzed in Matlab environment. For the analysis, only seven signals from electrodes placed over the primary visual cortex were used (positions PO7, PO3, O1, OZ, O2, PO4 and PO8). Remaining signals are planned to be used in our future studies. Preprocessing included:

- down-sampling of the signal to the frequency of 200 Hz using the standard Matlab procedure,
- comb filtering [12] in order to improve the quality of the signal: first, a filter with a length of 256 samples, then a filter with a length of 512 samples,
- computation of common-mode voltage (CMV) as an arithmetic mean of all analyzed signals,
- computation of 28 differential signals being all combinations of signal pairs from the set of 8 signals (7 electrode signals and computed CMV).

The set of 28 differential signals was subsequently divided into fragments starting with each stimulation event and lasting 12,5 seconds (2500 sample). Length of data segments roughly covered the duration of target stimulation event (8 seconds) and the signal delay introduced by the comb filters. This gives a total of 135 signal fragments for each signal (27 stimulation frequencies for each of the 5 colors). Then each fragment was analyzed through computation of:

- signal spectrogram (STFT) with a 256-samples-wide rectangular window and 50% overlap,
- signal power spectral density (PSD) – absolute value of each spectrogram was squared and averaged with two previous results,

- signal-to-background ratio (SBR) value for each discrete Fourier frequency:

$$SBR(f) = \frac{2N \cdot PSD(f)}{\sum_{i=1}^{N} (PSD(f - i \cdot \Delta f) + PSD(f + i \cdot \Delta f)} \quad (2)$$

where $\Delta f = {}^{1}/_{1.28}$ [Hz] and $N = 10$.

For each signal fragment, maximum SBR value for corresponding stimulation frequency (first SSVEP harmonic) and twice of that frequency (second SSVEP harmonic) was selected.

3. Results

In the first step, SSVEP response in channel O1-O2 was analyzed only, as it was done in our prototype BCI system [6–7]. Maximum SBR values for each stimulation frequency were averaged for all colors and all subjects, independently for fundamental and second harmonic SSVEP. This analysis showed dependence of mean SBR value on stimulation frequency. Computed characteristics are shown in Figs. 5 and 6.

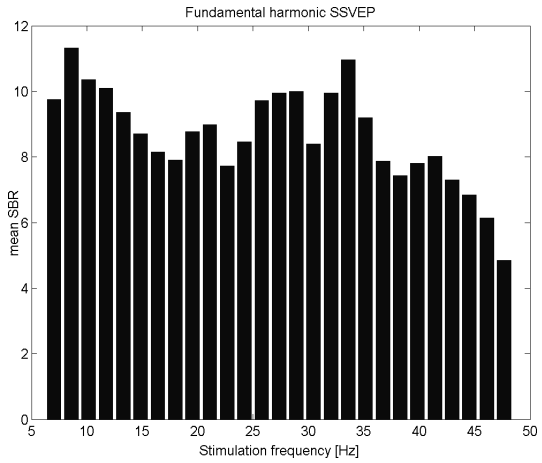


Fig. 5. Averaged SBR characteristic for fundamental harmonic SSVEP

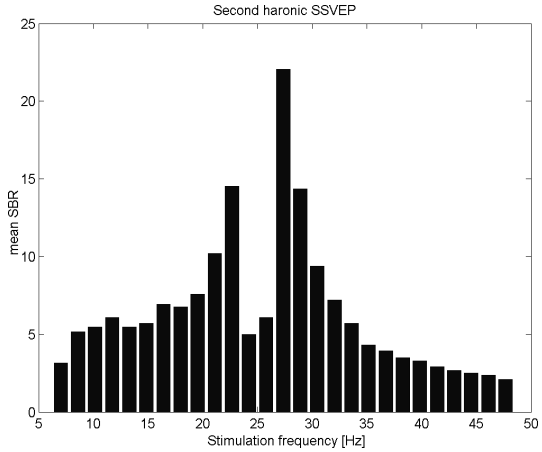


Fig. 6. Averaged SBR characteristic for second harmonic SSVEP

The SBR frequency response for fundamental harmonic SSVEP is approximately flat (standard deviation does not exceed 1.5) what means, that stimulation frequency has weak influence on mean SBR of first harmonic SSVEP. However, for second harmonic, SSVEP of mean SBR strongly depends on stimulation frequency (the standard deviation equals 4.5). It is clearly visible within the range 20–30 Hz, where SBR significantly exceeds values for other stimulation frequencies, and is greater than SBR for fundamental harmonic. An SBR drop around 25 Hz probably results from activity of 50Hz notch filter, which was used for reduction of mains interferences (frequency of second harmonic response to 25 Hz stimulus equals 50 Hz, so this component is suppressed by the filter). The presence of the notch filter can be accounted for and corrected. One can notice that the measured SBR frequency response in the CMV channel can be used to estimate the filter frequency response, as shown in Fig. 7 (it is very unlikely that magnitude of the SSVEP in the CMV channel will be of any significance). In this work, dividing the computed SBR values by SBR values measured in the CMV channel was used for correction. The effect is illustrated in Fig. 8.

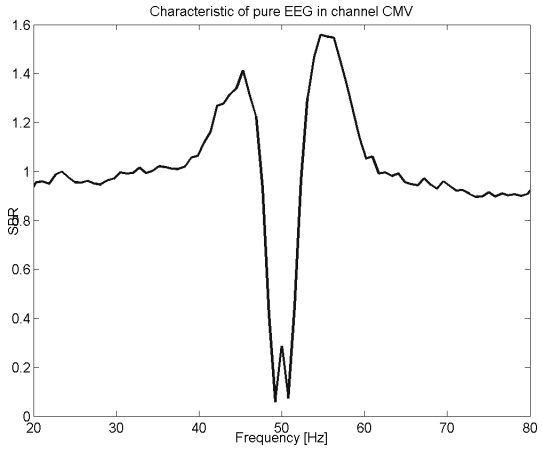


Fig. 7. SBR characteristic of pure EEG in channel CMV

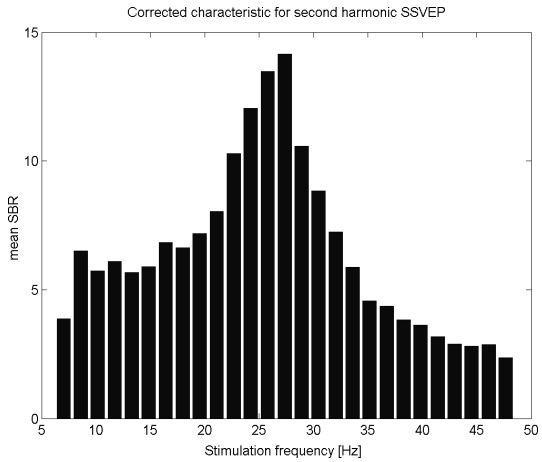


Fig. 8. Corrected SBR characteristic for second harmonic SSVEP

Above characteristics show only averaged relation between frequency of the stimulus and SSVEP amplitude. Figure 9 presents characteristics for each color of the stimulus. It is

clearly visible that shapes of the charts for fundamental harmonic SSVEP are different. Thus amplitude of SSVEP depends on combination of color and frequency of the stimulus. Characteristics for second harmonic SSVEP are very similar, and the color of the stimulus has influence mainly on the peak value.

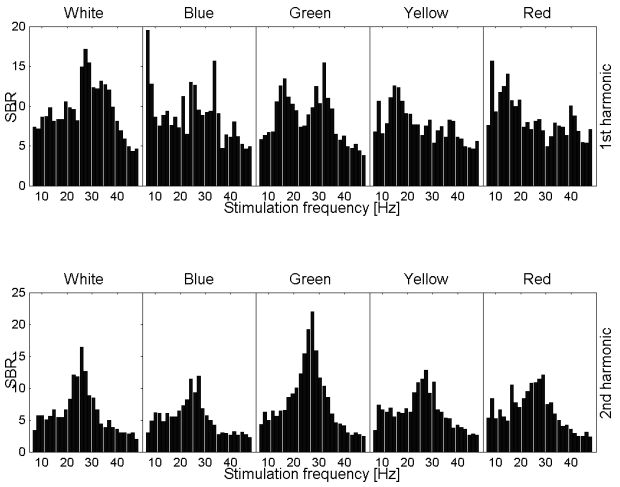
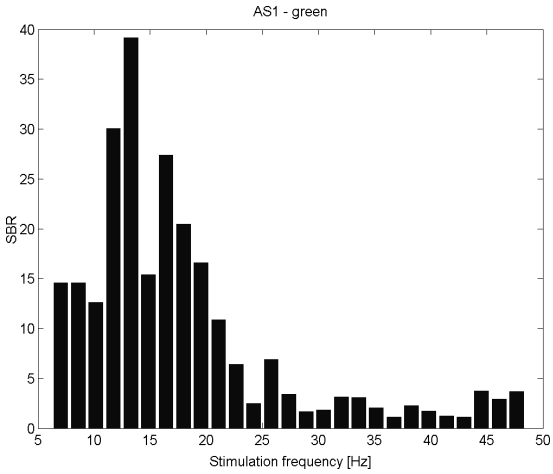


Fig. 9. SSVEP characteristics for each color of the stimulus

a)



b)

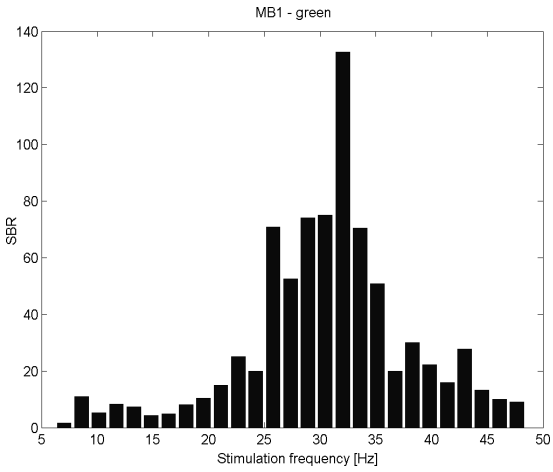
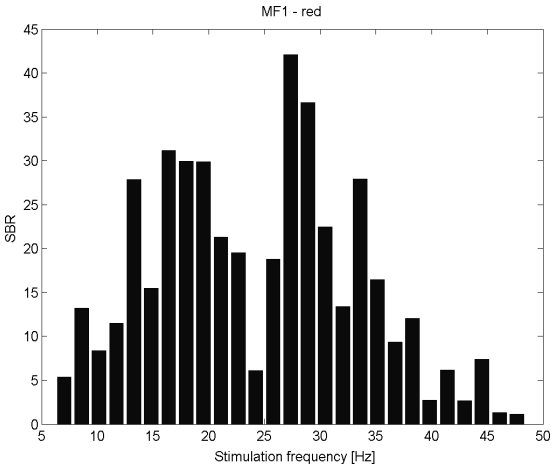


Fig. 10. Fundamental harmonic response to green stimulus for subjects AS1 and MB1

For more detailed analysis, SSVEP characteristics of each subject were compared. This analysis shows definite diversity of subjects' response to alternate half-field stimulus. Figures 10 to 12 present examples of the most differing characteristics. For green stimulus, strong fundamental harmonic SSVEP may be observed in the range 10–20 Hz for subject AS1, whereas response for subject MB1 is stronger in the range 25–35 Hz (Fig. 10). Another example shows Fig. 11. A response of the subject MF1 to red stimulus is strong within wide frequency range, whereas characteristics for the subject MB1 have two peaks in narrow bands around frequencies 10 Hz and 41 Hz. Different responses may be observed also for second harmonic SSVEP, that was shown in Fig. 12. This analysis suggests, that stimulation parameters, such as color and frequency, should be individually adjusted to each subject to maximize SSVEP response.

a)



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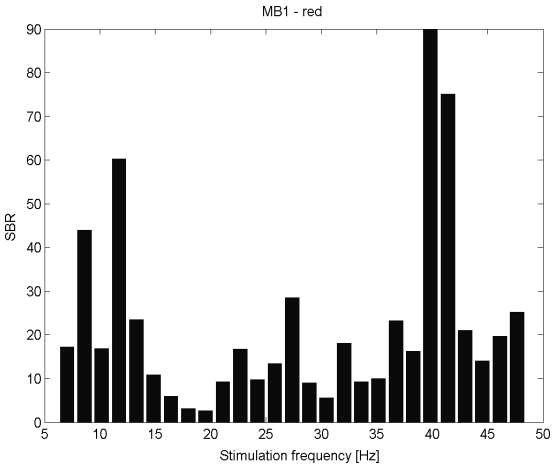
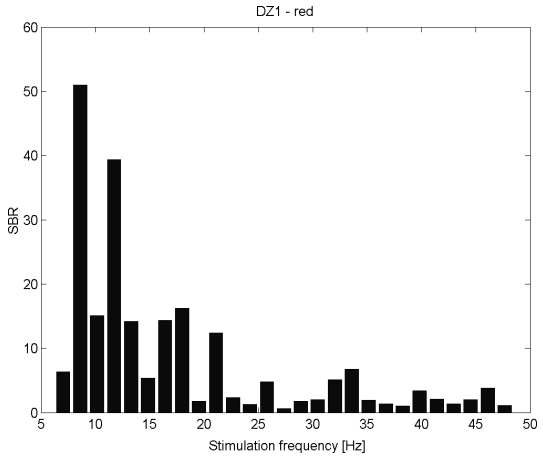


Fig. 11. Fundamental harmonic response to red stimulus for subjects MF1 and MB1

Analysis of recorded EEG signals in remaining channels (other than O1-O2) showed, that SSVEP signals may have better quality in other electrode configurations, and a choice of the optimal configuration may be different for each subject. This phenomenon is known from the literature for a standard, the uniform SSVEP BCI stimulus (where both visual fields of the eye are excited by the signal of the same phase, e.g. [9]).

a)



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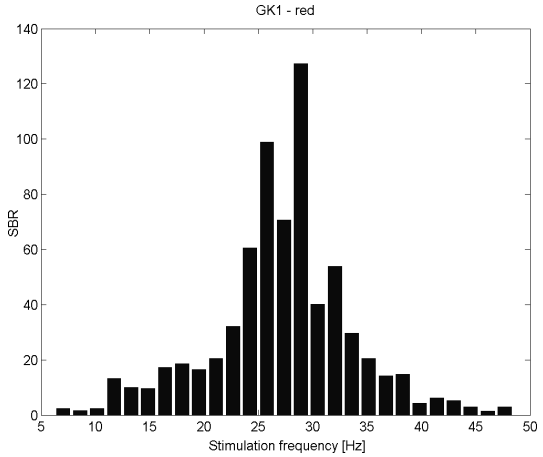

Fig. 12. Second harmonic response to red stimulus for subjects DZ1 and GK1

However, our analysis showed, that a selection of optimal measurement channel should be done independently for fundamental and second harmonic SSVEP, because bipolar measurements may attenuate or amplify individual SSVEP harmonics due to their different phase shifts. Moreover, optimal channel may be different for each color for the same subject. Detailed results of multichannel analysis were presented in Table 1.

4. Conclusions

The design of a visual stimulus has a significant influence on SSVEP-based BCI performance. For example, an alternate half-field stimulation method leads to a substantial enhancement of the SSVEP. The experiment presented in the paper shows that SSVEP response to alternate half-field stimulus depends on its parameters, such as color and frequency. The relation between these parameters and SSVEP amplitudes is subject dependent. There is no standard stimulus configuration that is optimal and applicable for wide range of subjects. To take account of this fact and to improve the subject applicability, a procedure of parameter customization for individual subject's preferences must be executed before BCI operation. From practical point of view, the method of system adaptation to the user should be fast and reliable to reduce preparation time. Another issue is whether or not optimal stimulation parameters vary between different sessions for the same user and what causes possible differences. This will be investigated in our future work.

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Table 1
Selection of optimal channel for each subject, SSVEP harmonic and color of stimulus based on mean SBR

Subject	First harmonic					Second harmonic				
	White	Blue	Green	Yellow	Red	White	Blue	Green	Yellow	Red
AA1	O1 - O2	O1 - OZ	O1 - OZ	CMV - O1	O1 - OZ	CMV - OZ	CMV - OZ	CMV - OZ	OZ - PO4	CMV - OZ
AG1	PO7 - PO4	CMV - PO4	CMV - PO4	CMV - PO4	CMV - PO4	CMV - PO3	CMV - PO3	CMV - PO3	CMV - PO3	CMV - PO3
AG2	O1 - OZ	PO3 - OZ	CMV - OZ	PO3 - OZ	O2 - OZ	PO3 - OZ	PO3 - OZ	PO3 - OZ	PO3 - OZ	PO3 - OZ
AH1	O1 - PO7	PO3 - OZ	O1 - PO7	PO3 - OZ	PO3 - OZ	CMV - PO4	OZ - PO4	PO3 - PO4	CMV - PO4	PO7 - PO3
AI1	PO7 - PO4	O2 - PO3	O2 - PO3	PO3 - PO4	PO3 - OZ	CMV - OZ	OZ - PO4	OZ - PO4	OZ - PO4	OZ - PO4
AL1	O1 - O2	CMV - O1	CMV - O1	O2 - OZ	CMV - O1	CMV - OZ	CMV - OZ	CMV - OZ	CMV - OZ	CMV - OZ
AS1	PO3 - PO4	O2 - PO3	PO3 - PO4	PO3 - PO4	PO3 - PO4	CMV - OZ	O2 - OZ	PO3 - OZ	O2 - OZ	O2 - OZ
AS2	O1 - OZ	PO3 - PO4	PO3 - PO4	PO3 - PO4	CMV - PO3	O1 - PO4	OZ - PO4	OZ - PO4	PO3 - PO4	PO3 - PO4
AW1	OZ - PO4	PO3 - PO4	PO3 - PO4	OZ - PO4	O1 - O2	O1 - PO7	CMV - PO3	CMV - PO3	CMV - PO3	CMV - O1
DK1	O1 - O2	O1 - O2	O2 - PO3	O2 - PO3	O1 - O2	O1 - PO4	O1 - PO4	O1 - PO4	O1 - PO4	O1 - PO4
DZ1	O1 - O2	O1 - O2	CMV - O2	CMV - O2	PO3 - PO4	OZ - PO4	O1 - PO4	OZ - PO4	OZ - PO4	OZ - PO4
ES1	PO7 - PO4	CMV - PO4	PO3 - PO4	OZ - PO4	OZ - PO4	PO4 - PO8	O1 - PO3	CMV - OZ	PO3 - OZ	OZ - PO8
GK1	O1 - O2	O1 - OZ	O1 - OZ	O1 - OZ	O1 - O2	OZ - PO4	O1 - PO4	O1 - PO4	O1 - PO4	O1 - PO4
MB1	O1 - O2	O1 - O2	O1 - O2	O1 - O2	O1 - O2	O1 - O2	CMV - O2	CMV - O2	O2 - PO3	CMV - O2
MF1	O2 - PO3	PO3 - PO8	PO3 - PO4	PO3 - PO4	PO3 - PO4	PO3 - PO4	OZ - PO4	OZ - PO4	PO3 - PO4	OZ - PO4
MK1	PO7 - PO3	O1 - PO3	PO7 - PO4	O1 - PO7	CMV - PO3	O2 - PO4	O2 - PO4	CMV - PO4	PO3 - PO4	O2 - PO4
ML1	O2 - PO4	O2 - PO8	CMV - PO4	CMV - PO8	CMV - PO8	PO7 - PO8	O2 - PO8	PO7 - PO4	CMV - O1	PO7 - PO4
MO1	CMV - OZ	O1 - O2	OZ - PO4	CMV - OZ	OZ - PO4	PO3 - OZ	PO3 - OZ	PO3 - OZ	CMV - OZ	PO3 - OZ
PP1	O1 - O2	O1 - O2	O1 - O2	O1 - O2	O1 - O2	CMV - OZ	CMV - OZ	OZ - PO4	CMV - OZ	CMV - OZ
PW1	O1 - PO3	O1 - PO4	O1 - PO4	PO3 - PO4	PO3 - PO4	CMV - OZ	OZ - PO8	CMV - PO3	CMV - OZ	OZ - PO4
WG1	PO3 - PO4	O1 - PO4	PO3 - PO4	O1 - PO4	O1 - O2	CMV - OZ	OZ - PO4	OZ - PO4	OZ - PO4	OZ - PO4

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