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Optimization of SSVEP brain responses with application to eight-command Brain–Computer Interface

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ABSTRACT

This study pursues the optimization of the brain responses to small reversing patterns in a Steady-State Visual Evoked Potentials (SSVEP) paradigm, which could be used to maximize the efficiency of applications such as Brain–Computer Interfaces (BCI). We investigated the SSVEP frequency response for 32 frequencies (5–84 Hz), and the time dynamics of the brain response at 8, 14 and 28 Hz, to aid the definition of the optimal neurophysiological parameters and to outline the onset-delay and other limitations of SSVEP stimuli in applications such as our previously described four-command BCI system. Our results showed that the 5.6–15.3 Hz pattern reversal stimulation evoked the strongest responses, peaking at 12 Hz, and exhibiting weaker local maxima at 28 and 42 Hz. After stimulation onset, the long-term SSVEP response was highly non-stationary and the dynamics, including the first peak, was frequency-dependent. The evaluation of the performance of a frequency-optimized eight-command BCI system with dynamic neurofeedback showed a mean success rate of 98%, and a time delay of 3.4 s. Robust BCI performance was achieved by all subjects even when using numerous small patterns clustered very close to each other and moving rapidly in 2D space. These results emphasize the need for SSVEP applications to optimize not only the analysis algorithms but also the stimuli in order to maximize the brain responses they rely on.

The ability of the human brain to control directly objects other than its own body has become reality in the past few decades with the success of the interdisciplinary Brain–Computer Interface (BCI) paradigm [5,13,16,18]. BCI offers disabled and healthy users an important alternative channel of communication and control by conveying intent through premeditated modification of the brain activity, instead of using muscles. Recent studies have indicated an increased interest in BCI systems which are based on conscious modification of natural brain responses to external stimuli with various sensory modalities [2,16]. Such BCI methods, in spite of the necessity for stimulation equipment and increased attention efforts by the user, allow advantages such as a very large number of commands, high reliability, shorter or no subject training, and higher resistance to artifact contamination, when compared to BCI approaches based only on mental imagery. In the Steady-State Visual Evoked Potential (SSVEP) BCI paradigm [10], the user focuses attention selectively on one of multiple patterns/lights which reverse/flicker repetitively at slightly different frequencies. This continuous visual stimulation evokes a precisely synchronized, recognizable "steady-state" brain activity which depends on the user's choice of a target, as each reverse or flicker at its own unique frequency. SSVEP BCI systems have been used, for example, as a two-command flight simulator control device [10], or the BCI NASA Earth viewer in which large stationary patterns on the edges of the screen reversing at 5–7 Hz enabled four-command control of the scrolling direction of a satellite map of the Earth [17]. Reportedly, BCI systems based on SSVEP stimulation have been tested successfully for up to 48 commands, even though with just one user [6]. In a previous report [9] we showed a four-command BCI design with pre-selected stimulation frequencies, mean success rate of 94.7%, and mean command delay of 3.7 s. In the present study we aimed to increase the number of commands to 8, while improving the BCI performance. In addition, we decreased substantially the size of the checkerboard stimuli in order to free up screen space for application purposes. To minimize visual occlusion, all 8 patterns were assembled in a very tight but simultaneously moving spatial configuration around a controlled object, in a novel dynamic paradigm for pattern SSVEP BCI [3]. Even though relatively robust, the cortical SSVEP oscillations depend strongly on stimulation characteristics, including repetition rate, stimulus size, spatial frequency, contrast and color [14], as well as attention [12] and proximity of other simultaneous stimuli. In this study, we investigated the effect of

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the stimulation frequency on the SSVEP response (Experiment 1), as well as its time dynamics (Experiment 2). These results were used to construct, evaluate and account for the performance of an eight-command SSVEP-based BCI system (Experiment 3), featuring a robust optimized stimulation which is extendable to higher number of commands.

Brain signal acquisition in SSVEP Experiments 1 and 2 was performed with 128 active electrodes at a sampling rate of 2048 Hz (Biosemi Inc., Amsterdam). In BCI Experiment 3, a lower sampling rate of 256 Hz was used, and 5 occipital electrodes were placed in an inverted T-shape configuration (with OZ at the crossing point). An additional electrode was placed in an anterior location (FZ) to aid the automated removal of ocular artifacts. Four healthy subjects with normal or corrected-to-normal vision participated in this conceptual study. The subjects were fully informed of all procedures and signed an informed consent agreement, in accordance with the Declaration of Helsinki, and including a statement that they have no known neurological disorders. Before each experiment they were briefly tested for photosensitive epilepsy. Subjects, who did not have any prior training except for a short practice run during the briefing, were seated 0.9 m from a 21″ CRT computer display operated at a high vertical refresh rate (setting 170 Hz, measured 168 ± 0.4 Hz). SSVEP stimulation was achieved using small reversing black and white checkerboards with 6×6 checks. The checkerboards had dimensions $1.8^\circ \times 1.8^\circ$ arc, so that the diameter (2.5° arc) would just cover the size of the fovea.

Experiment 1 was designed to expose the brain frequency responses for our small patterned stimuli. A single reversing checkerboard was presented on a black background in the middle of the screen in this experiment. The rate of reversal of the pattern was changed every 6 s and increased stepwise, with larger steps at higher stimulation frequencies due to the limitations imposed by the discrete refresh cycle of the computer display. Overall, 32 reversal frequencies were shown: 5.1, 5.25, 5.4, 5.6, 5.8, 6.0, 6.2, 6.5, 6.7, 7.0, 7.3, 7.6, 8.0, 8.4, 8.85, 9.3, 9.9, 10.5, 11.2, 12.0, 12.9, 14.0, 15.3, 16.8, 18.7, 21.0, 24.0, 28.0, 33.6, 42.0, 56.0, 84.0 Hz. Due to the discrete vertical refresh rate of the computer monitor and to avoid improper partial display, these frequencies were obtained by dividing the measured refresh rate of 168 Hz by integer values (33, 32, ..., 2). After re-referencing the original EEG data to the central CZ electrode, eye blink and muscle artifacts were extracted and removed using a blind source separation (BSS) approach utilizing modified Robust Second Order Blind Identification with Joint Approximate Diagonalization (SOBI) and automatic Hoyer sparsity ranking of the components [4]. This pre-processing procedure served to increase the success rate of the system by reducing the probability for false positive recognition of BCI commands. Artifact-free responses for each of the 32 stimulation frequencies were band-passed at their individual stimulation frequencies (± 0.1 Hz) using a zero-phase finite impulse response (FIR) filter configured for a 0-dB magnitude response at the center frequency of the passband. The response strength for each band and subject were estimated as the mean *z*-score of the band power throughout the stimulation interval. The average *z*-score across all subjects was calculated for each pattern reversal rate as a measure of the frequency response of the brain.

In Experiment 2, a single small checkerboard stimulus was displayed for three reversal frequencies sequentially (8, 14 and 28 Hz), covering each of the three SSVEP response regions (low-, medium-, and high-frequency) as defined by Regan [14]. Six trial repetitions were used for each frequency. Each trial consisted of 5 s baseline rest (black screen) and 15 s stimulation. To remove the interference caused by the synchronous SSVEP response oscillations, and to observe their envelope, we applied a demodulation procedure [12]. Our modified quadrature amplitude demodulation (QAD) method recovered the amplitudes of phase-shifted messages Y_1 and Y_2 in a modulated carrier input signal X (SSVEP):

$$Y_1 = X\cos(2\pi ft), \quad Y_2 = X\sin(2\pi ft) \tag{1}$$

and reconstructed the original modulating signal using the following equation:

$$Z = |H^f(Y_1)| + |H^f(Y_2)|, \tag{2}$$

where f is the counterphase modulation frequency, and H^f is a low-pass Butterworth filter at cutoff frequency f applied to filter out the carrier signal. The QAD model output Z represented the recovered single-trial SSVEP response envelope, which could be used further to measure the characteristics of the signal dynamics. The demodulated, squared and normalized SSVEP brain response signals were subjected to peak analysis for each frequency, trial and subject. The onset was defined as the envelope value on a rising slope for which the baseline oscillation maximum was exceeded by 10%. The first peak was defined as the first extremum of the signal following the onset point. Single-trial latencies for the SSVEP onset and first-peak delays were measured and evaluated through two-factor ANOVA statistical analysis. Data series were considered significantly different if the 95% probability threshold ($p < 0.05$) was passed, indicating that they do not belong to the same sample populations.

The goal of Experiment 3 was to evaluate an online eight-command SSVEP BCI system with frequency-optimized stimuli. The system consisted of the following basic modules: (1) data acquisition module, (2) user neurofeedback and stimulation module, and (3) data analysis/command recognition module. Eight checkerboard patterns were displayed simultaneously, each allowing control of one independent BCI command (Fig. 2). The patterns, reversing at optimized frequencies of 6.0, 7.3, 8.4, 11.2, 12.9, 14, 15.3, 16.8 Hz, were fixed very close to a moving controllable object, and allowed its spatial translation in 8 directions with 45° resolution in 2D space. Shortly after a subject's attention was directed to a selected pattern, the synchronized SSVEP brain responses were identified by the BCI analysis module, and the online visual neurofeedback enabled the movement of the controlled object (a small car in this case) in the desired direction: UP, RIGHT, DOWN, LEFT, UPPER-LEFT, UPPER-RIGHT, LOWER-RIGHT, LOWER-LEFT, as well as IDLE. In addition, the first byte of the transmitted command data indicated the strength of the current EEG command feature, so that the speed of the car object moving on screen was higher for stronger brain responses. Three different modes of operation were enabled in BCI Experiment 3: (a) short classifier training mode, (b) performance evaluation mode, and (c) self-paced free roaming mode, which are not discussed further in this report. For all modes of operation the user's neural commands were detected and sent for visual feedback every 120 ms. During the classifier training mode (~2 min duration), each of the eight BCI commands was requested three times in random order, in addition to a no-stimulation command. After hearing a command request, the subject switched attention as soon as possible to the corresponding reversing pattern, or, in case of a no-stimulation request, to the controlled object between them. The voice requests were short pre-recorded messages asking the user to attend a specific pattern. Each command request was also accompanied by a thin red frame appearing around the requested pattern to minimize the searching delay. Neurofeedback was disabled during the training mode, and all user interface objects remained stationary. The second, evaluation mode served the purpose of measuring objectively the mean success rate and time delay of the BCI system. Six repetitions for each of the eight commands were presented to the user in random order, after which the success rate was measured, as well as the recognition time delay. The dynamic neurofeedback was fully enabled in evaluation mode. A thin red frame aided the user to find the requested command pattern quickly, while a green frame showed which command was recognized. The BCI data analysis module utilized