

Self-Paced Operation of an SSVEP-Based Orthosis With and Without an Imagery-Based “Brain Switch:” A Feasibility Study Towards a Hybrid BCI

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Abstract—This work introduces a hybrid brain-computer interface (BCI) composed of an imagery-based brain switch and a steady-state visual evoked potential (SSVEP)-based BCI. The brain switch (event related synchronization (ERS)-based BCI) was used to activate the four-step SSVEP-based orthosis (via gazing at a 8 Hz LED to open and gazing at a 13 Hz LED to close) only when needed for control, and to deactivate the LEDs during resting periods. Only two EEG channels were required, one over the motor cortex and one over the visual cortex. As a basis for comparison, the orthosis was also operated without using the brain switch. Six subjects participated in this study. This combination of two BCIs operated with different mental strategies is one example of a “hybrid” BCI and revealed a much lower rate of FPs per minute during resting periods or breaks compared to the SSVEP BCI alone (FP = 1.46 ± 1.18 versus 5.40 ± 0.90). Four out of the six subjects succeeded in operating the self-paced hybrid BCI with a good performance (positive prediction value PPV_b > 0.70).

Index Terms—Brain-computer interface (BCI), brain switch, event-related desynchronization (ERD)-based BCI, hand orthosis control, hybrid BCI, motor imagery, steady-state visual evoked potential (SSVEP)-based BCI.

I. INTRODUCTION

BRAIN-COMPUTER interfaces (BCIs) are primarily developed for severely disabled people to improve their quality of life [1]–[4], but can also be used by healthy people to decrease their workload at the workspace, such as by providing a “third-hand.” Such a “third hand” can be used to press a button, switch on an apparatus, flip through a repair manual, or browse through several menus. Robustness and on-demand operability are in this case extremely important issues. These applications should function outside the laboratory, using as few as possible EEG channels; this task could be realized through a “brain switch.” A brain switch is a BCI system designed to detect only one brain state (brain pattern) in the ongoing EEG signal. One important feature of such a brain

switch is that unintended activations should not occur. That is, the false positive (FP) rate should be zero or close to zero.

A brain switch can be realized either with steady-state visual evoked potentials (SSVEPs) elicited by flickering lights [5], by recognition of motor-related potentials [6], or by detection of the peri-imagery event-related desynchronization (ERD, [7]) and postimagery beta event related synchronization (ERS, [7]) i.e., an increase (following a decrease) of spectral amplitudes of central beta rhythms in the range from 13 to 35 Hz [8]. Midden-dorf *et al.* [5] reported on different types of brain switch operations by modulation of flickering lights at 13.25 Hz. Similarly, Cheng *et al.* [9] reported on a virtual keypad, whereby the battery of flickering lights is turned on/off by a flickering on/off button. Birch and Mason [10] proposed a low-frequency asynchronous switch design (LF-ASD) able to automatically recognize single-trial, voluntary motor related potentials from ongoing EEG in six bipolar channels. Recent work demonstrated that a single channel brain switch can be also realized when the postimagery beta event-related synchronization (ERS) is detected in the EEG during motor imagery [8], [11].

One interesting application of a brain switch could be to turn on the flickering lights fixed on a hand orthosis only when the user wants to use the orthosis to perform a specific task (e.g., fetching something) and to turn the light(s) off during long resting periods. The number of FPs would otherwise be relatively high during such resting periods, when the lights are still flickering and SSVEP detection is active. Here, we report, for the first time, the use of the postimagery beta ERS as a switch to turn on/off a four-step electrically driven hand orthosis with two flickering lights (one for opening and one for closing). We wish to answer the following questions.

- 1) Is it feasible to operate a self-paced 1-channel imagery-based brain switch sequentially with a 1-channel SSVEP-based BCI? That is, can subjects perform two different cognitive tasks (motor imagery and spatial visual attention) in the same experimental session in a self-paced mode? Nobody has ever used a 1-channel imagery-based BCI to turn on/off a SSVEP BCI, and never a sequentially operating hybrid BCI with two cognitive tasks was reported.
- 2) Can the rate of FPs be reduced when in resting periods the flickering lights of an SSVEP-based BCI are switched off?

The combination of motor-imagery-based and SSVEP-based BCIs in one application is one possible type of a hybrid BCI. Two BCIs are in one “box” like a hybrid car with a gasoline and electric engines inside. The major goals of such a hybrid car

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are to enhance their energy efficiency and to reduce their CO₂ output. The goal of this hybrid BCI is to improve the overall performance of such a system. We describe the self-paced (asynchronous) operation of this hybrid BCI and discuss different performance measures.

II. METHOD

A. Subjects and EEG Recording

Six healthy subjects (age 26.1 ± 2.9 years) without any experience with hybrid BCIs participated in this pilot study, but five subjects had some experience with ERD and/or SSVEP BCI experiments. Each participant gave written informed consent. The experiment was approved by the Ethics Board of the Medical University Graz. One single Laplacian derivation at electrode position Cz was computed using five closely spaced (2.5 cm) Ag/AgCl EEG electrodes. The reference was located at the left mastoid. For SSVEP recording, one bipolar EEG channel was used with electrodes at positions 2.5 cm anterior and posterior O1. The ground electrode was located at the right mastoid. The signals were recorded with a biosignal amplifier (gBSamp, g.tec, Graz, Austria). Data were recorded with a bandpass filter between 0.5–100 Hz and a 50-Hz notch filter. The sample frequency was 256 Hz.

The subjects were seated comfortably in a chair facing the orthosis which was placed about 40 cm in front of the subject on a table. The computer monitor was on the same table, about 1 m from the subject. The visual angle between the LEDs mounted on the orthosis was 12°. The arrangement allowed the subject to look at both the orthosis lying on the table and the monitor when looking above the orthosis.

B. Experimental Task

1) *Operating the SSVEP-BCI:* The task was to control a four-step electrical hand orthosis (Otto Bock Healthcare Products GmbH, Vienna, Austria) by focusing on an 8-Hz LED on the left side of the orthosis to open it, and focusing on a 13-Hz LED on its right side to close the orthosis (Fig. 1). In each run, the user had to open and close the orthosis three times, each at self paced intervals (activity period), with two 60-s periods between the activity periods without any control activity (resting period; a beep indicated the beginning and ending of this resting period). When an error was made during the activity period, the user was told to select the incorrect light again to correct the error, and go on with the task. Fig. 2(a). shows examples of complete cycles, composed of three activity periods and two resting periods.

2) *Cue-Based Training for Imagery-Based BCI:* The subjects started with some actual executions of brisk feet dorsiflexions to become familiar with the task. Then, the cue-based imagery task started. In the paradigm, a green cross was displayed on the center of the screen at $t = 0$ s. After 2 s, a beep and an arrow were given as cues. The arrow (red) was presented on top of the cross from the center out. The arrow could point up, indicating no movement (no motor imagery), or down, indicating a brisk feet movement (brisk feet motor imagery). The arrow disappeared at $t = 3.25$ s and the cross disappeared at $t = 6$ s.

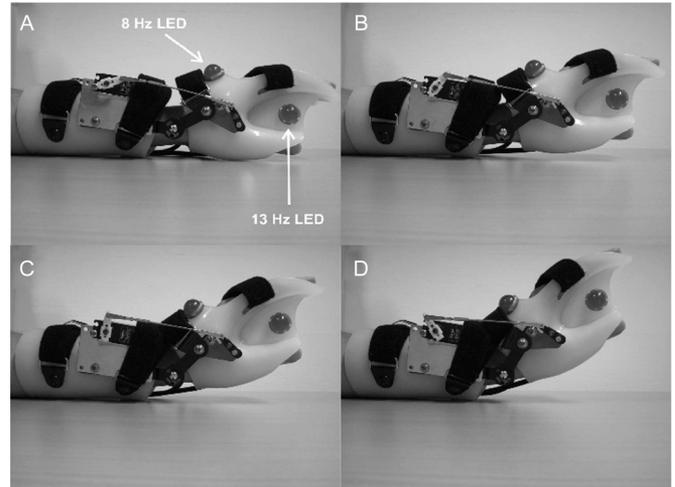


Fig. 1. Hand orthosis with two mounted LEDs; A to D: 4 steps of “opening.”

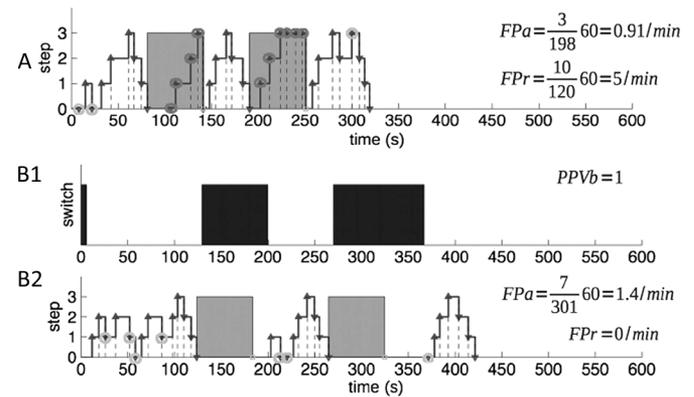


Fig. 2. Examples of two runs over some minutes each in subject s6. One run was made without (A) and one with (B1 and B2) the ERD/S-based brain switch. Trace A displays the 4-step sequence of opening/closing the SSVEP-based orthosis with two 60-s breaks. The rate of FPr in the resting periods (breaks) was 5/min. Trace B1 shows the ERD/S-based switch operation (black bars indicate switch opened) and trace B2 the SSVEP-based orthosis control. In this case, no errors occurred in resting periods ($FPr = 0$).

One trial had a length of 8 s plus a random interval between 0.5 and 1.5 s. Two runs of motor imagery were recorded using the training paradigm described above. Each run consisted on 15 trials per class and the cue presentation was randomized. The subjects did not receive feedback during these runs.

3) *Self-Paced Operation of Both, the Imagery-Based Brain Switch and the SSVEP-Based BCI:* After the training session and setup of the classifier, the first session with feedback started. The following instructions were given to the subjects.

- 1) Activate the brain switch through motor imagery (“close” the brain switch) and then use the SSVEP-BCI to open or close the orthosis. It took four consecutive signals to completely open or close the orthosis.
- 2) Turn off the SSVEP-BCI by “opening” the brain switch after completion of the full orthosis cycle.
- 3) Keep the brain switch open during the resting period of 60 s as indicated on the monitor.
- 4) Repeat the four-step orthosis control two more times with one resting period using the brain switch.

The time limit for one run was 10 min. If the subjects could not complete the full orthosis cycle within this time, the recording was stopped.

4) *Control Experiment*: After self-paced operation of both the brain switch and SSVEP BCI, an additional run was made with the SSVEP BCI alone. The subjects were instructed to perform self-paced the complete orthosis cycle with three activity and two resting periods.

C. Data Processing and Classification

1) *SSVEP-Based BCI*: SSVEP data were processed by calculating the power density spectrum of the past 1-s EEG segment over one bipolar channel every 250 ms with a discrete Fourier transform. A weighted sum of each stimulation frequency and its second and third harmonic produced the harmonic-sum-decision (HSD). The flickering light source with the highest HSD was selected if detected consecutively several times (for further details see [12]). Two measures were obtained from the activity period, the true positive rate (TPa) and the FPa, and one from the resting period (FPr). The dwell time (amount of time that the signal must cross the threshold to be considered a valid detection) was 1.56 s (400 samples) and the refractory period (which is a period after the dwell time has been met, where the signal will be ignored) was 4 s. With the given dwell time of 1.56 s and refractory period of 4 s, the minimum time to complete the complete assigned task was 208 s. The actual time needed was between 229 and 536 s (time limit for one run was 600 s), as shown in Tables II and III.

2) *Imagery-Based Brain Switch*: The motor imagery based asynchronous brain switch is designed to detect brisk imagined (or executed) foot movements in one Laplacian EEG channel recorded at the vertex (Cz) ([8], [11], [13], [14]). Actually, two oscillatory phenomena, the peri-imagery ERD and the postimagery beta ERS, are important ([7], [15]). The latter is known as beta rebound. In this paper, only the postimagery-ERS is considered. The classifier used to detect the ERD/ERS patterns during foot imagery can be set up quickly and easily after analyzing 1-channel EEG data. From the training data (30 trials during motor imagery and 30 trials during resting periods), time-frequency representations (ERD/ERS maps) were calculated. The frequency bands with the most pronounced beta ERS was used to setup the classifier. A Fisher’s linear discriminant (LDA) classifier was trained to detect the beta ERS using the data from the cue-paced motor imagery runs. The EEG was described by the logarithmic band power in the selected beta band. The EEG was filtered with a Butterworth filter of fifth order, squared and averaged in a moving window of 1 s. The training of the LDA was done with a 10×10 cross-validation, and the classifier with the highest classification accuracy was used for online classification. Next, two parameters were defined: the threshold and the dwell time. The threshold was defined as the average plus one standard deviation of the LDA distance obtained at the maximum (cross validated) classification accuracy, and the dwell time was set to 1 s. Both parameters were later adjusted manually (for further details see [14]). A postimagery beta ERS [11] occurred whenever the LDA distance exceeded the threshold for a time equal or greater than the dwell-time. The LDA output,

TABLE I
SUBJECT IDENTIFICATION (ID), AGE, SELECTED FREQUENCY BANDS AND CLASSIFIER ACCURACY OF THE INDIVIDUAL SUBJECTS. IN ADDITION THE MEANS AND SDS ARE INDICATED

ID	age (years)	ERS	Classifier offline
		Frequency Band (Hz)	accuracy (%)
s1	26	26 - 32	90
s2	29	25 - 29	82
s3	28	34 - 36	83
s4	22	22 - 26	84
s5	26	25 - 27	76
s6	29	20 - 24	95
mean	26,7	25,3 - 29	85,0
SD	2,7	4,8 - 4,4	6,6

and thus the brain switch operation, was disabled for 2 s after one detection. This 2-s period is called the refractory period. Before the self-paced experiment, the subject was free to perform a variable number of brain switch activations and reported on their success or failure. These runs were used for fine adjustment of threshold and dwell time.

D. Performance Measures

The experiment is relatively complex and requires shifting between motor attention and spatial visual attention. Through motor attention, the peri-imagery ERD and a postimagery ERS (beta rebound) is induced whereas the SSVEPs are modulated through visual attention. Throughout the task, the user always obtained feedback about success or failure of BCI operation, and could therefore adapt his or her mental strategy if necessary. The following measures are used to evaluate the performance of the brain switch and the SSVEP-based BCI during self-paced operation.

- 1) Correct brain switch operations (TP) and errors (FP) are counted during the total time of the experiment (duration around 4 min). From TP and FP, positive predictive value (PPVb) is calculated: $PPVb = TP / (TP + FP)$.
- 2) From the SSVEP-BCI, the true positives (TPa), the errors made during orthosis control (FPa), and the errors in the resting periods (FPr) are measured. The PPV is calculated for the activity periods based on TPa and FPa. Two PPVs are obtained—one from the experiment with brain switch and SSVEP BCI (PPVba) and one from the control experiment (PPVa).

III. RESULTS

Table I summarizes the selected frequency bands and the offline classifier accuracy obtained from the cue-based training data. The average frequency band was 25.3–29.0 Hz and the classifier accuracy $85.0\% \pm 6.6\%$ (mean \pm SD).

Tables II and III summarize all performance measures from the hybrid BCI (imagery-based brain switch and SSVEP-based BCI) and the SSVEP BCI alone. When two runs were available, the data from both runs were averaged. Five subjects showed good results in SSVEP-based orthosis control ($PPVa > 0.7$) with and without brain switch, four subjects were able to handle the brain switch without major problems ($PPVb > 0.7$), and

TABLE II

SUMMARIZED RESULTS OBTAINED IN THE HYBRID BCI STUDY (BRAIN SWITCH AND SSVEP). DISPLAYED ARE THE PERFORMANCE MEASURES (IN SOME SUBJECTS THE AVERAGE OVER TWO RUNS) PPVb, PPVba, TPa, FPa, FPr, AND TRIALTIME (TTRIAL). THE NUMBER OF RUNS IS INDICATED AFTER THE SUBJECT ID

ID / runs	BS and SSVEP					Ttrial (s)
	FPa (min ⁻¹)	TPa (min ⁻¹)	PPVba (min ⁻¹)	FPr (min ⁻¹)	PPVb	
s1 / 2	2.73	2.69	0.50	0.25	0.86	457
s2 / 2	0.77	3.58	0.82	2.00	0.63	465
s3 / 2	0.37	2.38	0.87	3.25	0.55	536
s4 / 1	0.00	5.80	1.00	1.00	0.73	346
s5 / 1	0.27	5.04	0.95	2.00	0.78	306
s6 / 2	0.91	4.29	0.83	0.25	0.93	468
Mean	0.84	3.96	0.83	1.46	0.74	430
SD	0.98	1.34	0.18	1.18	0.14	86

TABLE III

SUMMARIZED RESULTS OBTAINED IN THE CONTROL EXPERIMENT. DISPLAYED ARE THE PERFORMANCE MEASURES PPVb, TPa, FPa, FPr, AND TTRIAL. EACH SUBJECT PERFORMED ONE RUN

ID	SSVEP alone					Ttrial (s)
	FPa (min ⁻¹)	TPa (min ⁻¹)	PPVb (min ⁻¹)	FPr	PPVb	
s1	2.18	3.70	0.64	5.63	321	
s2	1.38	5.77	0.81	6.75	339	
s3	0.63	5.97	0.90	4.50	311	
s4	0.00	10.10	1.00	4.50	232	
s5	0.54	9.64	0.95	6.00	229	
s6	0.91	6.06	0.87	5.00	319	
Mean	0.94	6.87	0.86	5.40	292	
SD	0.76	2.48	0.13	0.90	48	

three showed good performance with the hybrid BCI (brain switch and SSVEP). Tables II and III indicate that the errors during the breaks (FPr) are significantly ($p < 0.003$ paired sample t-test) reduced from 5.40/min to 1.46/min, and also show a small, but significant decrease ($p < 0.01$ paired sample t-test) of the TPa rate. Tables II and III also show that the FPa rate of the SSVEP BCI when used in conjunction with the brain switch diminished slightly, an effect that did not reach significance, although the PPV was relatively unchanged.

Fig. 2 displays an example from one subject (s6). The upper diagram (A) indicates the operation of the SSVEP-based four-step orthosis control alone. The orthosis operation had to be performed three times with 60 s breaks (indicated as “grey” blocks) in between. In the first cycle, two errors were made and corrected; 10 errors occurred within the two breaks with a clear bias towards opening (8-Hz flickering LED, FPr = 5/min). In the middle diagram (B1), the position of the brain switch (open brain switch → “black” blocks) is indicated. The subject activated the brain switch five times through foot motor imagery and correctly turned the SSVEP BCI on and off; no unintended control signals occurred (PPV = 1). Fig. 2(b) shows the SSVEP-based orthosis operation in the hybrid approach. In the first cycle, the user had some problems, and had to correct

the orthosis position four times. The total error rate in the activity periods was FPa = 1.4/min. No false orthosis movements were made in the resting periods (breaks; FPr = 0) because the SSVEP BCI was not activated.

IV. DISCUSSION

In this study, we showed for the first time that the rate of unintended commands for SSVEP-based hand orthosis control (FPr) can be reduced by more than 50% when utilizing a hybrid BCI. Another way to reduce the errors in the resting periods (FPr), which are caused partially by spontaneous EEG, whose power is dominant at the alpha band (8–13 Hz), is to select stimulus frequencies that are outside of band ([16]). The slight drop of the TPa and FPa rates in the hybrid condition occurred because the subjects needed more time to perform the hybrid task (see example in Fig. 2 and Tables II and III), and may be interpreted as result of the higher cognitive load when subjects must repeatedly switch between motor imagery and visual attention tasks.

For switch operation, a special motor imagery-based BCI was designed able to detect brisk imagined foot movements in a single EEG channel with a low rate of FPs. Two goals can be achieved by combining imagery-based and SSVEP-based BCIs. First, the high rate of FPs in breaks or resting periods between SSVEP applications can be reduced. Second, the feasibility of a simple imagery-based brain switch can be tested and optimized in a real world application with feedback. The combination of two sequentially operating BCIs is one type of hybrid BCI. Only two EEG channels (one bipolar recording at O1 and a Laplacian EEG channel at Cz) are needed for this hybrid BCI application, which is important for applications in field settings such as homes, hospitals, offices, or in outer space.

Fatourechi *et al.* [17] reported an asynchronous switch design with a low FP rate. Based on 18 bipolar EEG channels, executions of finger movements were detected with a TP rate of 56%. However, this is not a real self-paced BCI because a BCI is defined as “non-muscular channel for sending messages and commands to the external world” [3]. Bai *et al.* [18] used ERD/ERS patterns to classify motor imagery and reported a decoding accuracy of about 80%. Starting with 29 EEG signals, one Laplacian channel was selected and used for self-paced operation of a binary-cursor-control game.

Our reported approach is very simple, based on standard EEG recordings at the vertex (Laplacian derivation) and over the occipital cortex (bipolar derivation at O1). Only one beta band for the switch design is selected and used for self-paced operation. Hence, there are many avenues that could make this hybrid BCI faster, easier, more accurate, and more flexible through optimization. For example, the electrode locations could be optimized, one bipolar channel over the sensorimotor cortex selected, and both the peri-imagery ERD and post-imagery ERS used for classification [11]. The beta rebound after movement imagination is a very stable EEG pattern [7], [8], most prominent after foot motor imagery and less prominent after hand imagery [19]. This may be explained by the observation that each motor imagery task involves neural networks in not only the primary motor area but also in the midcentrally localized supplementary motor area (SMA). In the case of foot motor imagery, both networks are close to each other, and very probably help

generate the beta rebound. In the case of hand movement, beta rebounds are found over the hand area and over the SMA.

The use of a flickering light as the on/off button may be simpler than the approach described here, especially if implemented with software generated flickering stimuli [9]. However, an on/off button based on a flickering light would yield the same problem as other flickering lights: a high false positive rate. The approach described here may be more complicated, but results in far fewer false positives. When LEDs are used, such as when a patient wears a hand orthosis, either an additional LED can be mounted and used for the switch operation, or an imagery-based brain switch implemented. Another possible hybrid BCI could use 4 LEDs to control a hand prosthesis [20]. In this application, an additional LED button to turn the device on/off is probably not the best solution, and a brain-based on/off switch would work better.

V. CONCLUSION

The SSVEP-based orthosis system introduced here can be seen as "benchmark" application suitable to investigate, test and develop different brain switch designs in real time applications with feedback. Such a "benchmark" is not only helpful to further improve the EEG-based brain switch, such as by classifying the peri-imagery beta ERD and the post-imagery beta ERS and/or using motor execution data for fast-to-set-up of the classifier [11], but also to develop new brain switch concepts. One such concept could be the detection of imagery induced (de)oxyhemoglobin changes measured with the near-infrared spectroscopy (NIRS) as shown recently on a poster presentation at the Berlin BCI Workshop 2009. The high PPVs calculated in the activity periods with and without the brain switch shows that subjects can perform four-step orthosis control with self-paced error correction. Both the orthosis operation and the brain switch operation are self-paced and include visual feedback. This means that both types of BCIs fulfill the requirements of a BCI, namely non-muscular control, extraction of specific brain signal features that reflect the user's intent, real time processing and feedback [3].

The hybrid BCI here differs from the approach described in another recent study [21]. In that paper, subjects imagined moving the left/right hand while also focusing on a left/right LED. Therefore subjects tried to perform the tasks associated with two different BCI approaches simultaneously, rather than sequentially. The benefit of such a hybrid BCI approach is not reduced FPs, but increased classification accuracy. The fact that two different hybrid BCI ideas show promising results should encourage further hybrid BCI research efforts.

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