"Virtual Keyboard" Controlled by Spontaneous EEG Activity

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***Abstract*—A "virtual keyboard" (VK) is a letter spelling device operated for example by spontaneous electroencephalogram (EEG), whereby the EEG is modulated by mental hand and leg motor imagery. We report on three able-bodied subjects, operating the VK. The ability in the use of the VK varies between 0.85 and 0.5 letters/min in error-free writing.**

***Index Terms*—Brain–computer interface (BCI), electroencephalogram (EEG), virtual keyboard (VK).**

I. Introduction

RECENTLY, the group of Birbaumer presented a spelling device [1] [thought translation device (TTD)] for a patient suffering from late stage of amyotrophic lateral sclerosis (ALS) causing a locked-in syndrome (LIS). Patients suffering under LIS have the ability to perceive their environment via optical, acoustical, and somatosenoric stimuli but they are not able to interact with it. LIS can also be caused by severe cerebral palsy, head trauma, and spinal injuries. It is important, however, that the intellectual functions stay relatively unaffected [2], and, therefore, the need of communication is essential. The TTD is currently used by three ALS patients, trained over a period of some months in more than 100 sessions. The patients have to produce slow cortical potential (SCP) shifts either in a positive or a negative direction to operate the TTD. Two of the three patients achieved a classification accuracy of 70%–80%, allowing them to write with a speed of approximately one letter every 2 min. The spelling rate σ is defined as the number of correctly selected letters per minute and is, therewith, 0.5 for these patients.

Even though the ALS patients regain (a certain level of communication abilities) through the TTD, there is the problem of the low σ caused by the relatively high classification error of these patients. The TTD is based on a binary decision, and, therefore, a classification error of 30% corresponds to one wrong decision out of three. Wrong decisions have to be corrected and, therefore, decrease σ.

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To increase σ, the classification error has to be decreased. The Graz brain–computer interface (Graz-BCI) [3]–[5] was developed by the group of Pfurtscheller at the Department of Medical Informatics at the University of Technology Graz. It is a small and portable system optimized for daily use of patients suffering under any kind of severe motor disabilities. The system gets its control information from the online classification of motor-imagery-related EEG patterns. The classification of two EEG patterns (classes) corresponds to a binary decision, and, therefore, the control signals are of binary type too. This makes the Graz-BCI predestined as the base of a spelling device. In this paper, we present an alternative spelling device called "virtual keyboard" (VK), based on the Graz-BCI [6], and the first results achieved by three able-bodied subjects using it.

II. Methods

A. Standard Graz-BCI Paradigm

The motor imagery is performed in a fixed repetitive scheme called a trial. Each trial starts with the presentation of a fixation cross at the center of the monitor, followed by a short warning tone at second two. At second three, an arrow is displayed at the center of the monitor for 1.25 s. Depending on the direction of the arrow (left or right), the subject is instructed to imagine a movement of either the left or the right hand. In the period from second 4.25 to second 8.0 a bar (feedback), either extending to the left or right, is displayed. During feedback, the subject's task is to extend the bar via mental activity to the side that was indicated by the cue stimulus. The trial ends after 8 s and a blank screen is shown until the beginning of the next trial. The intertrial period (ranging from 0.5 up to 2.5 s), as well as the sequence of left and right trials, is randomized to avoid adaptation.

This standard paradigm was expanded to a more general one using two out of the following four types of motor imageries (left hand, right hand, both feet, and tongue) and one mental task (arithmetic task). The two tasks were determined based on an experiment where all types of imageries had to be performed [7]. The used electrode positions in the experiment are depicted in Fig. 1. The two most discriminatable were selected for each subject individually, as the ones for the Graz-BCI.

B. Two-Classes BCI-System Comprising Hidden Markov Models (BCI-HMM)

Two HMMs—one representing type A motor imagery (HMM_A) and one representing type B motor imagery (HMM_B)—were trained using the trials recorded during the corresponding motor imagery tasks. The feature vector sequence $\overline{\mathbf{Y}}$ was calculated in the period from the beginning of

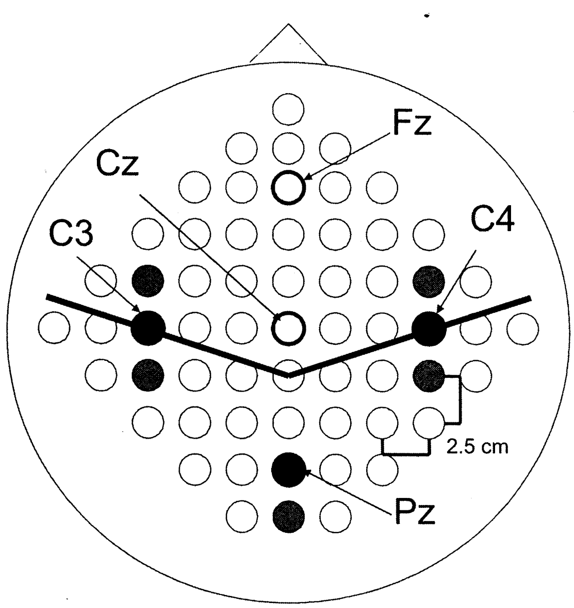

Fig. 1. Electrodes used are located either at positions C3, Pz, and C4 (10–20 system), and/or at positions anterior or posterior to them. The specific positions depend on the most discriminatable imageries. The black line indicates the central sulcus (marking the border between the primary sensorimotor areas).

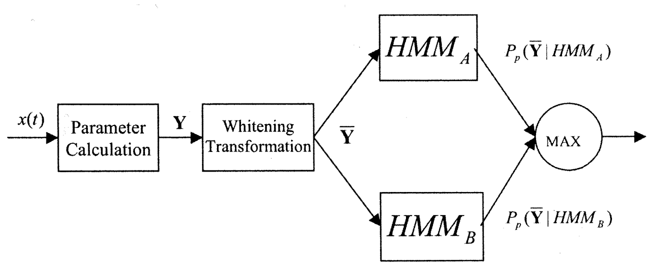

Fig. 2. BCI-HMM comprising the feature estimation the Whitening Transformation and the HMM classifier. Classification is based on maximum selection of the likelihood.

the feedback (second 4.25) to the end of the trial (second 8.0). Classification of an unknown trial was the selection of maximum probability of $P_p(\overline{\mathbf{Y}}|HMM_A)$ and $P_p(\overline{\mathbf{Y}}|HMM_B)$. In the case of the presented offline analysis, this probability was first calculated using $\overline{\mathbf{Y}}$ for (HMM_A) and then for (HMM_B). A block diagram of the used classifier is depicted in Fig. 2.

C. VK

The operation of a VK is an application of the Graz-BCI. The spelling consists of the selection of a letter using successive steps of isolation. Starting with the complete set of letters, successive subsets are selected via mental activity until the selection of the desired letter.

1) Structure of the VK: The structure of the VK (see Fig. 3) contains five consecutive levels of selection and two further levels of confirmation (OK) and correction "BACK/DEL." In a dichotomous structure with five levels, 32 letters can be selected. Therefore, the alphabet was extended by six special characters. The correction has to be performed in a further level due to two different actions needed. First, "BACK" allowing a cancellation of the actual selection with a subsequently return to the first selection level. Second, "DEL," which deletes the last

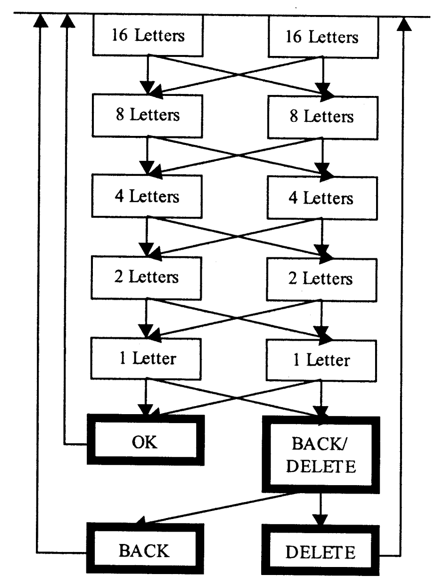

Fig. 3. VK realized by dichotomous search procedure followed by two levels for confirmation and correction.

written letter, the selection done during the five preceding steps is not considered. If the user makes a wrong decision during the selection it is mandatory to reach the correction level. Further intermediate correction possibilities are not considered in this presented VK structure.

The structure of a trial during spelling was identical to the one described before (standard Graz-BCI paradigm) except that no arrow indicates the motor imagery to be performed. The subject himself has to decide which type of motor imagery has to be performed to select the subset containing the desired letter. At the end of the trial, the selection region is updated according to the classification result. The break between two trials was omitted in order to increase the number of trials resulting in a maximum σ of 1.25.

2) Experimental Paradigm: The subjects performed two sessions conducted on two different days. The session on the first day started with four runs containing 40 trials each used to setup the two-classes BCI-HMM. In order to overcome to problem of the altered temporal properties of the brain-patterns due to the feedback given during copy spelling, the BCI-HMM comprises HMMs of just one state $(s = 1)$. The training was followed by the copy spelling phase, where every subject had to spell first his own name and, thereafter, the words "VIRTUAL KEYBOARD." The first session ended when both, the name and "VIRTUAL KEYBOARD" were written correctly. On the second day, the subjects directly started with the same spelling tasks as performed on the first day. Training was omitted and the two-classes BCI-HMM from the first day was used. In Fig. 4, the performed experimental paradigms are displayed. The arrows indicate that copy spelling was done based on the two-classes BCI-HMM from the first day. This approach is valid given the experience from prior studies of the Graz-BCI paradigm [4], [8], [9].

3) VK Based on the Two-Classes BCI-HMM: The VK is controlled by the classification result of the two-classes BCI-HMM. Selection of a letter is done corresponding to the

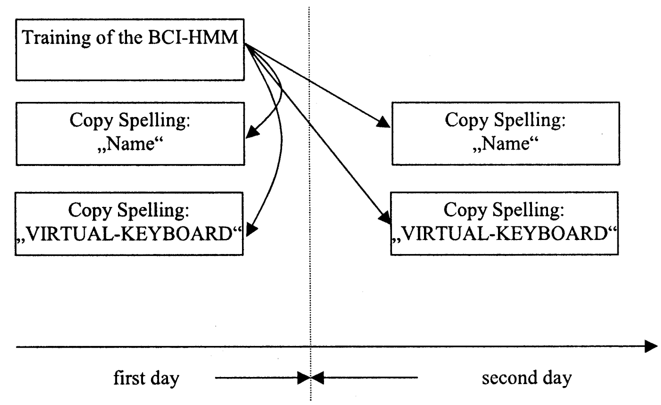

Fig. 4. Experimental paradigm performed on two different days. On both days the spelling tasks stayed the same, on the first day an additional training had to be performed. The arrows indicate that the copy spelling on the first and on the second day was based on the BCI-HMM setup on the first day.

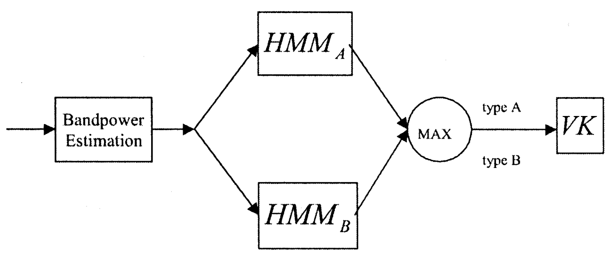

Fig. 5. Block diagram of the VK based on a two-classes BCI-HMM. HMM_A and HMM_B refers to an HMM modeling the two mental tasks.

classified result. For example, a subject selects the left alphabet subset by a left motor imagery and the right alphabet subset by a right motor imagery, respectively. In Fig. 5, the block diagram of the used VK in combination with the two-classes BCI-HMM is depicted.

4) Screen Content of the VK: As a final step, the Graz-BCI and the structure of the VK is combined. The screen content of the Graz-BCI was extended by three areas.

1) Text region: The text region at the top of the screen displays the text already written.
2) Selection region: The middle region of the screen displays the contents of the subsets in a selection level or the commands of the function level.
3) Feedback region: The bottom region displays a feedback to help the user.

5) Subjects: The three young, healthy subjects, (i6 and k3 nonnaive, and m6 naive) were selected to participate because they could achieve a classification error lower than 10% in two-classes BCI-HMM experiments. The two nonnaive subjects achieved this error level after several training periods, subject m6 could achieve this error level in his first BCI session. For all subjects, two bipolar EEG channels were determined according to the mental tasks to be perform. The features for classification were logarithmic band-power estimates in two subject specific EEG bands. Band-power estimation was done sample-by-sample at a sampling frequency of 128 Hz. In Table I, the mental tasks, electrode setup, and used EEG bands are summarized.

TABLE I
OVERVIEW OF THE SELECTED MENTAL TASKS (L: LEFT-HAND MOTOR IMAGERY, R: RIGHT-HAND MOTOR IMAGERY, AND T: TONGUE MOTOR IMAGERY) ELECTRODE POSITIONS AND EEG BANDS. ELECTRODE POSITIONS ARE GIVEN ACCORDING TO THE INTERNATIONAL 10–20 SYSTEM, POSITIONS DEVIATING ARE GIVEN AS ANTERIOR OR POSTERIOR $(+, -)$ A DISTANCE IN CENTIMETERS (E.G. $C3 + 2.5$ REFERS AN ELECTRODE POSITION 2.5 cm ANTERIOR TO C3)

Subject	Mental Task	Electrode Position	EEG Bands
i6	L-R	(C3+2.5, C3-2.5),(C4+2.5, C4-2.5)	8-12Hz, 16-24Hz
k3	R-T	(C3, C3+2.5), (Pz, Pz-2.5)	11-13Hz, 16-20Hz
m6	L-F	(C4, C4+2.5), (Pz, Pz-2.5)	8-12Hz, 16-24Hz

TABLE II
NUMBER OF WRITTEN LETTERS, PERFORMED TRIALS, AND RESULTING σ

Subject	Letters	Trials	σ
i6	44	388	0.85
k3	46	340	1.02
m6	44	494	0.67

III. RESULTS

In Table II, the total number of spelled letters, the number of trials in both days and the resulting spelling rate σ for error-free spelling are presented.

As a second result, the evolution of the number of spelled letters over the performed trials for "VIRTUAL KEYBOARD" is presented in Fig. 6. An error-free letter selection is done in six trials. A decrease of the number of spelled letters can occur when a wrong letter is confirmed and a deletion has to be performed. For example this is the case twice for subject i6 on the first day. Furthermore it has to be noted, that the subjects i6 and k6 wrote "VIRTUAL KEYBOARD" on the second day with just two and three wrong selections, respectively. Given the number of performed trials this results in an online classification error of less than 2% and 3%, respectively.

As an interesting fact, it has to be noted that the two nonnaive subjects could use the VK without any intermediate training sessions. This was not the case for the naive subject m6. When m6 used the VK for the first time, the excellent results of the Graz-BCI could not be repeated, and, therefore, the use of the VK was not possible. Subject m6 had to perform some intermediate sessions of sole Graz-BCI training until he could finally use the VK.

IV. DISCUSSION AND CONCLUSION

The results of the spelling rate (σ) achieved by the three subjects show that the proposed design of the VK is useful as an alternative spelling device. The subjects could achieve a σ varying between 1.02 and 0.67 letters/min.

The fact that subject m6 was not able to use the VK in his first session was caused by too demanding goals set by the authors. In Birbaumer's publication [1], where two locked-in patients are presented, a text had to be written solely by the use of a BCI-based spelling device. This text was the outcome of a long and tenacious period of training. One can conclude that also subject m6 must have a certain level of self confidence using the Graz-BCI, before he can use the VK. The use of a

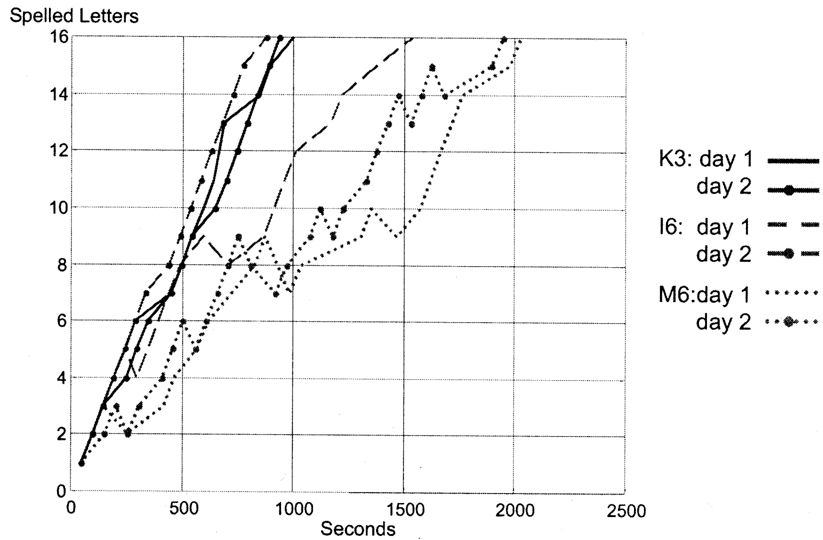

Fig. 6. Propagation of the number of spelled letters during writing "VIRTUAL KEYBOARD" over performed seconds.

VK is more demanding than just the use of the Graz-BCI, because beside performing a predefined (by the symbol) mental task, additionally this mental task depends on the desired letter. This additional task necessitates a certain level of self confidence in the use of the Graz-BCI in order not to get irritated. Subject m6, therefore, performed some intermediate sessions of solely Graz-BCI training. The two other subjects did not need any further training because they already performed numerous BCI-sessions. This explanation can also be further stressed to explain the difference in the performance of σ between the two nonnaive and the naive subjects.

Furthermore, it has to be noted that the online classification error on the second day, writing "VIRTUAL KEYBOARD" of the subjects k3 (3%) and i6 (2%), are lower compared with the cross-validation errors of the BCI-training sessions. This difference can be explained by the fact that during copy spelling, a wrong decision has consequences—a wrongly selected letter has to be written again. This additional motivation to avoid wrong selections is not given during training.

The propagation of the number of spelled letters presented in Fig. 6 demonstrate very clearly the way the VK works. A correct letter selection is done in six trials, a wrong decision results in at least 13 additional trials (six trials performed during the selection of the wrong letter, one for correction and six further ones to write the desired letter). The results of all subjects on the first day are worse than the ones on the second day. Maybe this can be explained by the fact that the subjects get more familiar with the use of the VK and therefore a training effect occurred. This assumption is based on the knowledge of training effects given the standard Graz-BCI paradigm [9].

Even the results achieved are promising it is of importance to keep in mind that all subjects are healthy and do not have any neurologically impairment. Nevertheless, in this early stage of investigations, first basic experiences have to be collected in order to an successful application to patients. First experiences with a patient using the VK are reported in [10].

Further, it would be worth to investigate how alternative optimization methods of the HMM classifier can lead to improvements of the classification results regarding lower classification error as well as shortening of the trial. This would result in both cases in an increase of σ. Given these increases in classification results and speed, this approach may provide the possibility to apply this experience to other applications like described in Wolpaw [11].

Finally, we want to point out that the VK has a potential for further increasing the number of letters spelled per minute. This could be either done by decreasing the break between two imaginations, or by the shortening of the motor imagery phase. Expanding the number of classes to more than two seems feasible when HMMs are used [7]. It could also be considered that the letters have a probability of occurrence (e.g., the letter "e" has the highest probability of occurrence in the German language) and a consideration of these probabilities will also improve the spelling rate. These aspects will have a great impact on the spelling rate of a future version of the VK.

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