A Brain–Computer Interface Speller with a Reduced Matrix: A Case Study in a Patient with Amyotrophic Lateral Sclerosis

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***Abstract*—Visual P300-based Brain–Computer Interface (BCI) paradigms for spelling are aimed at offering a non-muscular communication channel for those people with severe motor impairment, such as locked-in patients. To be as effective as other assistive technologies, these systems have to achieve a greater communication rate. One way to do so is to develop better interfaces. In this regard, we thought of using a 4 x 3 symbol matrix based on the T9 interface developed for mobile phones. Due to presenting a reduced matrix and relying on an adaptation of the T9 predictive text system, we expected that this speller would provide a higher communication rate than usual 6 x 6 matrix spellers that are based on Farwell and Donchin's classic proposal. As a proof of concept, a locked-in patient with amyotrophic lateral sclerosis tested our T9-like visual BCI speller along with two different 7 x 6 conventional matrix spellers. The comparison of her performance results with those of a sample of three healthy participants suggested that it was possible for this locked-in patient to control the T9-like speller as well as they did, and thus, write a target sentence considerably faster than when she used the alternative spellers.**

Keywords-Brain-Computer Interface; P300; Speller; T9 interface, Amyotrophic Lateral Sclerosis.

I. INTRODUCTION

Patients who have suffered a brainstem stroke, a cerebral palsy or that have been diagnosed with a neurological disease such as the Amyotrophic Lateral Sclerosis (ALS) face severe motor impairments. In some cases, they may even enter in a locked-in state [1], in which they lose control of practically all muscular activity. These patients are believed to retain their cognitive abilities intact, although some authors disagree with this assumption (cf. [2][3]).

Brain–Computer Interface (BCI) systems [4] have been developed during the last 40 years to offer a non-muscular channel to these patients, so that they can communicate or control external devices [5][6]. These systems transform the user's brain activity into commands that are interpreted by a machine through which they can control the environment or express needs and feelings.

Regarding the type of brain activity required from the user, BCIs can be roughly divided into those based on spontaneous brain activity, such as Slow Cortical Potentials (SCP, [7]) and SensoriMotor Rhythms (SMR, [8]) and those based on brain responses to external events, mainly the P300 Event-Related Potential (ERP) [9].

To be used efficiently, SCP- or SMR-based BCIs demand from the user an adequate control of his/her brain activity, which is usually acquired after a training period that might take even months. By contrast, P300 is a naturally elicited, positive deflection of the electroencephalogram (EEG) typically appearing about 300 ms after the presentation of an unexpected stimulus. Thus, P300-based BCIs do not demand such an intensive training. Users have simply to attend to the stimulus that is associated to a certain option as it is displayed among other non-relevant stimuli. This elicits a brain activity that is systematic enough so as to be classified with usually perfect accuracy, so that the desired option can be identified.

The first P300-based BCI paradigm for communication purpose was the visual speller developed by Farwell and Donchin [10]. In this speller, a 6 x 6 matrix of symbols was shown to the user. Its rows and columns were randomly intensified for a certain time, during which he/she counted the number of times that the row/column containing the desired symbol was intensified. Those intensifications or flashes constituted the infrequent stimuli, which elicited the P300. Once a sequence of flashes was over, the symbol belonging to the row and column that had produced the largest P300 was regarded as the attended matrix element and displayed to the user.

The effectiveness of this visual speller is supported by several studies that have tested it not only with healthy participants [11]–[15], but also with users affected by some motor disability [16]–[21]. However, the communication rate of these systems is still lower than that of alternative assistive technologies such as the eye tracker.

Aimed at improving the usability of BCI spellers, some authors have examined the impact of user-centred factors on performance. In this regard the mental fatigue induced by a long use [22]–[24], the sustained attention at a symbol that it demands [25][26], the resting heart rate variability [27] or the user's motivation [22][28][29] can influence or be related with performance (see [30], for a review) At the same time, other authors have explored the extent to which performance can be improved by providing BCI spellers with predictive text techniques [31]–[34], or by modifying the temporal of spatial aspects of their interface [35]–[40].

Following these latter research lines, we hypothesized that restricted BCI end-users could benefit from using a visual P300-based BCI paradigm for spelling that shows a reduced 4 x 3 symbol matrix, resembling the T9 interface developed for mobile phones [41]. Specifically, we expected that locked-in patients would benefit from needing less time to select a symbol—due to using a matrix with fewer rows and columns than usual—as they frequently cannot stare at the desired symbol for a long time.

Although a reduced matrix interface has already been proposed with an auditory [42] and a visual P300-based speller [43], it has never been tested, to our knowledge, with BCI end-users. Such a test is necessary because the performance results from a sample of healthy participants do not necessarily apply to end-users in the locked-in state [44]. For example, the higher frequency with which the attended row/column would be intensified together with the complexity of typing through a T9-like interface could overload the cognitive resources of a BCI end-user, which may not be fully available [2][3].

In order to obtain a proof of concept of its actual usability, a locked-in patient diagnosed with ALS performed a copy spelling task using the proposed T9-like speller and also two adaptations of the classic Farwell and Donchin speller. Her performance results were compared with those of a sample of three healthy subjects that had participated in a previous experiment [45]. In the following sections, we will provide a detailed account of the experimental procedure and of the results, and finally discuss their implications.

II. METHODS

A. The case

We visited a 62-year-old woman on two separate days with a time interval of two days between them. She was diagnosed with amyotrophic lateral sclerosis in 2008 and is currently in the locked-in state. Without any independent means of communication, she relies on a partner-scanning approach based on eye blinks to communicate with her relatives and caregivers and on assistive technology (i.e., an eye-tracker system connected to her personal laptop) in order to browse the Internet and interact with friends in social networks.

B. Experimental setup

We carried out only morning testing sessions. The patient sat comfortably in an armchair. A laptop was placed before her over a tray attached to the armchair (see Figure 1). The viewing distance was about 75 cm.

On our first visit to the patient's home, we conducted two sessions to test two BCI paradigms: first, an adaptation of Farwell and Donchin's 6 x 6 matrix speller (hereafter termed *Spellermod*), and then, a Spellermod that included a word predictor (hereafter termed *SpellermodPred*). The proposed T9-like 4 x 3 matrix speller (hereafter termed *SpellerT9*) was tested on a third session on our second and last visit. These three BCI paradigms are described next.

Figure 1. Experimental setup at the patient's home.

C. Tested BCI spellers

To make a proper comparison of the three mentioned BCI spellers in terms of typing speed, the values of all the temporal parameters related to the selection of a symbol were equal across them. These values were based on those used by [12]. Specifically, each row and column was randomly flashed 10 times. Therefore, each character was randomly intensified 20 times. The duration of each flash was 125 ms and the InterStimulus Interval (ISI) between flashes was also 125 ms. There was a pause of 2 s after each sequence of flashes (i.e., after a character had been selected) and also in the beginning of each trial. It is important to notice that the duration of a sequence of flashes depended on the size matrix, so that bigger matrices entailed longer sequences.

1) SpellerT9: The SpellerT9 presented the user a 4 x 3 virtual keyboard (see Figure 2a), in which only eight keys - the ones corresponding to the numbers 2 to 9 - were used for spelling. Each of those keys corresponded to three to four letters. To disambiguate key sequences, we implemented a modified version of the T9 predictive text system, which worked as follows. Given a certain sequence, the system computed the corresponding *textonyms*, that is, all the possible combinations of letters with lexical meaning that could be formed with those contained on the selected keys. These textonyms were then ordered according to their lexical frequency in the Spanish language [46]. The system regarded the most frequently used one as the word the user was trying to type and accordingly displayed it in the text box below the keyboard (see Figure 2a). If that was indeed the desired word, the user accepted it by selecting the key 0 (i.e., selecting the command *espacio*), which simply added a blank space afterwards. Otherwise, he/she could personally disambiguate the key sequence by selecting the key C (i.e., select the command *cambiar*) to switch to a new keyboard that displayed the four most frequently used textonyms in row-major order. For example, given the key sequence 2272, the word *casa* would be displayed in the text box below the keyboard. If the user selected the key C, then the textonyms *casa*, *cara*, *capa*, and *basa* would be displayed on the new keyboard (see Figure 2b). The user could then select one of those textonyms, in which case the word plus an additional blank space were displayed in the mentioned text box. Alternatively, he/she could go back to the previous keyboard by selecting the left arrow key (i.e., selecting the command *volver*).

In order to further increase typing speed, we decided to provide the SpellerT9 with a word predictor. In this case, given a certain key sequence, the predictor computed the lexical frequency of all the words starting with any of all the possible combinations of letters contained on the selected keys, that is, not only textonyms—as in the implemented T9 predictive text system—but also combinations with no lexical meaning. The predictor then regarded the most frequently used one as the word the user was trying to type and displayed it in a text box to the left of the keyboard (see Figure 2a). If that was indeed the desired word, the user could validate it by selecting the key 1 (i.e., selecting the command *validar*). As a consequence, the word plus an addition blank space were written in the text box below the keyboard. In the previous example, the predicted word would have been *barcelona*. Therefore, whereas the word predictor could suggest the user words of more letters than the number of keys selected, the T9 predictive text system only computed words of as many letters as selected keys.

To delete characters the user had to select the key X (i.e., select the command *borrar*). To write digits, he/she had to select the key C just after a blank space had been introduced, either to validate a textonym or because of having accepted the word retrieved by the word predictor. The user could then type the digits from 0 to 9 just by selecting the corresponding keys. Once the desired sequence digits was written, the user had to select the key C again to continue writing words. This selection automatically added a blank space to the numeric sequence.

As the SpellerT9 displayed a 4 x 3 keyboard, the time needed to select a key was 19.5 s, that is, the initial 2 second pause plus the time needed to flash four rows and three columns 10 times each.

2) Spellermod: The Spellermod presented the user a 7 x 6 virtual keyboard, shown in Figure 3a. The last row contained only two command keys - BORRAR and ESPACIO - for deleting the last inserted character and introducing a blank space, respectively. The characters typed by the user were displayed inside a text box below the keyboard.

According to the aforementioned temporal parameters, the time needed to select a key of the Spellermod interface was 34.5 s - the initial 2 second pause plus the time needed to flash seven rows and six columns 10 times each - , that is, almost twice the time needed to select a key from the SpellerT9.

3) SpellermodPred: As we had implemented a word predictor in the SpellerT9 to make typing faster, we decided to add that feature to the Spellermod to control its influence on user performance. Thus, we developed the SpellermodPred, which presented a 7 x 6 virtual keyboard that included the command key VALIDAR (see Figure 3b). The time needed to select a key using the SpellermodPred was 34.5 s, like in the Spellermod.

The typed characters were displayed in a text box below the keyboard and fed into the word predictor. The suggested word was displayed in an additional text box to the left of the former (see Figure 3b). In case that word was the one the user wanted to write, he/she could do it by selecting the command key VALIDAR. As in the SpellerT9, that selection implied writing the suggested word and adding a blank space afterwards.

D. Testing sessions

Prior to all testing sessions, we verbally informed the patient in detail about the procedure and obtained her consent to participate in the study and proceed with the different sessions through partner scanning. The experiment was conducted in accordance with standard ethical guidelines as defined by the Declaration of Helsinki [47].

Each testing session was divided into two phases: a first one for calibration purpose and a second one to evaluate user performance. At the beginning of each session, the researchers explained the patient how to spell words with the corresponding speller. They told her to silently count how many times the symbol she wanted to select was intensified (i.e., flashed) during a sequence of flashes. They informed her that during calibration she would not be receiving any feedback (i.e., the attended symbol). As for the SpellermodPred and the SpellerT9, they also explained her how the word predictor and the T9 predictive text system worked.

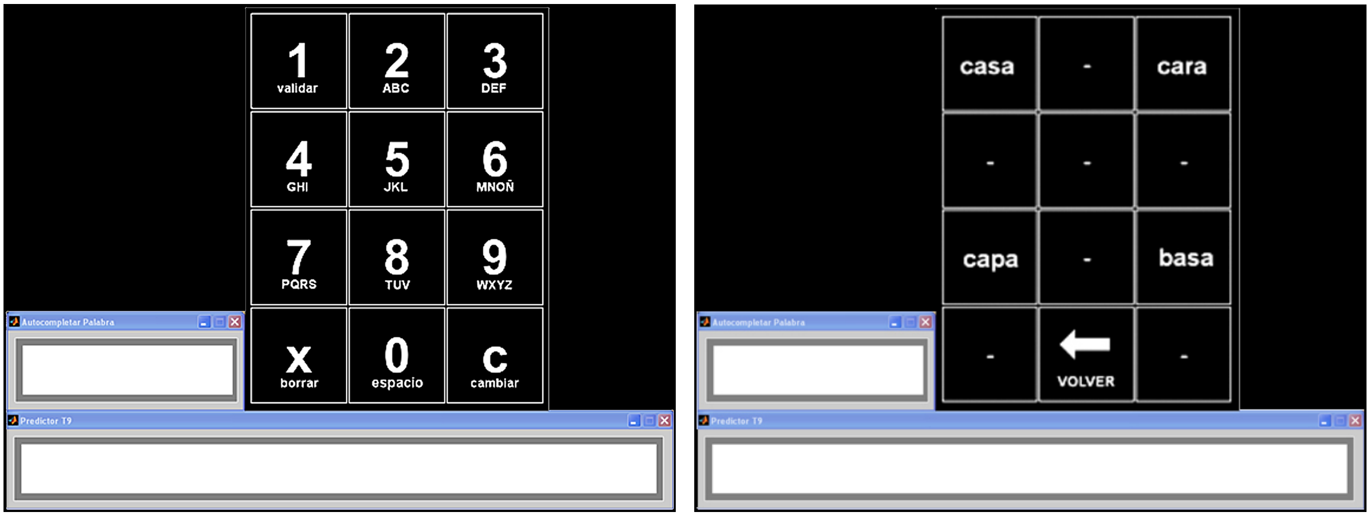
In the calibration phase, the patient was asked to copy spell five sequences of three to four characters, specifically “hoy”, “sin”, “casa”, “remo”, and “tus” for the Spellermod and “159”, “357”, “1xc3”, “4796”, and “258” for the SpellerT9. The classification weights from the Spellermod were also used for the SpellermodPred. In the evaluation phase, she was asked to write the sentence “experiencia bci en la universidad de malaga” (i.e., bci experience at the university of malaga).

Two days after our second visit, we contacted the patient through e-mail to gather her experience as user of the three spellers. We asked her to complete a test consisting of nine questions to be answered with a 5-point Likert scale and also to reply to six open-answer questions, e.g., whether she had any suggestions concerning the interfaces she had interacted with. Her answers were recorded by her relatives and e-mailed back to us six days later.

E. Data acquisition and analysis

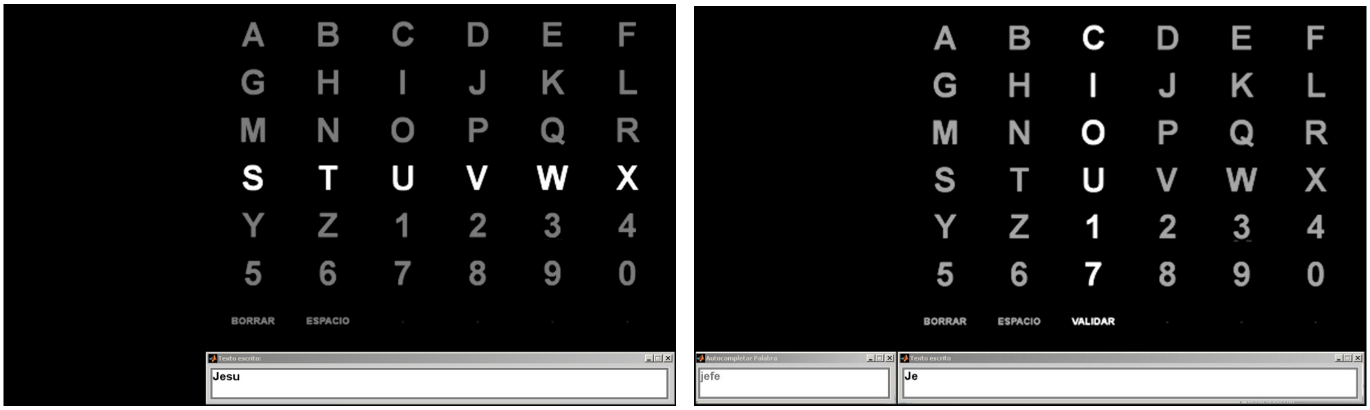
Scalp EEG signals were recorded from eight positions according to the 10-20 standard (FPz, Cz, Pz, Oz, P3, P4, PO7, and PO8) using active electrodes (actiCAP, Brain Products Gmbh, Germany). All channels were referenced to the left earlobe and grounded to FPz. The EEG signals were amplified with an actiCHamp amplifier (Brain Vision LLC, USA), and recorded at 200 Hz using BCI2000 [48].

The stimulation paradigms of the three spellers were implemented using BCI2000. The T9 predictive text system as well as the word predictor used both by the SpellerT9 and the SpellermodPred were implemented as MATLAB R2007a (The MathWorks Inc., USA) routines that were called from the BCI2000 framework. The P300 component was classified using stepwise linear discriminant analysis like in [10].



(a) (b)

Figure 2. The two different interfaces of the SpellerT9. (a) The 4 x 3 virtual keyboard for typing. The text box below the keyboard showed the user's message interpreted by the predictive text system, while the text box to the left displayed the outcome of the word predictor. (b) In case the textonym selected was not the word desired by the user, he/she could disambiguate the key selection by choosing among the four most frequently used textonyms. In the figure, the selected keys would have been 2272. See text for details.



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(a) (b)

Figure 3. The interfaces of the two 7 x 6 matrix spellers that were tested: the Spellermod (a) and the SpellermodPred (b). The Spellermod presented a 7 x 6 virtual keyboard and a text box for displaying the user's message, whereas the SpellermodPred showed an additional text box for displaying the word suggested by the word predictor.

III. RESULTS AND DISCUSSION

The time needed by the locked-in patient and by the three healthy participants to spell each word of the target sentence (i.e., "experiencia bci en la universidad de malaga") using the three compared spellers are shown in Table I. Unfortunately, most of the data corresponding to the first testing session (i.e., the one corresponding to the Spellermod) at the patient's home were lost due to a software failure.

Table I also shows the minimum required times, that is, the time that a user that made no mistake nor slip would need to write each word. As can be seen, the total spelling times of the locked-in patient were similar to those of the healthy participants when using the same speller, that is, the SpellermodPred and the SpellerT9.

The data from healthy participants suggest that the word predictor included in the SpellermodPred contributed to reducing the overall time needed to write the target sentence with respect to the Spellermod. Comparing the results of the SpellermodPred and the SpellerT9, it also seems likely that using a matrix with fewer rows and columns increased the communication rate further than the word predictor did. In fact, the locked-in patient wrote the target sentence over 1.5 times faster with the SpellerT9 than with the SpellermodPred. It is also remarkable that the patient made no mistake nor slip using the SpellerT9 when writing four of the seven words of the target sentence (i.e., "experiencia", "en", "la", and "de").

As for her personal assessment of the spellers, she regarded the SpellerT9 as the fastest of all three and did not find it too difficult to use. She also indicated that all the spellers were equally exhausting to use. Despite her good performance, she found the SpellerT9 more confusing to use than both the

TABLE I. TIME NEEDED BY THE LOCKED-IN PATIENT AND BY THE THREE HEALTHY PARTICIPANTS TO WRITE EACH WORD OF THE TARGET SENTENCE AS A FUNCTION OF THE SPELLER THEY USED.

	Time for each word (s)							
Speller	"Experiencia"	"BCI"	"en"	"la"	"Universidad"	"de"	"Málaga"	Total time (s)
				Locked-in patient				
Spellermod	586.5							
SpellermodPred	172.5	138	103.5	103.5	207	103.5	207	1035
SpellerT9	78	97.5	58.5	39	136.5	39	214.5	663
				Healthy participant 1				
Spellermod	414	138	103.5	103.5	621	103.5	276	1759.5
SpellermodPred	172.5	138	103.5	69	207	103.5	207	1000.5
SpellerT9	78	78	58.5	39	97.5	39	117	507
				Healthy participant 2				
Spellermod	483	345	310.5	172.5	483	103.5	276	2173.5
SpellermodPred	138	103.5	103.5	172.5	517.5	69	345	1449
SpellerT9	78	156	58.5	78	214.5	78	177	840
				Healthy participant 3				
Spellermod	414	138	103.5	103.5	414	172.5	270	1615.5
SpellermodPred	138	138	103.5	69	172.5	69	207	897
SpellerT9	78	117	78	39	97.5	39	156	604.5
				A user that made no mistake				
Spellermod	414	138	103.5	103.5	414	103.5	270	1546.5
SpellermodPred	138	103.5	103.5	69	172.5	69	207	862.5
SpellerT9	78	78	58.5	39	97.5	39	117	507

Spellermod and the SpellermodPred, particularly due to not knowing which letter was going to be chosen after a key selection. Nevertheless, she also found it more entertaining than those two. Importantly, she thought she needed more training with all the spellers.

IV. CONCLUSION AND FUTURE WORKS

The main goal of this study was to obtain a proof of concept that a locked-in patient diagnosed with amyotrophic lateral sclerosis could efficiently control a visual P300-based speller with a T9-like interface consisting of 4 x 3 virtual keyboard and an adaptation of the T9 text predictive system of mobile phones.

Our data suggest that the locked-in end-user that participated in the study was able to control the proposed speller as well as a sample of healthy participants did. Importantly, the communication rate the patient achieved with this new speller was higher than the one achieved when using a 7 x 6 matrix speller, even when this also included a word predictor.

However, it should be kept in mind that this particular locked-in patient uses her laptop almost daily to browse the Internet or interact in social networks. Besides, she is always greatly motivated to participate in research studies and has a very supportive circle of relatives and friends around her. Therefore, her good performance results and her assessment of the proposed speller cannot be fully generalized to other locked-in patients. More studies involving other locked-in end-users should be done to account for individual differences.

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