Highlights

- We propose a novel P300-based lateral single-character (LSC) speller, that explores layout, event strategy, and hemispheric asymmetries in visual perception to improve the performance of brain-computer interfaces;
- The online performance of LSC paradigm is compared to that of the standard row-column (RC) paradigm;
- The paradigms are tested by individuals with neuromuscular disorders (amyotrophic lateral sclerosis, cerebral palsy, Duchenne muscular dystrophy, and spinal cord injury);

Comparison of a Row-column Speller vs a Novel Lateral Single-character Speller: assessment of BCI for severe motor disabled patients

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Abstract

Objective: Non-invasive brain-computer interface (BCI) based on electroencephalography (EEG) offers a new communication channel for people suffering from severe motor disorders. This paper presents a novel P300-based speller called lateral single-character (LSC). The LSC performance is compared to that of the standard row-column (RC) speller (Farwell and Donchin, 1988).

Methods: We developed LSC, a single-character paradigm comprising all letters of the alphabet following an event strategy that significantly reduces the time for symbol selection, and explores the intrinsic hemispheric asymmetries in visual perception to improve the performance of the BCI. RC and LSC paradigms were tested by 10 able-bodied participants, 7 participants with amyotrophic lateral sclerosis (ALS), 5 participants with cerebral palsy (CP), one participant with Duchenne muscular dystrophy (DMD), and one participant with spinal cord injury (SCI).

Results: The averaged results, taking into account all participants who were able to control the BCI online, were significantly higher for LSC, 26.11 bit/min and 89.90% accuracy, than for RC, 21.91 bit/min and 88.36% accuracy. The two paradigms produced different waveforms and the signal-

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to-noise ratio was significantly higher for LSC. Finally, the novel LSC also showed new discriminative features.

Conclusions: The results suggest that LSC is an effective alternative to RC, and that LSC still has a margin for potential improvement in bit rate and accuracy.

Significance: The high bit rates and accuracy of LSC are a step forward for the effective use of BCI in clinical applications.

Keywords: Brain-computer interface, Electroencephalography, P300, Event related potential, Visual-paradigm, Rehabilitation

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1. Introduction

Brain computer interfaces (BCIs) can offer new communication opportunities to individuals with severe motor disabilities (Wolpaw et al., 2002). Individuals who suffer from severe motor disabilities by disorders such as amyotrophic lateral sclerosis (ALS), progressive muscular dystrophy, cerebral palsy (CP) and spinal cord injuries (SCI) are potential BCI users (Mak and Wolpaw, 2009). BCI can also represent an alternative to other interfaces for individuals who still retain a weak ability to control some part of the body, but whose motor performance is very low and show difficulty in controlling some standard interfaces. Increasing the communication abilities of these individuals by improving the accessibility to computers and means of locomotion such as wheelchairs, provides a higher level of independence and self-satisfaction, thus enhancing their quality of life.

A P300 BCI is a non-invasive interface based on EEG which has already been used successfully by people with several types of motor disabilities (Mak and Wolpaw, 2009). A P300 BCI requires little training favouring its effective clinical application. P300 is an event related potential (ERP) detected mainly over central and parietal regions, that is elicited by a relevant stimulus in an oddball paradigm (Farwell and Donchin, 1988; Comerchero and Polich, 1999). The first BCI system using this neuromechanism was introduced by Farwell and Donchin through the well known row-column (RC) speller device (Farwell and Donchin, 1988).

Implementation of a P300-based BCI system can generically be divided in two parts: (a) signal processing and classification methods; and (b) design of the paradigm/protocol. Until now, most of the research has focused on the improvement of signal processing and classification methods, but recently there has been a growing interest in paradigm design. By improving simultaneously these two issues it is possible to greatly increase the accuracy and transfer rates of P300 BCIs. While in (a) the main concern is to improve the detection of the P300 component, by means of new signal preprocessing, feature extraction, feature selection and classification methods, in (b) the main concern is to improve the 'quality' of the P300 evoked potential as well as to improve the time for symbol selection. The term 'quality' embodies aspects related to waveform morphology, variability, and discrimination of ERP from the background EEG. As regards signal processing and classification, many successful methods have been proposed (e.g., (Donchin et al., 2000; Kaper et al., 2004; Krusienski et al., 2006; Rakotomamonjy and Guigue, 2008; Lenhardt et al., 2008; Hoffmann et al., 2008b; Pires et al., 2011b)). Concerning the visual paradigm design, the topic of the work presented in this paper, several approaches have been recently investigated and assessed as described in the following sections.

1.1. Design of P300 paradigms

P300-based BCIs should be designed to enhance simultaneously: (1) the 'quality' of the P300 component, which has direct influence on the classification accuracy; (2) the amount of encoded information; and (3) the number of decoded symbols per minute. Increasing one of these parameters while decreasing the others may have little impact on the improvement of communication rates. It is known that the P300 ERP represents cognitive functions that vary according to stimulus modality, stimulus probability, stimulus onset asynchrony (SOA), task-relevance, decision making, selective attention, expectancies and relative perceptual distinctiveness among stimuli (Polich, 2007; Rohrbaugh et al., 1974; Polich et al., 1996; Comerchero and Polich, 1999; Heinrich and Bach, 2008). In essence, a P300-based BCI uses an attention task where temporal, spatial, object-based and featural attention can be manipulated (Correa et al., 2006; Mercure et al., 2008). Thereby, there are many parameters that can modulate the P300 component and that can be configured in P300-BCIs to enhance the evoked P300. On the other hand, issues such as user-friendliness and comfort, should not be overlooked when the interface is intended to be used on a daily basis.

1.2. Standard RC speller

The original RC speller is the most widely used P300 speller and has already shown to achieve effective transfer rates for clinical use (Kubler and

Birbaumer, 2008). It encodes a large number of symbols with a small number of events, which potentiates high information transfer rates (ITRs). Notwithstanding, the RC speller presents some issues that limit its performance. Two known problems identified from our own experience and well documented in Townsend et al. (2010) are the adjacency-distraction errors and the double-flash errors. In the first case, non-targets rows/columns adjacent to target rows/columns may distract or deceive the user and be erroneously selected. This is an example of spill-over of spatial attention. The second case occurs when there are two consecutive target flashes. The second flash is usually unnoticed by the user, and does not evoke a P300 signal. Even if the second flash is noticed, there will be an overlap of the two components causing a change of the P300 waveform morphology increasing its variability (Martens et al., 2009). This is an example of spill-over of temporal attention and target-to-target interactions. The frequent occurrence of overlap in the RC paradigm is due to its short target-to-target interval (TTI), which is in turn related with the short SOA (stimulus onset asynchrony - interval between the onset of two consecutive stimuli) and with the high target probability (1:6). The P300 amplitude is adversely affected by the high target probability because amplitude and probability are inversely proportional. Overcoming these two aspects by modifying the original RC paradigm represents a considerable challenge. For example, increasing the SOA leads to a lower ITR. Moreover, a decrease of the probability can only be achieved with a larger matrix, possibly encoding unnecessary symbols and increasing the time for symbol selection.

1.3. New visual paradigms and RC modifications

Several studies have investigated new strategies for stimuli presentation and the impact of their physical properties (see a summary in Table 1). Studies in Allison and Pineda (2003); Sellers et al. (2006); Nam et al. (2009) investigated the effect of changing the size of the original RC matrix on the P300 amplitude, and showed that larger matrix sizes increased the amplitude. Notwithstanding, in Sellers et al. (2006) the smaller matrix reached higher accuracy, possibly due to the better separated spatial attention signals (better attentional 'zoom-in'). The effect of different SOAs in the RC speller was also analyzed and non-consensual results were reached. In Farwell and Donchin (1988); Nam et al. (2009), a longer SOA increased the P300 classification accuracy. In Sellers et al. (2006); Meinicke et al. (2002), a shorter SOA led to a higher accuracy, but to lower P300 amplitudes (Sellers et al., 2006). In experiments addressing either probability or the role of SOA, it seems that there is no straightforward probability and SOA relation between P300 amplitude and classification accuracy. This may be due to the fact that one may have to take into account the joint effects of spatial, temporal and object based attention, and the final result will depend on an amplitude vs. overlap tradeoff.

P300 is considered an endogenous component not very influenced by the physical attributes of the stimuli (Sanei and Chambers, 2007). However, such physical attributes might indirectly affect the response by modulating perceptual saliency as suggested by our own observations (Teixeira et al., 2010). Accordingly, exogenous attributes such as intensity, color and size can enhance stimulus discrimination and perception, eliciting higher and faster components (Polich et al., 1996; Treder and Blankertz, 2010). In Salvaris and Sepulveda (2009) and Takano et al. (2009), several physical parameters of the original RC speller were changed and assessed, namely, background and symbol color, symbol size, inter-symbol distance, and luminance/chromatic flicker.

New flash-patterns presentations have been proposed as alternatives to the standard RC approach. In Allison and Pineda (2006) a multi-flash approach was analyzed aiming to reduce the number of necessary flashes within a trial to detect a symbol. A fewer number of flashes can lead to an increased ITR if the level of accuracy is kept. Townsend et al. (2010) introduced a new paradigm referred as checkerboard that relies on a "splotch" stimulus presentation (Allison, 2003), where the stimuli of the matrix are presented in predefined groups instead of rows and columns. The checkerboard approach eliminates the double flash effect, reduces the problem of component overlapping, and avoids the adjacency-distraction issue. Despite the fact that the standard matrix is increased to a 8×9 matrix requiring 24 flashes per selection, thus increasing the time to make a selection, the achieved results show even so an increased performance over the standard RC paradigm. Also based on the "splotch" concept, the use of different number of flashes was compared, showing improvements over the RC speller (Jin et al., 2011).

An alternative to the RC-based speller is the single-character (SC) speller wherein each symbol is individually highlighted. In the SC speller, each event only encodes a single symbol, resulting in low ITR. Moreover, the number of distractor symbols is larger than in RC, since the number of flashes is the same as the number of symbols. However, on the other hand, the SC speller has a lower target probability and the TTI is larger, which are two

Table 1: Summary of new stimuli presentation paradigms and the effects of stimuli properties.

Stimuli properties and presentations	Studies
Manipulation of RC properties:	
- Effects of matrix size and ISI	Allison and Pineda (2003); Sellers et al. (2006); Nam et al. (2009)
- Effects of SOA	Farwell and Donchin (1988); Meinicke et al. (2002); Sellers et al. (2006); Nam et al. (2009)
- Effects of physical attributes: color, luminance, size, inter-symbol distance	Salvaris and Sepulveda (2009); Takano et al. (2009)
Manipulation of flash patterns:	
- Multi-flash	Allison and Pineda (2006)
- 'Splotch'	(Allison, 2003; Townsend et al., 2010; Jin et al., 2011)
- Single-char	Guan et al. (2004); Guger et al. (2009)
Gaze independent paradigms:	
- Two-level based	Treder and Blankertz (2010); Pires et al. (2011a)
- Sequential central disk	Liu et al. (2010)

parameters that can enhance the P300 amplitude and avoid overlapping. Guan et al. (2004) compared the SC speller with the RC speller and achieved significantly better results with the SC speller. However, in a study made by Guger et al. (2009) with 100 participants, the results showed a significantly higher accuracy with the RC speller. Although the P300 amplitude has been higher for the SC speller than for the RC speller, the average accuracy was worse for SC.

Several speller paradigms addressing the gaze-independence issue have also been proposed. A two-level speller is presented in Treder and Blankertz (2010) and in Pires et al. (2011a). In Liu et al. (2010) rows and columns are displayed sequentially in a central disk . The main goal of these approaches is to improve the spatial arrangement of the symbols (central layout with larger symbols) in order to allow a covert attention task, i.e., target detection without requiring eye movements to gaze the target symbol. This issue is particularly important when individuals with severe motor disability lose the ability to move the eyes (Palmowski et al., 1995).

1.4. Proposed speller and analysis

This study proposes a novel speller, henceforth called lateral single character (LSC) speller (described in section 2.3). It introduces new features that overcome some of the limitations found in current SC spellers and in standard RC spellers. Namely, compared to other SC spellers, the layout reduces the effect of local and remote distractors, and the flashing/event strategy allows to drastically reduce the SOA. This reduction makes the overall time of one trial very similar to those usually achieved in the RC speller with the same amount of encoded symbols. By bringing together these features with the inherent lower target probability and higher TTI of SC spellers, LSC elicits a P300 with higher 'quality', thus improving the classification accuracy. Furthermore, the paradigm is expected to be more visually attractive and comfortable.

In this study, LSC and RC spellers are compared based on online sessions performed by able-bodied and disabled persons, by assessing the accuracy, symbols per minute and ITR. Participants answered to a questionnaire to assess both subjective and objective parameters of the interfaces. The BCI performance is also compared with the performance achieved with non-EEG interfaces for those participants who use standard interfaces in their daily lives. Datasets gathered during calibration sessions were used for an offline analysis. We compared the amplitude, latency and signal-to-noise ratio (SNR) of the ERPs elicited by the RC and LSC paradigms. In which concerns LSC, new discriminative neurophysiologic features related with the lateral layout and event strategy are investigated and discussed in section 4.3.

2. Materials and Methods

2.1. Participants

The experiments were performed by ten able-bodied participants, five participants with cerebral palsy (CP), one participant with Duchenne muscular dystrophy (DMD), one participant with spinal cord injury (SCI) and seven participants with amyotrophic lateral sclerosis (ALS). All participants gave informed consent to participate in the study. Table 2 shows a summary of clinical data of the participants with motor disabilities, as well as their main signs, levels of functionality, and interfaces currently used in their daily lives. Participants S18, S19, S20, S21 and S24 are confined to a wheelchair, and use adapted interfaces to steer the wheelchair and to access the computer. Participant S23 is also confined to a wheelchair but cannot control it, and recently lose the ability to control an head-tracker. All these participants suffer from severe motor disabilities and are highly dependent of human assistance. Participant S22 can walk but requires a special device to access the computer keyboard. One of the above individuals is in the borderline range of intellectual functioning. Participants S11-S17 have ALS with either bulbar or spinal onset. Their main signs are respectively dysarthria and dysphagia, and muscular weakness. None of the ALS individuals are in an advanced stage of the disease and therefore none of them currently uses adapted interfaces. The degree of disability was rated by using the revised ALS functional rating scale (ALSFRS-r) where 48 represents a normal score and 0 a complete loss of functionality (Cedarbaum et al., 1999). The group of able-bodied participants is composed of 3 males and 7 females with ages ranging from 24 to 38 years old, averaging 29.2 years old. Able-bodied participants are referred as group I, ALS participants are referred as group II, and for sake of concise presentation, CP, DMD and SCI participants, all suffering from severe communication and mobility limitations, are referred as group III. Participants of group III, all use in their daily lives non-EEG interfaces to control the computer and/or the wheelchair, and thus their BCI performances were compared to those achieved with their usual non-EEG interfaces.

2.2. Standard paradigm: Row-Column speller

The RC speller is based on the original 6×6 matrix. It comprises the alphabet letters and other useful symbols such as the 'spc' and 'del' as shown in Fig.1a). The SOA was settled to 200 ms, and the highlight time for each row/column was settled to 100 ms. The rows and columns are randomly highlighted by changing the color from gray to white. The size of the symbols are slightly increased by $\approx 15\%$ when highlighted. A sub-trial (complete round of rows and columns flashes) takes $12 \times 0.2 = 2.4$ s. A trial (set of sub-trials necessary to select a symbol) was adjusted according to user performance. The inter-trial interval (ITI) was settled to 2.5 seconds to allow the user to switch the attention focus for a new mentally selected symbol. It was assumed that the user could gaze the symbol (overt attention).

Table 2: Motor disabled individuals: summary of main signs, functional status, and interfaces.

Subject/ Sex	Age	Diagnosis	Time since diagnosis	Main signs / Main functionality	Adapted interfaces and assistive devices
S18/F	18	CP	Posnatal	Tetraparesis, dystonia with spasticity and dysarthria / Head control	Powered wheelchair: head-switch connected to a scanning interface; Computer: head-switch and head-tracking
S19/M	34	CP	Perinatal	Tetraparesis, dystonia with spasticity, and high dysarthria / Head and right foot control	Powered wheelchair: adapted joystick controlled by right foot; Computer: controls mouse and keyboard with the right foot
S20/M	46	CP and discal hernia C3-C4	Perinatal	Tetraparesis, spasticity and dysarthria / Head control	Powered wheelchair: joystick adapted to chin; Computer: head-tracking
S21/M	45	CP	Neonatal	Tetraparesis, choreoathetosis and high dysarthria / Head and feet control	Manual wheelchair: foot; Computer: helmet with pointing device to select letters of the keyboard
S22/F ID07	42	CP	Neonatal	Tetraparesis, ataxia (high motor incoordination) and dysarthria / Walking ability and coarse control	Computer: grid over the keyboard and use of track-ball (with difficulty)
S23/M ID05	30	DMD	>22 years	Tetraplegia / Slight movements of the head, jaw control	Manual wheelchair: no control; Computer: used to control head-tracking
S24/M ID06	28	Spinal cord injury: C3-C4 lesion	12 years	Complete spatic tetraplegia and tracheotomy / Slight movements of the head and of the left upper limb	Powered wheelchair: joystick adapted to chin; Computer: head-tracking
S11/F	67	Bulbar-onset ALS (FRS-r 46)	7 years	Dysarthria, dysphagia, and muscular weakness in upper limbs / -	-
S12/F	75	Bulbar-onset ALS (FRS-r 40)	1 year	High dysarthria and dysphagia / -	-
S13/M	58	Bulbar-onset ALS (FRS-r 47)	1 month	Slight dysarthria and dysphagia / -	-
S14/F	78	Spinal-onset ALS (FRS-r 32)	1 month	Muscular weakness in limbs and high dysarthria / -	Manual wheelchair
S15/M	80	Bulbar-onset ALS (FRS-r 44)	1 month	Dysarthria / -	-
S16/M	66	Spinal-onset ALS (FRS-r 41)	2 months	Muscular weakness (left leg) and slight dysarthria / -	Crutch
S17/M	78	Spinal-onset ALS (FRS-r 40)	5 months	Hands and arms weakness and slight dysarthria / -	-

2.3. Novel paradigm: Lateral single-character speller

The proposed LSC speller is shown in Fig.1b). It encodes 28 symbols comprising all letters of the alphabet, and the 'spc' and 'del' symbols. It has a lateral and symmetrical arrangement where the symbols flash alternately between the left and right fields of the screen (see the temporal diagram of Fig. 1c)). There is always a symbol highlighted, thus the ISI (inter-symbol interval) is eliminated. The SOA coincides with the highlight time of a symbol, which substantially reduces the sub-trial time. The symbols are flashed pseudo-randomly since the side of consecutive flashes is controlled, but within each side the symbols are flashed randomly. The user is overtly focused on the left or on the right side of the screen and therefore the participant sees virtually only half of the stimuli, because stimuli on the opposite side are nearly ignored (remote distractors). Likewise, despite the target probability being 1:28, the user perceives virtually a target probability of 1:14. Moreover, the user sees the on-off visual effect although there is always an active symbol, i.e., the ISI is zero, but for each side of the screen there is respectively a left ISI and a right ISI. In the experiments, the SOA was settled to 75 ms and thus each round of flashes took $28 \times 0.075 = 2.1$ s. The symbols are arranged to minimize the effect of local distractors. This effect depends on the number and distance of the surrounding stimuli. In the typical 6×6 RC or on a SC matrix layout, a central symbol has 8 surrounding distractors, while in the LSC speller the maximum number of surrounding distractors is 4 (see Fig. 1d)). The circular layout of the speller provides similar eccentricities for all symbols, avoiding large eye movements to see symbols in the corners, as occurs in RC. The highlighting of each symbol is made by changing the foreground/background color of the symbol from white/grey to red/green, and by increasing the size by $\approx 15\%$. Finally, in the LSC speller, the spelled or copied letters are presented in a central position of the screen, while in the RC speller they are presented at the top of the screen. The central position avoids large eye movements to check the detected spelled symbol.

2.4. Calibration and online sessions

The experiments consisted of calibration and online sessions that took place at facilities of the Cerebral Palsy Association of Coimbra (APCC) (group III), at the Hospitals of the University of Coimbra (HUC) (Group II) and at our laboratory facilities (Group I). The online sessions were preceded by a calibration session. The participants were instructed to be relaxed and attend to the desired target, while mentally counting the number of

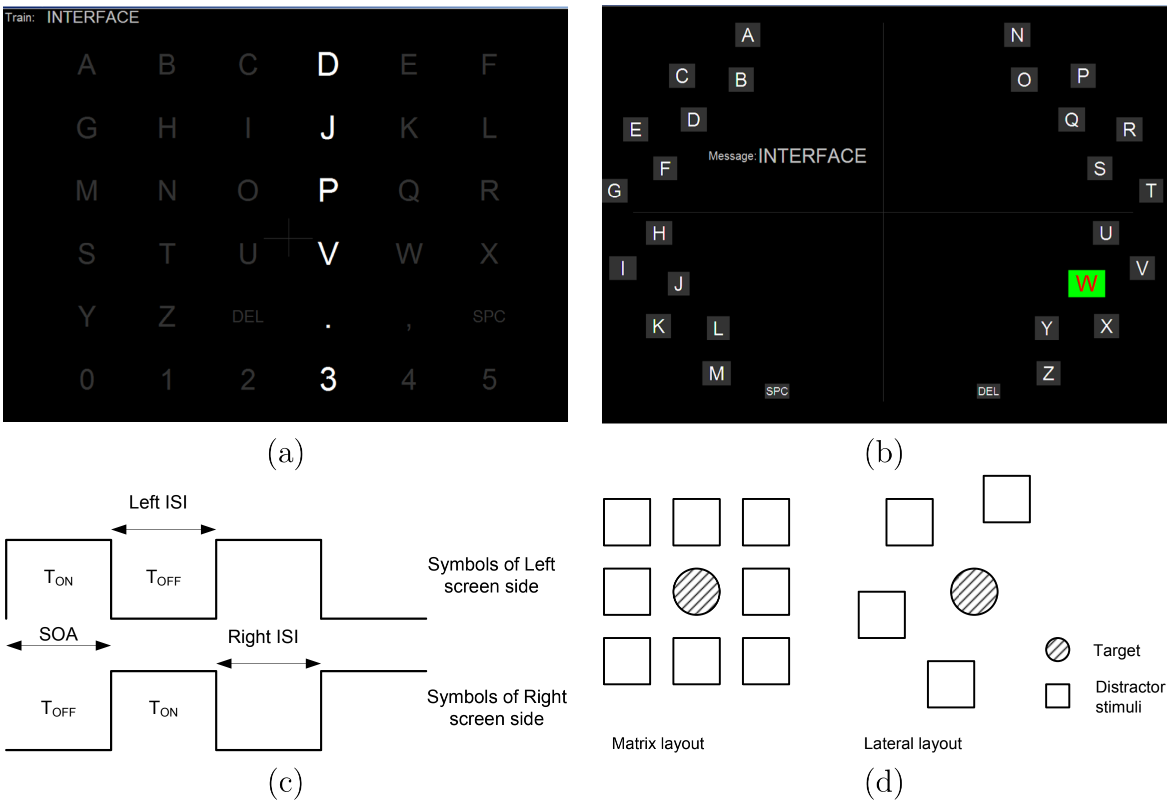

Figure 1: (a) Screenshot of the 6 × 6 matrix of the standard RC speller; (b) Screenshot of the LSC speller (RC and LSC paradigms are drawn with the same scale); (c) Temporal diagram of the LSC stimuli/events. T_{ON} is the highlight time and T_{OF} is the time between flashes on each screen side (Left ISI or Right ISI). T_{ON} has to be equal to T_{OFF}; d) Local distractors on a matrix layout and on the LSC layout.

'perceptual intensifications' of such target events. Participants S18-S21, S23-S24 and S14 were seated at their own wheelchairs (see a photo taken during one experimental session in Fig. 2). The remaining disabled and able-bodied participants were seated on a standard chair. A computer screen was placed at a distance around 60 cm, adjusted to each participant.

During the calibration phase, the participants attended the letters of the word 'INTERFACE' (9 characters) which were successively provided at the top of the screen in the RC speller, and at the center of the screen in the LSC speller. For each calibration letter, each symbol was flashed 10 times. The calibration session takes less than 5 minutes for both paradigms. The EEG data segment (epoch) associated to a flashing event has a duration of

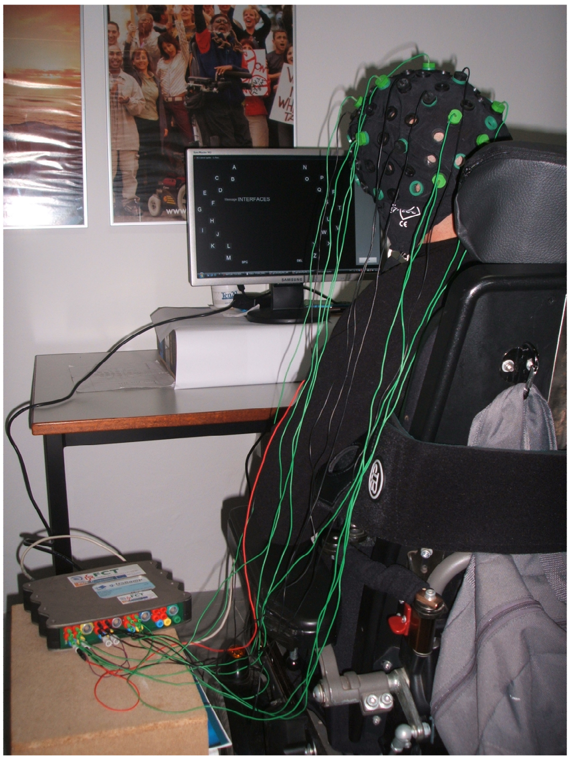

Figure 2: Photo taken at APCC during an experimental session.

1 s, recorded from the onset of the flash. The calibration dataset of each participant contains 180 target epochs and 900 non-target epochs for the RC speller, and 90 target epochs and 2430 non-target epochs for the LSC speller. These datasets were used to obtain the classification models through a process that takes only a couple of minutes. The online sessions occurred under the same conditions as the calibration phase. There was no difference in the procedure between the able-bodied participants and the impaired participants, except for subject S14. This participant had a low visual acuity and it was necessary to point out the location of each letter. It was asked to the able-bodied participants to spell the sentence 'THE-QUICK-BROWN-FOX', and it was asked to the motor impaired participants, not familiarized with the English language, to write the portuguese sentence 'ESTOU-A-ESCREVER'. The sentences were written at once without interruptions. In case of error, participants could opt to correct the character using the 'del' symbol. The duration of each experiment depended on the number of sessions, which in

turn, varied according to the participant's performance.

2.5. EEG recording

The EEG activity was acquired with a g.tec gUSBamp amplifier. Signals were recorded from 12 Ag/Cl electrodes at positions Fz, Cz, C3, C4, CPz, Pz, P3, P4, PO7, PO8, POz and Oz of the international extended 10-20 standard system with a g.tec cap. The electrodes were referenced to the right or left ear lobe and the ground was placed at AFz. Signals were sampled at 256 Hz, and filtered by a 0.1-30 Hz bandpass filter and a 50 Hz notch filter. The electrodes impedance varied from subject to subject, but were almost always kept under $10K\Omega$. The placement of electrodes in participant S22 was hampered by her high motor incoordination, and thus a different electrode-cap (also from g.tec) was also tested.

2.6. Classification

The offline and online classification was performed following the methodology presented in Pires et al. (2011b). It uses a statistical spatial filter that is a cascade of a Fisher beamformer and a Max-SNR beamformer (C-FMS). The twelve input channels are transformed into two high SNR projections used as features for a naïve Bayes classifier (NB). The spatial filter is applied to the average of the epochs collected from the repetitions of the same event. The spatial filter and classification models were obtained for each participant from the calibration data. In the RC speller the whole calibration data set was used (180 target epochs and 900 non-target epochs), while in the LSC speller it was used the 90 target epochs and 840 of the 2430 non-target epochs (to have more balanced datasets). In RC, the online selection of the symbol resulted from the combination of the row and column with highest scores. In LSC, the detected symbol was the one associated with the event with the highest score.

2.7. Bit rate metrics

The ITR is an important metric to assess BCI performance. It reflects simultaneously the accuracy, the symbols per minute (SPM) and the amount of encoded information. The following formula was used to compute the ITR in bits per minute (bpm) (Wolpaw et al., 2002)

$$ITR = M\left[\log_2(N_s) + P_{ac}\log_2(P_{ac}) + (1-P_{ac})\log_2\frac{(1-P_{ac})}{(N_s-1)}\right] \qquad (1)$$

where N_s is the number of possible selections, P_{ac} is the accuracy, and M is the number of possible decisions per minute, computed from $M = 60/(N_{rep} \times (N_{ev} \times SOA) + 1 + ITI)$. N_{rep} is the number of repetitions, N_{ev} is the number of events per round, and the value 1 is the time required to record the epoch of the last event of a trial. For instance, in RC, $N_{ev} = 12$ and thus $M = 60/3.4$ for one repetition omitting the ITI; in LSC, $N_{ev} = 28$ and thus $M = 60/3.1$ for one repetition omitting the ITI. The online spelling accuracy, P_{ac} was measured according to

$$P_{ac} = 1 - \frac{N_e}{N_c + N_{ce}} \tag{2}$$

where N_e is the number of misspelled characters/symbols, N_c is the number of characters of the sentence and N_{ce} is the number of corrected errors with 'del'. To correctly evaluate the effective use of a BCI system, the ITR should always be presented with its respective accuracy (Sellers et al., 2006). For example, in a 6×6 matrix with $N_{rep} = 5$, $ISI = 200$ ms and $ITI = 0$ condition, a classification rate of 60% accuracy provides a reasonable ITR of 9.9 bpm, however it would be required 50 selections to correctly complete a 10-character sequence, which is unacceptable for an effective communication. On the other hand, if errors are not corrected, the sequence is not intelligible. Thus, an accuracy of at least 70% is usually required (Townsend et al., 2010). So, from a practical point of view, a bit rate taking into account the number of retries to correctly spell a character is more effective. A practical bit rate (PBR) was computed based on the number of retries, N_r (Dal Seno et al., 2010; Townsend et al., 2010)

$$N_r = \frac{1}{1 - 2(1 - P_{ac})} \qquad if \quad (1 - P_{ac}) < 0.5. \tag{3}$$

The practical bit rate can then be obtained from

$$PBR = \frac{M}{N_r} \log_2 N_s. \tag{4}$$

2.8. SNR contribution to ERP variability analysis

Several studies referred in section 1.3 show non-consensual results suggesting the absence of a straightforward relation between P300 amplitude and classification accuracy. SNR measurement of target ERPs can add valuable information to their characterization in addition to the waveform morphology, since it assesses the variability of inter-trial ERPs. Although classification accuracy depends not only on the ERP variability, but also on the separation between target and non-target ERPs, our own observations indicate a direct relationship between SNR and classification performance (Pires et al., 2011b). To infer this relationship and to assess the inter-trial variability of ERPs, the SNR was computed for both paradigms. Suppose a target epoch recorded from a trial k at an arbitrary channel, defined as

$$\mathbf{x}_k = \mathbf{s}_k + \mathbf{n}_k \tag{5}$$

where s_k is the signal component and n_k is the uncorrelated noise component. Let us consider that the noise process n_k has an ensemble mean zero and an ensemble variance σ_n^2, and that the signal process s_k has an ensemble average $\overline{s}$, and an ensemble variance σ_s^2. The SNR of $\mathbf{x}$ can be estimated from (Lemm et al., 2006)

$$\begin{aligned} \mathrm{SNR}(\mathbf{x}) &= \frac{\mathrm{var}_t(\mathrm{E}_k[\mathbf{x}])}{\mathrm{E}_k[\mathrm{var}_t(\mathbf{x} - \mathrm{E}_k[\mathbf{x}])]} \\ &= \frac{\mathrm{var}_t(\bar{\mathbf{x}})}{\mathrm{E}_k[\mathrm{var}_t(\mathbf{x} - \bar{\mathbf{x}})]} \equiv \frac{\overline{\mathbf{x}}^2}{\sigma_{\mathbf{x}}^2} \end{aligned} \tag{6}$$

where $E[\cdot]$ denotes the mathematical expectation operator, and var_t is the variance computed over the time samples.

3. Results

3.1. Online accuracy and bit rate

Online results consisting on accuracy, number of event repetitions (N_{rep}), SPM and ITR in bpm for each paradigm are shown in Tables 3, 4 and 5. The last column of Tables 3 and 4 and the second last column of Table 5 indicate the order by which the two paradigms were tested. Each participant performed a series of sessions that depended on his/her performance. If the participant had a good performance, the number of repetitions was decreased and the whole sentence was spelled again. If the performance was weak, then the number of repetitions was increased. The notes (a), (b), (c) and (d) in Tables 3, 4 and 5, describe particular occurrences during online sessions, namely (a) test not performed or skipped; (b) test aborted due to excessive number of errors; (c) test not performed because offline classification was unable to detect P300 with an accuracy above 80%; (d) test aborted due to user visual discomfort. Concerning the results presented in Tables 3, 4 and 5, we have considered the ITI time, however for comparison with other research groups, the averages were also computed omitting the ITI (referred to in tables as *average*$^{(2)}$). For a proper comparison of the two paradigms, the averages were computed by choosing, for each participant, the number of repetitions (N_{rep}) that provides the highest PBR, i.e., considering that all mistakes would be corrected[1].

Participants who have not been able to use effectively the BCI online, with an accuracy above 60%, were discarded from the averages in Tables 3, 4 and 5 (the two average values of N_{rep} refer respectively to RC and LSC). Five participants were unable to effectively control RC, namely S05, S15, S19, S21 and S22, and six participants were unable to effectively control LSC, namely S14, S15, S19, S20, S21 and S22. For group I (excluding participant S05), the results showed a 5.52 ITR improvement of LSC over RC (statistical paired *t-test*, $p < 0.001$). For group II, the ITR of LSC was 3.74 higher than for RC, but the statistical test only approached statistical significance ($p = 0.074$, t-test performed excluding participants S14 and S15). For group III, the ITR of RC was 1.48 higher than for LSC, but the difference was not statistically significant (t-test performed excluding participant S19, S20 and S21). Comparing the three groups, LSC was on average better for group I and group II, and RC was better for group III. The ITR average taking together the three groups was 26.11 bpm (89.90% accuracy, 4.47 N_{rep} and 6.58 SPM) for LSC, and 21.91 bpm (88.36% accuracy, 4.82 N_{rep} and 5.26 SPM) for RC. The ITR difference, 4.20 bpm, was statistically significant, $t(16) = 3.62$, $p < 0.002$ using a paired *t-test*, excluding participants S05, S14, S15, S19, S20, S21 and S22.

For group III, it was asked to participants to write a sentence with the same number of characters of the one tested on the BCI experiments, using their usual non-EEG interfaces. The last column of Table 5 shows the achieved SPM. These experiments were performed on a different day of the BCI experiments. Participants used different systems according to their main disability profile, namely, a head-tracker (HT), a scanning-switch (SS), a head-pointing-device (HPD), a mouse controlled by the foot (FM) and a keyboard-grid (KG). Participants S19, S21, S22 who were unable to control the BCI are the ones who reached the highest SPMs. These communication rates are much higher than the ones achieved in current BCI systems.

[1]It should be noted that the PBRs are not shown in Tables 3, 4 and 5, but they were computed to select, for each participant, the N_{rep} taken for average.

Participants S18, S20 and S24 achieved an SPM approximately two to three times the SPM achieved with BCI. Participant S23, who is currently unable to control any interface, achieved a BCI performance of 4.28 SPM with 87.5% accuracy.

3.2. Questionnaire

Users were asked to answer a questionnaire whose aims were to assess the degree of user satisfaction and to identify limiting factors for both paradigms. Participants with high dysarthria in the ALS group answered the questionnaire with the assistance of relatives. Participants of group III answered the questionnaire with the assistance of occupational therapists. The results of the questionnaire are in Table 6. The answers to each specific question/item are shown as the percentage over the sample of the participants. The results show that most of the participants liked more the LSC speller. This subjective answer has no straightforward relation with user performance. There were cases in which the user liked more one of the interfaces and yet had a worse performance. Also, 50% of the participants reported that RC speller caused higher eyestrain and discomfort than the LSC speller, causing for instance 'weeping' and 'visual after-effect'. Participants reported that the ITI should be increased (50% for RC and 31.8% for LSC), and that some errors might have occurred because of this limited time. The difficulty to find the letters according to the layout was higher for RC. Participants were asked to mention other effects that affected their performance. Three items (mental counting, distractors and double flash) were reported by their own initiative. For the RC speller, 55% of the participants reported that the frequent mental counting of the target events was tedious and somehow made them lose focus. This perception experienced by the participants may be explained by the fact that in the RC speller, users have to count twice (one for target row and one for target column) for each round of flashes, while in LSC speller, users have to count only once for each round of flashes (target symbol). The double-flash effect was also reported only for the RC speller by 13.6% of the participants. The adjacency distractors were pointed out for both paradigms, but with higher incidence for the LSC speller. Participants were asked to propose modifications and improvements to the paradigms. For RC, it was suggested to soften the colors. For LSC, it was suggested to increase the distance between symbols, to increase the symbols size, and to change the style of the letter "I" to improve its perception.

Table 3: Online results of able-bodied participants (group I). See text for notes (a), (b), (d).

		RC speller			LSC speller			
Subject	N_{rep}	SPM	P_{ac} (%)	ITR (bpm)	SPM	P_{ac} (%)	ITR (bpm)	order (1st/2nd)
S01	5	3.87	89.47	16.04	4.28	90.00	16,55	RC/LSC
	4	4.58	85.00	17.36	5.04	90.47	19.66	
	3	(b)	-	-	6.12	81.81	19.95	
S02	5	3.87	86.60	18.63	(a)	-	-	LSC/RC
	4	(b)	-	-	5.04	100.0	24.23	
	3	(a)	-	-	6.12	90.47	23.88	
	2	(a)	-	-	7.79	81.81	25.39	
S03	7	2.95	84.21	11.02	3.29	90.47	12.85	LSC/RC
S04	5	3.87	82.60	13.97	4.28	90.00	16.55	LSC/RC
S05	5	(d)	-	-	4.28	89.47	16.37	LSC/RC
S06	5	3.87	100.0	20.01	4.28	94.737	18.25	LSC/RC
	4	4.58	84.21	17.08	4.28	95.00	21.59	
S07	5	3.87	95.00	17.91	4.28	89.47	16.37	RC/LSC
	4	4.58	90.47	19.36	(a)	-	-	
	3	5.60	79.16	18.85	6.12	85.71	21.65	
S08	5	3.87	85.00	14.17	4.28	90.47	16.71	RC/LSC
	4	4.58	70.37	12.70	5.04	86.36	18.07	
	3	(a)	-	-	6.12	90.00	23.65	
S09	5	3.87	100.0	20.01	4.28	90.47	16.71	RC/LSC
	4	4.58	86.36	17.84	(a)	-	-	
	3	5.60	90.47	23.70	6.12	95.00	26.22	
	2	7.22	95.00	33.44	7.79	100.0	37.45	
S10	5	3.87	100.0	20.01	4.28	100.0	20.60	RC/LSC
	4	4.58	90.47	19.36	5.04	100.0	24.23	
	3	5.60	95.00	25.94	6.12	95.00	26.22	
	2	(b)	-	-	7.79	85.71	27.55	
Average(1)	4.44/3.90	4.49	89.32	18.94	5.48	91.68	22.16	
Average(2)	4.44/3.90	5.64	89.32	23.97	7.29	91.68	29.49	

(1) Average of the elements in the table (includes ITI).
(2) Average if ITI would be excluded.

3.3. Adjacency errors

To analyse the influence of the adjacency distractors, the number of errors was computed according to spatial location of the respective events. This

Table 4: Online results of ALS participants (group II). See text for notes (a) and (b).

		RC speller			LSC speller			
Subject	N_{rep}	SPM	P_{ac} (%)	ITR (bpm)	SPM	P_{ac} (%)	ITR (bpm)	order (1st/2nd)
S11	5	3.87	100.0	20.01	4.28	87.50	15.72	RC/LSC
	4	4.58	81.25	16.08	5.04	87.50	18.50	
	3	(b)			6.12	87.50	22.46	
S12	5	3.87	93.75	17.46	4.28	93.75	17.88	RC/LSC
	4	4.58	87.50	18.25	5.04	100.0	24.23	
	3	5.60	87.50	22.34	6.12	81.25	19.71	
S13	7	2.95	93.75	13.33	3.29	93.75	13.75	LSC/RC
	5	3.87	68.75	10.33	(b)	-	-	
S14	7	2.95	100.0	15.28	3.29	43.75	3.77	LSC/RC
	6	3.35	68.75	8.95	(a)	-		
S15	≥ 7	(b)	-	-	(b)	-	-	LSC/RC
S16	4	4.58	87.50	18.25	5.04	100.0	24.23	LSC/RC
	3	5.60	87.50	22.34	6.12	93.75	25.54	
	2	(b)	-	-	7.79	73.33	21.06	
S17	5	3.87	81.25	13.59	4.28	81.25	13.79	RC/LSC
Average$^{(1)}$	5.0/4.40	4.14	91.67	17.82	4.97	91.25	19.95	
Average$^{(2)}$	5.0/4.40	5.10	91.67	21.83	6.37	91.25	25.57	

$^{(1)}$ Average of the elements in the table (includes ITI).
$^{(2)}$ Average if ITI would be excluded.

information was collected only from the disabled participants. For the RC speller, 90% of the errors were on the same row or on the same column (row: 38% and column 52%). Moreover, 54% of the errors were in one of the 8 adjacent symbols. In the LSC speller, 32% of the errors were in one of the 4 adjacent symbols. Also, 47% of the errors were on the same side and 53% in the opposite side. These results may indicate that most of the RC errors are due to adjacency distractors. In LSC, there is also a high percentage of adjacency errors, yet the percentage is considerably lower than in RC, which may indicate that the errors are mostly due to P300 variability, or due to remote distractors.

4. Offline analysis

An offline analysis was carried on to understand and corroborate the online results, but also to assess if our initial hypotheses were correct. The

Table 5: Online results of participants CP, DMD and SCI (group III) and performance with non-EEG interfaces. The non-EEG interfaces SS, HT, HPD, FM, KG, refer respectively to scanning-switch, head-tracker, head-pointing-device, foot-mouse and keyboard-grid. See text for notes (a), (b) and (c).

		RC speller			LSC speller				Non-EEG interface
Subject	N_{rep}	SPM	P_{ac} (%)	ITR (bpm)	SPM	P_{ac} (%)	ITR (bpm)	order (1st/2nd)	SPM
S18	8	(a)			2.95	94.75	12.33	LSC/RC	SS: 6.8
	7	(a)			3.29	81.25	10.61		
	6	3.35	100.0	17.32	3.72	68.75	9.0		
	5	3.87	88.88	15.85	(a)				
S19	(c)	-	-	-	-	-	-	-	FM: 43.2
S20	6	3.35	93.37	15.12	3.72	50.00	5.32	RC/LSC	HT: 9.6
S21	≥ 9	(c)	-	-	(b)	-	-	RC/LSC	HPD: 51.4
S22	(c)	-	-	-	-	-	-	-	KG: 31.7
S23	7	(a)	-	-	3.29	93.75	13.75	LSC/RC	HT: 0.0
	6	3.35	68.75	8.95	3.72	87.50	13.67		
	5	3.87	75.00	11.90	4.28	87.50	15.72		
S24	8	2.64	73.33	7.83	2.95	56.25	5.13	RC/LSC	HT: 7.2
	7	2.95	37.50	2.98	3.29	62.50	6.82		
Average[(1)]	6.25/6.67	3.30	85.43	13.04	3.51	81.58	11.62		
Average[(2)]	6.25/6.67	3.84	85.43	15.18	4.13	81.58	13.70		

[(1)] Average of the elements in the table (includes ITI).
[(2)] Average if ITI would be excluded.

Table 6: Results of the questionnaire.

Question/item	RC	LSC	Similar	None
Paradigm most appreciated	13.6%	72.7%	13.6%	n.a.
Paradigm that caused more eyestrain/visual discomfort	59.0%	0.0%	n.a.	41.0%
ITI is not long enough	50.0 %	31.8%	n.a.	50.0%
Symbols are difficult to find	50.0%	18.2 %	n.a.	27.3%
Undesired effects reported by users				
High mental counting	55%	0%	n.a.	n.a.
Double-flash	13.6%	0%	n.a	n.a.
Distractors	4.5%	13.6%	n.a.	n.a.

n.a.: not applicable

analysis was based on the datasets collected during the calibration phases.

4.1. Waveform morphology

The analysis was focused on channels Pz and PO7, two of the most discriminative channels (Kaper et al., 2004; Krusienski et al., 2008; Townsend et al., 2010), and focused on the N200 and P300 ERP components, since they are the two main discriminative components. Fig. 3 shows the average of target epochs for each participant with both paradigms. For a better visualization, the epochs were low-pass filtered in the time domain at $f_c = 7$ Hz (it should be noted that the filter causes a temporal delay of ≈ 50 ms). The analysis hereinafter, however, uses raw EEG data, i.e., without filtering. The components of the ERP elicited in the RC speller, namely the evoked N200 and P300 components are sometimes difficult to discriminate. This might happen because the signal is strongly affected by a steady state visual evoked potential (SSVEP) that results from the 5 Hz stimulus flash, and also because target epochs temporally overlap due to the small TTI. In the LSC speller, the N200 and P300 components are usually clearly identified. Peak amplitude and peak latency were determined by selecting the largest positive or negative peak within the range 275-600 ms (P300) and 175-400 ms (N200). From the individual analysis, we concluded that participant S19 did not elicit any visible ERP component for both paradigms. Participant S22 exhibits components with very high amplitudes that reveal the presence of artifacts. These two participants were excluded from the analysis. Participants S15 and S17 exhibit a strong positive peak around 200 ms, but the P300 component is hardly noticeable. Nevertheless, they were not excluded from the analysis.

A summary of the average amplitudes and latencies of P300 and N200 peaks, as well as the respective statistical tests (paired *t-test*) is provided in Table 7. The P300 amplitude is larger for LSC than for RC and the latency is shorter for LSC than for RC. The statistical test fails to reject the null hypothesis only for the amplitude difference in channel PO7. For the N200 component, the amplitude is larger for RC, but the statistical test only approaches significance for channel Pz. The latency difference is not statistically significant.

The grand averages were computed for group I, group II, and participants suffering from CP (only S18, S20 and S21), as shown in Fig. 4. Qualitatively, it can be seen that the ERP waveform elicited by the LSC paradigm shows a clear classical morphology, particularly in able-bodied and CP participants. In RC, the waveforms morphology exhibit a more pronounced oscillatory component. The amplitudes and latencies of the P300 component (raw EEG

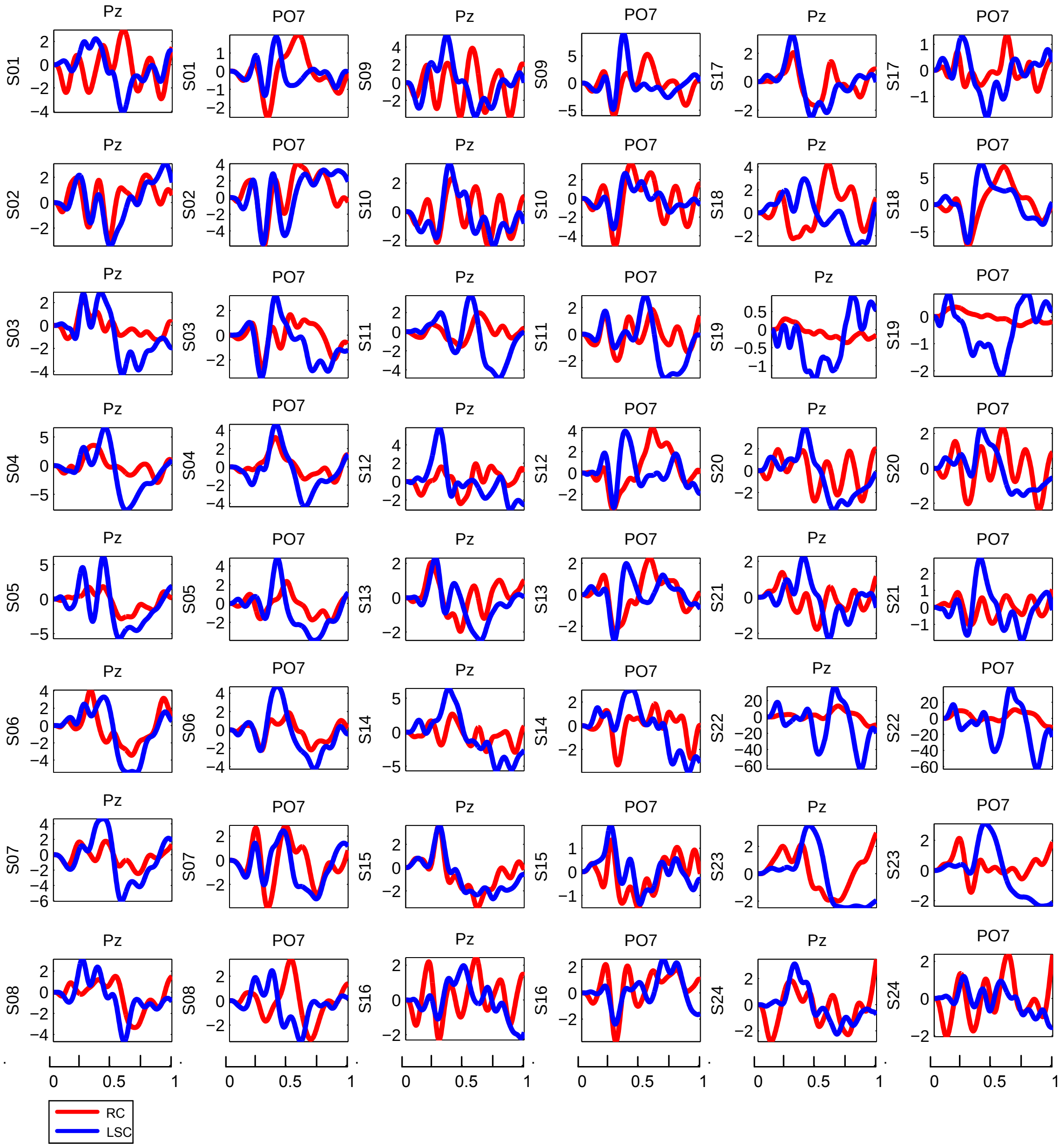

Figure 3: Averaged target epochs elicited by RC paradigm (red color) and LSC paradigm (blue color) at channels Pz and PO7 for each of the 24 participants (amplitudes units are μV). All waveforms were low-pass filtered ($fc = 7$ Hz) before plotting.

Table 7: Mean peak amplitudes and latencies of P300 and N200, LSC and RC differences, and statistical analysis (paired *t-test*).

Component (channel)	Property	Diff. between LSC and RC (stat. test)
P300 (Pz)	Amplitude LSC: 4.47 μV RC: 2.88 μV	dif = $+1.59\mu V$ ($t(21) = 3.1$, $p < 0.004$)
	Latency LSC: 341 ms RC: 415 ms	dif = -74 ms ($t(21) = 3$, $p < 0.006$)
P300 (PO7)	Amplitude LSC: 4.28 μV RC: 3.61 μV	dif = $+0.67\mu V$ (no stat. sign.)
	Latency LSC: 354 ms RC: 476 ms	dif = -122 ms ($t(21) = 6.2$, $p < 0.001$)
N200 (Pz)	Amplitude LSC: -1.71 μV RC: -2.35 μV	dif = $-0.64\mu V$ ($t(21) = 1.9$, $p = 0.07$)
	Latency LSC: 295 ms RC: 320 ms	dif = -25 ms (no stat. sign.)
N200 (PO7)	Amplitude LSC: -3.67 μV RC: -3.71 μV	dif = $-0.04\mu V$ (no stat. sign.)
	Latency LSC: 239 ms RC: 230 ms	dif = $+9$ ms (no stat. sign.)

data) of the able-bodied were statistically compared with those obtained with the ALS and CP groups, using a two-sample *t-test*. It should be noted that the sample size of the CP group is very small and therefore the statistics should be taken with care. The P300 amplitude was similar across groups and the latencies are shorter for the able-bodied participants, approaching statistical significance in RC speller (both channels), and being statistically significant between able-bodied and ALS in the LSC speller paradigm (PO7 channel).

4.2. SNR analysis

Fig. 5 shows the SNR averages (in dB) separately for able-bodied, ALS and CP participants, taking $K = 1 \cdots 7$ epochs for average. As expected,

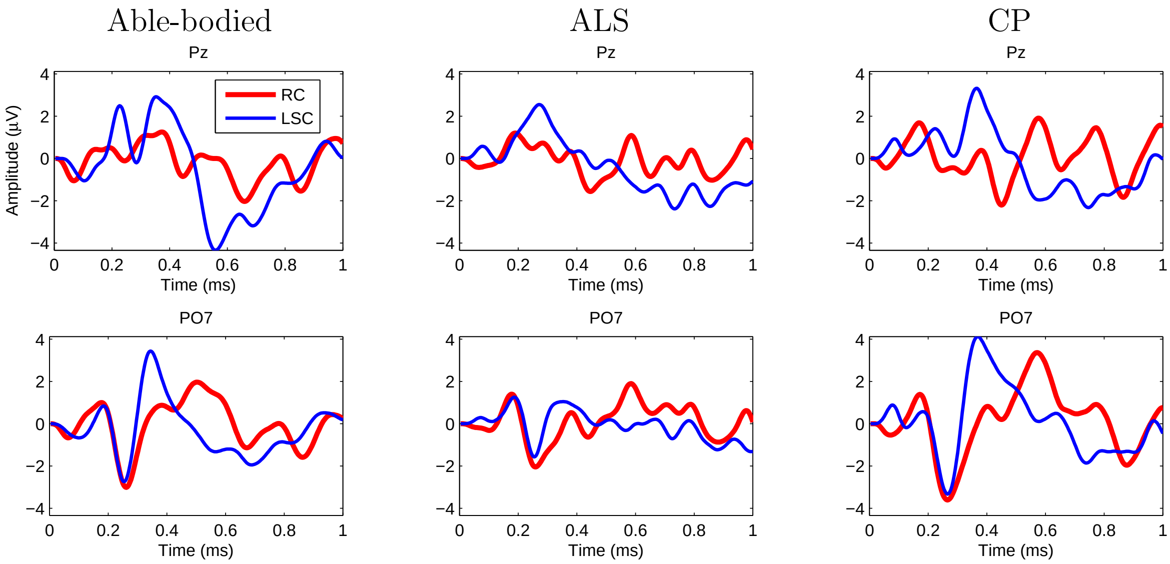

Figure 4: Grand averages computed over able-bodied group, over ALS group and over CP group (only S18, S20 and S21). All waveforms were low-pass filtered ($fc = 7$ Hz) before plotting.

and in line with the online results, the able-bodied group has the highest SNR for both paradigms, and the CP group has the lowest SNR, despite the CP participants exhibited a higher P300 amplitude. Comparing RC and LSC paradigms in the able-bodied group, the SNR of LSC is always at least 3.7 dB higher than RC, for $K = 1 \cdots 7$, p <0.006. The ALS group also shows a difference > 3.7 dB for $K = 1 \cdots 7$, but it only approaches statistical significance, $p < 0.08$. In the CP group (S18, S19 and S20), the difference is > 2.7 dB, but it is not statistically significant.

4.3. Searching for new discriminative features in LSC

The LSC paradigm was designed to overcome some limitations of the RC paradigm, as well as to investigate the emergence of new neurophysiologic features. For this purpose, the existence of discriminative features in the frequency domain was investigated, and also whether new neurophysiologic features could arise from the left/right layout and event presentation strategy of LSC.

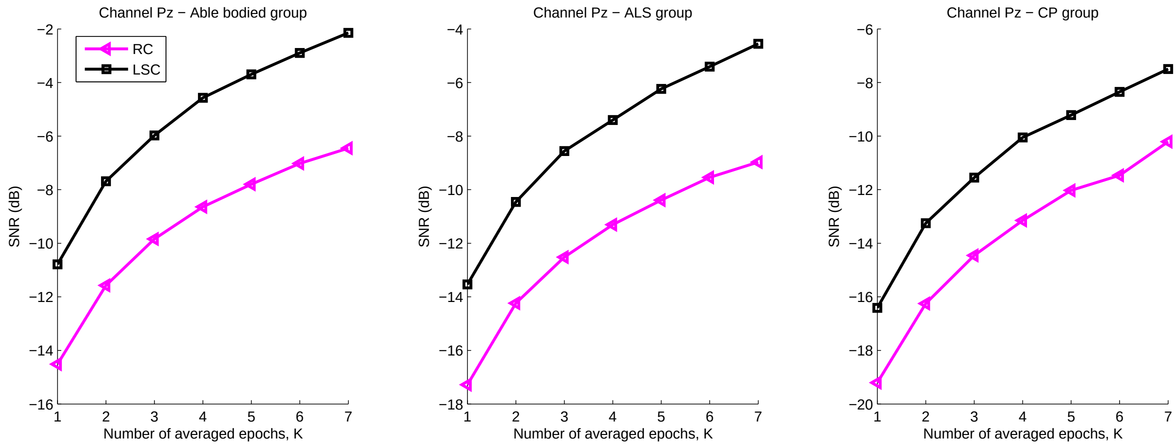

Figure 5: SNR estimated for able-bodied group, ALS group, and CP group (only S18, S20 and S21). The SNR was computed for $K = 1 \cdots 7$ averaged epochs.

4.3.1. Frequency analysis

As the user focuses only one side of the screen, it was initially hypothesized that the stimuli on the opposite side would have a small visual effect, and thus the user would virtually see a target probability of 1/14 and only half of the stimuli, having a perception of 6.5 Hz, i.e., half of the flashing frequency. Fig. 6 corroborates this assumption. Target epochs reflect a frequency at 6.5 Hz (7 Hz in the graph due to FFT resolution), and only a small peak at 13 Hz. Non-target epochs reflect only the 13 Hz flash. By contrast, the RC paradigm shows that the frequency of the flashes strongly affects both target and non-target epochs of the RC speller. The graphs in Fig. 6 suggest that RC and LSC may have discriminative features related to stimuli frequency that can be used to improve the classification.

4.3.2. Laterality analysis

Visual spatial attention modulates early ERP components such as the N100, P200 and N200 with lateralization effects (Luck and Hillyard, 1994; Makeig et al., 1999). However, experiments are usually performed based on covert attention, while in our case an overt attention paradigm was used. By computing the ERP waveforms elicited by left and right events, we investigated whether or not a laterality difference exists. Fig. 7 (top) displays the ERP waveforms of epochs recorded at PO7 and PO8 elicited by left and right target events. The waveforms are the grand averages computed over

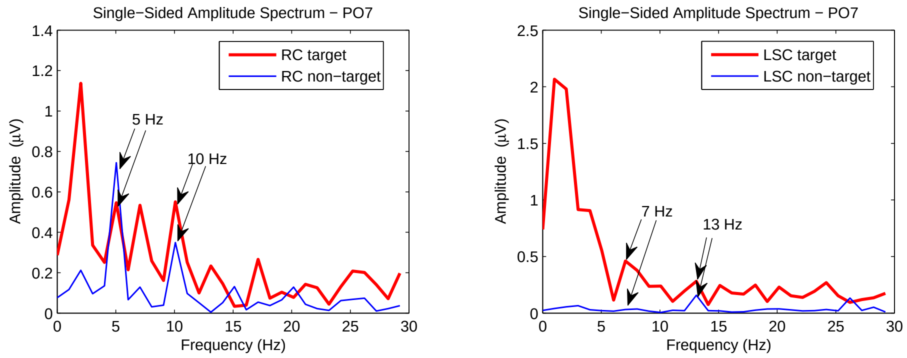

Figure 6: Frequency analysis illustrating the inter-stimulus flashing effect on RC and LSC. The plots correspond to the averages of 180 target FFTs and 900 non-target FFTs for RC, and 90 target FFTs and 840 non-target FFTs for LSC. The averages were computed from datasets chosen from a representative participant.

the group of able-bodied participants. Components N100, P200 and N200 of the ERP exhibit different waveforms for left and right events. The difference is more easily detected by computing the difference between PO8 and PO7 as shown in Fig. 7 (middle). For example, the component N200 is larger over PO7 for both left and right events, but the PO8-PO7 difference is larger for right events. The results suggest that the classification algorithms could benefit from two individual models, one for left events and the other for right events. Computing the PO8-PO7 difference for non-target epochs, a phase reversal on the SSVEP is evidenced in Fig. 7 (bottom). This phase reversal, which is produced by the left/right event strategy of the LSC paradigm, indicates that it is possible to detect the side of the event only by computing the phase between EEG signals from left/right symmetric locations.

5. Discussion

This paper presented a new P300-based speller paradigm, the lateral single character (LSC), and compared it to the standard row-column (RC) speller. The initial assumptions regarding the LSC paradigm, indicating that this approach could be an effective alternative to the RC paradigm, were assessed by online and offline analysis, and deserve now some further discussion.

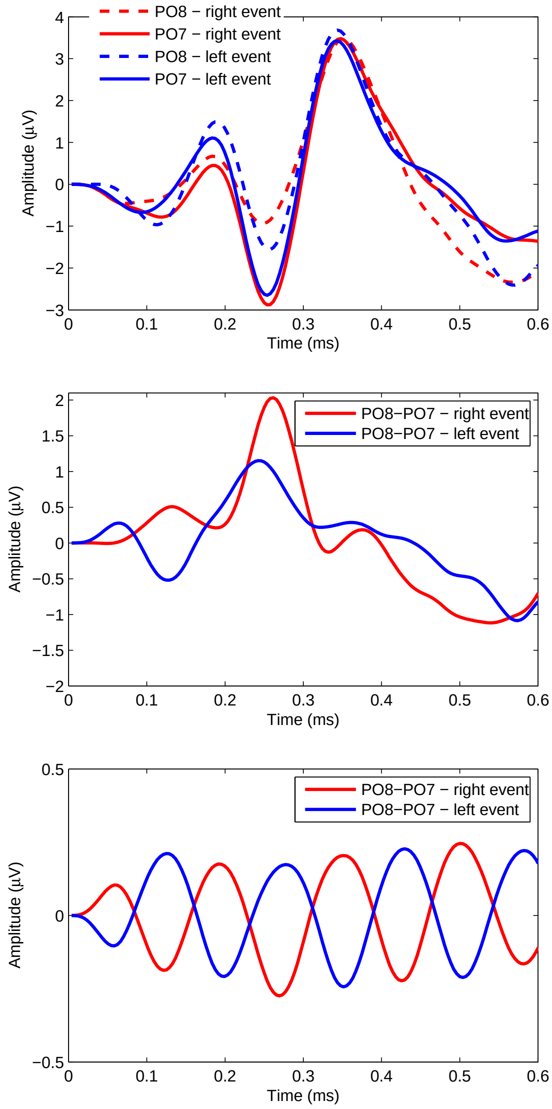

Figure 7: Grand averages computed over able-bodied participants. Top: target epochs recorded at PO7 and PO8 for left and right events; Middle: difference between target epochs recorded at PO8 and PO7 for left and right events; Bottom: difference between non-target epochs recorded at PO8 and PO7 for left and right events. The curves show a phase reversal effect.

5.1. Online performance and state-of-the-art comparison

The average results (including ITI) of the able-bodied participants were 18.94 bpm, 89.32% accuracy, 4.49 SPM and 4.44 repetitions for RC, and

22.16 bpm, 91.68% accuracy, 5.48 SPM and 3.90 repetitions for LSC. These results compare very favourably with those reported in the two studies with the highest performances. Namely, Townsend et al. (2010) reports a 19.85 bpm, 77.34% accuracy, 4.68 SPM and 4.5 repetitions for RC, and 23.17 bpm, 91.52%, 4.36 SPM and 3.61 repetitions for the checkerboard paradigm, and Lenhardt et al. (2008) reports a 3.91 SPM and 83.33% accuracy for RC. The online results achieved by motor impaired participants are also good in comparison with the results reported in other studies (Townsend et al., 2010; Hoffmann et al., 2008a; Sellers et al., 2006; Piccione et al., 2006; Donchin et al., 2000), however results cannot be directly compared because the levels of disability of the participants greatly differ.

Comparing LSC and RC, the overall averaged ITR (excluding only the subjects unable to participate online in one or both paradigms) was 4.20 bpm higher for LSC. The relevant improvement of LSC over RC, is a major achievement and shows that LSC is an effective alternative to RC. Nonetheless, while the ALS participants performed better with LSC showing only slightly worse results than those achieved by able-bodied participants, the participants of group III, in particular the CP participants, performed better with RC. The overall results obtained with CP participants are also relevant since there are very few studies examining the use of P300-based BCIs by individuals with CP (Hoffmann et al., 2008a). From the group of five CP participants, only two effectively controlled the BCI, namely S18 and S20. The overall results obtained with CP participants may suggest that these individuals may have more difficulties to control a BCI than the other disabled participants. In order to be more conclusive about the participants who performed worse, some participants of group III (S19, S20, S23 and S24) underwent pilot experiments with an additional paradigm similar to the one presented in Pires et al. (2008) called arrow paradigm. The aim was to assess whether the weaker results achieved by some participants of this group were only due to neurophysiologic causes, or depended more on the complexity of RC and LSC. The arrow paradigm has a simpler presentation than RC and LSC, consisting of only 11 large and well separated symbols that flash individually. Using this paradigm, participant S19 evoked a P300, although it was still weak and insufficient for online operation. Participants S20 and S24 significantly improved the online performance and S23 kept the online performance. These results suggest that it is worth to test different visual paradigms to increase the BCI performance.

5.2. Contributions of the LSC paradigm

The event strategy chosen for LSC allowed to significantly decrease the flashing time and to eliminate the ISI (while still keeping a virtual ISI effect). Thereby, the reduction of the time associated with the events allowed to achieve sub-trial times similar to those typically obtained with RC, leading to competitive ITRs. By reducing the surrounding symbols in LSC, it was possible to control the local distractors and thereby to reduce the adjacency errors. This percentage was 32%, while in RC it was 54%. The percentage of remote errors, in the opposite side of the target event, was 53%. We do not have enough information to conclude whether the error percentage is due to ERP variability or due to remote distractors, but according to the questionnaire, participants reported that distractors affected their performances. Other event strategies, for example, extending the left/right event strategy to the four quadrants of the screen, can potentially be explored in the future in combination with further manipulations of TTI, ISI and double-flash.

The questionnaire allowed us to assess some subjective issues concerning RC and LSC. The majority of participants, 72.7%, expressed a preference for LSC. Additionally, 59% reported that RC caused a higher eyestrain and visual discomfort, while in LSC none of the participants reported any visual discomfort. This is an important issue in BCI and should not be overlooked because it may limit the time period of BCI usage.

5.3. Neurophysiologic features

The grand-averages in Fig. 4 show that the ERP waveforms for both RC and LSC differ between Pz and PO7. The P300 amplitude in channel Pz is larger in LSC than in RC. The peak occurs also earlier in LSC than in RC, for channels Pz and PO7. These results corroborate our initial expectations that LSC, with a lower target probability, would elicit a larger P300 amplitude than RC. As concerns N200, the amplitude in Pz was larger in RC than in LSC, suggesting that the N200 component may have contributed more to the classification accuracy in RC than in LSC.

When searching for features induced by the lateral layout and event strategy of LSC, the grand averages suggested a discrimination between left vs right ERP targets. This discrimination can be exploited, by using left and right independent models in the classifiers. These asymmetries are a direct reflection of the hemispheric dominance of the right hemisphere in visuospatial attention (Silva et al., 2008, 2010). Other asymmetries (e.g. up/down) in the paradigm design can potentially be explored in the future.

A major achievement of LSC paradigm was the SSVEP phase reversal effect between left and right non-target events. This effect can enable the detection of the side of the target event by measuring the phase at symmetric electrode locations. The inclusion of phase information adds a new dimension to the P300-based BCI that can increase the classification accuracy. The phase information can be embedded in current classification algorithms or combined in a different classifier. Detecting the side of the incoming event can be used to discard the events from the opposite side, or to increase the estimated likelihood of the target event.

5.4. Effective use and limitative factors of BCI

One goal of this paper was to assess if BCI could be used by some of the participants as an alternative to their non-EEG interfaces. From the seven participants using standard interfaces, three participants use their standard interfaces much more efficiently than BCI, other three participants use standard interfaces with a speed two to three times their BCI speed. However, it should be mentioned that their speeds with standard interfaces were attained with the BCI by some of the able-bodied participants. Participant S23, who lost the ability to control the head-tracker and who is unable to control the wheelchair, achieved a BCI performance of 4.28 SPM with 87.5% accuracy. This result may suggest that BCI can be considered as viable alternative.

BCI is still limited by various factors. It usually requires more attention and may cause a higher fatigue than other standard interfaces. Attention tasks may be affected when users experience pain symptoms. For example, some of the participants of group III had to interrupt the sessions to alleviate the pain, by stretching the legs, arms and shoulders, or by changing the position of the head, which may have negatively influenced their performance. Curiously, participants of group III who were unable to control the BCI, were those who had better results with standard interfaces. Motivation may eventually play an important role on the achieved performances. Some participants, who are accustomed to use efficiently the same interface for more than a decade, were not highly motivated. Moreover, it was subjectively observed that the level of confidence and the fear to fail could influence the performance. Please see the study in Nijboer et al. (2010) where some of these issues are discussed.

5.5. Conclusion

This study presented a P300-based paradigm, the LSC speller, that showed an increase in performance over the standard RC speller. LSC paradigm explored the role of event related strategy and hemispheric asymmetries in visual processing to introduce new neurophysiologic dimensions that can be used in the future to improve bit rates and classification accuracy. The effective transfer rates achieved by motor disabled participants, particularly by ALS participants, for both LSC and RC spellers, are a step forward to their potential application as assistive devices for communication. The LSC speller paradigm should now be extended taking advantage of the proposed modifications and the newly identified neurophysiologic features. The enhanced LSC as well as other paradigm approaches should be tested on the participants who showed low BCI performances (in particular, the CP group) and extended to a larger group.

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