Chroma Speller: isotropic visual stimuli for truly gaze-independent spelling

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Abstract— **Brain Computer Interfaces (BCIs) can be used as communication devices for people affected by neurodegenerative diseases like Amyotrophic Lateral Sclerosis (ALS). The progressive motor-control impairment caused by ALS motivates the development of BCI paradigms that do not rely on eye-movements. In the present study, we investigated the feasibility of the first truly gaze-independent visual BCI, called Chroma Speller. Stimuli consist of colors displayed widescreen, which renders the focus of gaze irrelevant to the BCI-spelling. The speller was tested online with 9 healthy participants. Mean online symbol-selection accuracies of 88.4% and mean online spelling speed of 1.4 char/min were achieved, using 5 repetitions of the stimuli. These results demonstrate that the abstract association colors-symbols do not compromise the usability of the speller, leading to performances competitive with the most recent gaze-independent spellers in literature.**

I. Introduction

A Brain Computer Interface (BCI) establishes e direct link between the brain and an external device. One of the purposes of this technology is to let people affected by diseases like Amyotrophic Lateral Sclerosis (ALS) to communicate with the external environment. Patients affected by ALS head to increasing paralyses, until losing the control even of the eye movements. Since a BCI bypasses the standard pathways of communication, it can represent for these patients the last chance of expressing their wishes and necessities. Some of the BCIs use a category of brain signals called Event Related Potentials (ERPs), which are positive or negative deflections of the ongoing EEG activity, triggered by an internal or external event. The first BCI speller was the Matrix Speller, developed by Farwell and Donchin in the 80s [1]. In this paradigm, all the letters of the alphabet were arranged in a 6x6 matrix shape, in which columns and rows were flashed in a random order. Paying attention to how many times the target symbol was flashed elicited an ERP, which could be detected and used for classifying the letter that the user intended to spell. Recently, two independent studies demonstrated that the Matrix Speller can be operated with high efficiency only if the user overtly attends to the target letter [2,3]. Therefore, in the last years, many researches focused on developing ERP-based spellers based on a gaze-independent presentation of the visual stimuli. Successful examples can be found in [4-6]. In Treder at al. [4], the authors present three variants of a two stages visual speller, in which the selection is based on covert attention and spatial feature attention. The highest mean symbol-selection accuracy is reached by the Center Speller (about 97%, after 10 repetitions of the stimuli). In the first level of selection, the 30 characters (26 letters of the english alphabet plus 4 punctuation marks) are clustered in six groups, which are presented in a serial manner in the center of the display. Each group is associated to a colored geometrical shape to increase the discrimination between the stimuli. After the group's selection, the single letters of that group are presented in the same manner. So, in the second level, the user is able to select the target letter. Liu at al. [5] present a similar paradigm, in which the letters are grouped in six clusters and the user can select the intended symbol using a cover shift of attention. They reach an online symbol selection accuracy up to 96.3% with a Stimulus Onset Asynchrony (SOA) of 400 ms and 10 repetitions of the stimuli. In Acqualagna and Blankertz [6], the authors exploit a presentation based on the Rapid Serial Visual Presentation (RSVP) paradigm, in which the characters are displayed one after the other in the center of the screen. This paradigm uses a direct selection of the target letter, reaching an online mean accuracy of 94.8%, with a SOA of 116 ms and 10 repetitions. All these paradigms do not need the user to move the eyes in order to select the target symbol, but still assume fixation to the location of the display where the stimuli are shown. This characteristic can represent a limit if these spellers were used by patients at the latest stages of ALS, in which severe oculomotor impairments cause involuntary drifts of eye gaze. The proposed approach overcomes this problem using isotropic stimuli which trigger the same visuo-attentional processes irrespective of the location of eye gaze. This paradigm is called Chroma Speller, and the stimuli consist of colors displayed widescreen. Since the colors appear uniformly in all the directions, the location of the gaze is irrelevant to the BCI operation. In the Chroma Speller, the symbol selection is operated in two stages like in the Center Speller. Each color is associated to a group of characters in the first level and to single characters in the second one. We tested the Chroma Speller online, with healthy participants. This abstract association colors-symbols might cause a learning workload which can affect the usability of the speller. The aim of this study is to confute such hypothesis, proving that competitive performances can be achieved even with such an abstract design. In order to have a baseline for performances comparison, participants performed an online session also with the Center Speller.

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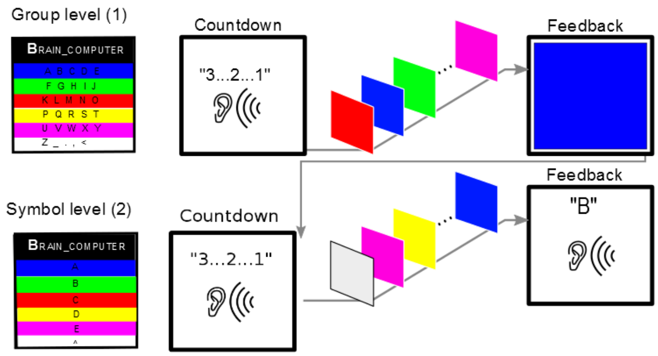

Figure 1: Chroma Speller, stimuli presentation. After the auditory countdown, the color are displayed widescreen in a serial manner with a SOA of 300 ms. In the fist level the feedback is given visually, in the second level in auditory way.

II. Methods

A. Subjects

9 subjects (4 males, aged 20-34) participated in the experiment. All had normal or corrected-to-normal visual acuity. None of them had a history of a neurological disease or injury. The study was performed in accordance with the declaration of Helsinki and all participants gave written consent.

B. Apparatus

EEG was recorded at 1000 Hz using BrainAmp amplifiers and an actiCAP active electrode system (Brain Products,Munich, Germany) with 64 electrodes. All the electrodes were placed according to the 10-20 system and referenced to left mastoids. For off-line analysis, all the electrodes were re-referenced to linked mastoids. All impedances were kept below 10 kΩ. Stimuli were presented on a 24" TFT screen with a refresh rate of 60 Hz and a resolution of 1920 x 1200 px^2 .

C. Design and procedure

In the Chroma Speller the stimuli consist of 6 colors (red, green, blue, yellow, magenta, white), which are presented one after the other in a serial manner (Fig.1). The colors are displayed widescreen for 150 ms with an Inter Stimulus Interval (ISI) of 150 ms, in which a black screen is interspersed. The selection process is divided into two levels, analogous to that described in Treder et al.[5]. In the first level (group level), each color is associated to a group of characters, i.e. BLUE:"a b c d e", GREEN:"f g h i j", RED:"k l m n o", YELLOW:"p q r s t", MAGENTA:"u v w x y", WHITE:"z - . , <". In the second level (symbol level), each color is uniquely associated to the letters of the group that has been selected. The sixth color, white, can be selected in the second level in case that the previous group level is classified wrongly. During the presentation, the order of the colors is randomized, and the whole sequence is repeated 5 times. For the detailed explanation of the design of the Center Speller, please refer to Treder et al [5]. In order to have a fair comparison between the performances of the two spellers, the Center Speller was operated with a SOA of 300 ms and using 5 repetitions of the stimuli.

Subjects sat an a comfortable chair at a distance of approximately 80 cm from the display. In both the spellers, they had to perform calibration and online copy-spelling. The order of the spellers was counterbalanced across participants. In the calibration phase, the target phrase was "BRAIN_COMPUTER" and it was written in the top of the screen. Before each trial, subjects had 5 seconds to identify the highlighted current target letter and to look to which color it was associated in a colored matrix displayed widescreen. The matrix was composed of 6 rows, each one being a box containing the group of letters (in the group level) or the single letter (letter level) and having as background colors the six corresponding ones. After that, a 3 seconds auditory countdown started and the colors' presentation followed. Participants had to silently count the number of occurrences of the target color in the presentation. In this phase, no feedback was given and the recorded data were used to train the classifier.

In the copy-spelling phase, the procedure was the same as in the calibration, but the given sentence was "THE_SUMMER_COMES_AGAIN." (and "LET_YOUR_BRAIN_TALK_NOW" for the Center Speller). In this phase, online feedback was provided to the subjects, according to the classifier's output. In the group level, the feedback was the selected color. In the letter level, a voice spelled the selected letter. In case that the wrong group of letters was classified, subjects were asked to focus on the white color in the second level. Note that in this study the subjects could not perform a real-time error correction, so they proceeded with the next target even if a wrong letter was selected. In a real-world application, the sixth color in the second level can be associated to the backdoor symbol, in order to go back to the group level, avoiding the spelling of a wrong character.

Both the Chroma and Center Speller were implemented in the open-source framework Pyff [7] using VisionEgg [8].

D. Data analysis

For ERP analysis, EEG data were down-sampled to 200 Hz and lowpass filtered with a Chebyshev filter using passbands of 40 Hz and stopbands of 49 Hz. They were divided into epochs ranging from -200 ms to 1000 ms relative to the onset of each stimulus. Baseline correction was performed on the pre-stimulus period of 200 ms. Epochs containing eye movements were detected and rejected using a min-max criterion (80 µV) on the channels F9, Fz, F10, AF3 and AF4. For classification, all epochs were used. For the grand average, the ERP curves were averaged across all trials and participants. To compare the ERP curves of two classes (target-nontarget), sgn r^2-values based on the point biserial correlation coefficient were calculated. Sgn r^2 -values were averaged across participants by using the z -transform. Classification was based on linear discriminant analysis (LDA) with shrinkage of the covariance matrix [9]. The time intervals for calculating the spatio-temporal features were determined by a heuristic searching for peaks based on the sgn r^2 [9]. During the training of the on-line classifier, 5 different temporal windows were selected and occasionally adjusted by the experimenter. The online spelling-speed was calculated considering the number of correctly written symbols during the experiment and the duration of the selection of one symbol, which comprises: the time of the target's presentation and countdown (8 s for Chroma and 5 s for Center), the SOA, the time necessary to display the classifier's output (2 s) and the number of sequences. The offline theoretical spelling speed considers a more realistic scenario, in which spelling a wrong letter would cost the selection of two symbols (backspace and new symbol) and spelling the wrong group, but selecting the correct backdoor symbol in the second level, would lead to no actual selection.

III. Results

A. ERP analysis

Fig 2 shows the ERPs averaged over all participants and trials. In the upper time plots the thick line represents channel CPz and the thin line channel PO7. The golden curves show the ERPs elicited by the targets and the grey ones the brain activity corresponding to the nontargets. there is a clear P3 component with a mean amplitude of 9.9 µV in the Chroma Speller and of 7.7 µV in the Center Speller. The mean latency of the P3 is about 430 ms in both the spellers. In both the spellers it is also visible a clear N2 component, more pronounced in the Center than in the Chroma Speller. The scalp plots underneath refer to the shaded intervals in the time plots and represent the location of such components. The P3 is mainly located on the central-parietal cortex, and the N2 around the PO7 channel. In the Center Speller, it is also visible an earlier frontal P3a subcomponent. Pairwise student t-tests were performed on both amplitude and latencies of the ERPs and did not show significant differences between the two spellers.

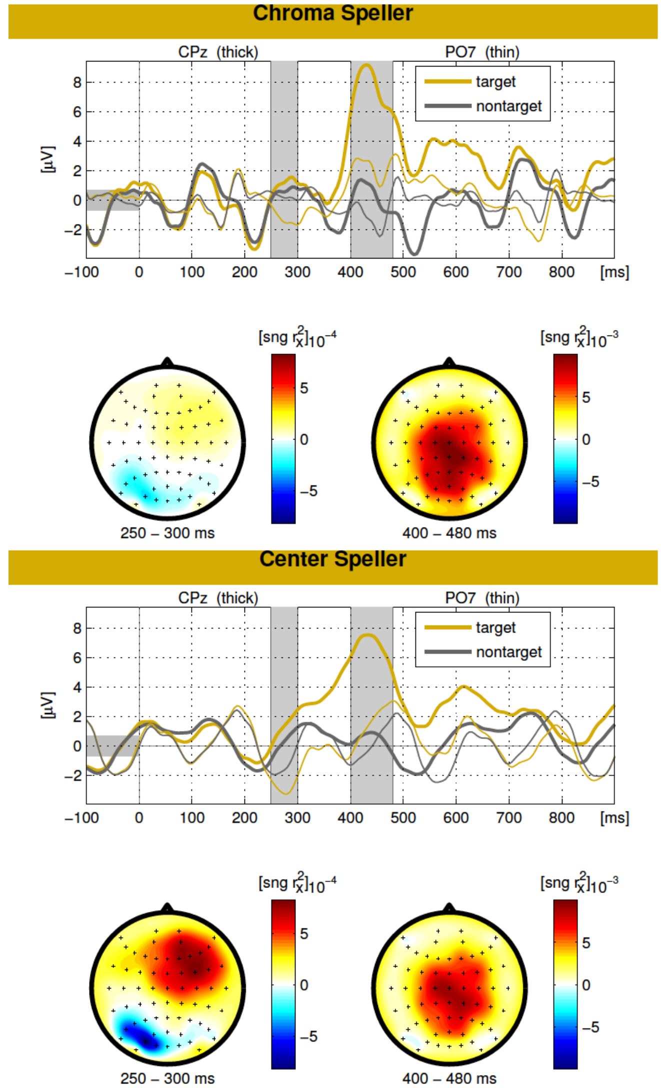

Figure 2: ERP analyses, Chroma Speller (top) and Center Speller (bottom). The time plots show the ERPs elicited by the targets (golden lines) and EEG activity related to the nontargets. The scalp-plots underneath refer to the shadowed areas in the time plot and show the location of ERP components. Clear N2 and P3 are elicited in both the spellers, respectively in the occipital and centro-parietal cortex.

B. Classification

Mean online classification accuracy of 88.4% for the Chroma Speller and 86% for the Center Speller were achieved (Fig. 3). Note that this result refers to the definition of symbol-selection accuracy adopted in the Matrix Speller (chance level 3.33%), in which if an error occurred in one of the two levels, the whole trial is considered misclassified. The mean online spelling speed achieved were 1.61 chars/min for the Center and 1.4 chars/min for the Chroma Speller. Fig. 4 shows the trend of the spelling-speed calculated offline as a function of the number of repetitions and of the classification's accuracy (red dashed lines). The highest values can be found after 4 repetitions, with 1.42 chars/min for the Center and 1.32 chars/min for the Chroma Speller.

IV. Discussion

The Chroma Speller shows a mean online symbol-selection accuracy of 88.4%, using 5 repetitions of the stimuli. This accuracy is higher than that one achieved with the Center Speller, 86%. The achieved accuracy is competitive not only to that one of the Center Speller with whom it was directly compared, but also with the most recent gaze-independent visual spellers [4-6]. It has to be noticed that in the current study we employed just 5 repetitions of the stimuli, while the accuracies reported in literature go beyond 90% using 10 repetitions. This classification's result reflects the trend of the ERP component P3, which shows an average higher amplitude in the Chroma than in the Center Speller. Since the amplitude of the P3 component is affected by the difficulty of the task, the ERPs analyses suggest that the discrimination of the bright colors of the Chroma Speller is easier than the identification of the target symbols in the Center Speller, leading to a higher classification accuracy. In order to consider a speller as an effective communication device, the spelling speed is another important parameter to be taken into account. In the Chroma Speller, an average of 1.4 char/min was achieved online, and a maximum theoretical offline speed of 1.32 char/min with accuracy of 87.9% and 4 repetitions. This result is competitive to those presented in [5,6], and it could be further improved adopting more sophisticated methods of online early-stopping [10] and error-potentials detection [11].

The initial hypothesis of increased difficulty due to an extreme abstraction of the presented stimuli, was proved to be unfounded. This demonstrates that once that the association color-symbol is learned, the task can be accomplished even if the letters are not explicitly printed in the display. In the presented study, the subjects could identify the target color thanks to a matrix displayed before each trial. If the Chroma Speller were used in an application with patients affected by insufficient eye motor control, this association can be learned by heart before the customary use or, alternatively, the letters associated to particular colors can be presented in auditory way before each trial, until the associations are remembered. The auditory feedback is also an important characteristic of this speller, since patients could not be able to discern clearly the spelled letters.

In conclusion, this study demonstrates that it is possible to develop a pure gaze-independent visual speller, which adopts an abstract association between stimuli and symbols, without losing in performances and ease of use. This is an initial online evaluation of the Chroma Speller paradigm with healthy people. An important second step is to assess its feasibility in a home application with patients, where the stimuli could be displayed even wider using a beamer or using video goggles. A potential extension could be also to associate such stimuli not only to symbols for a spelling application, but also to specific actions for the control of the environment.

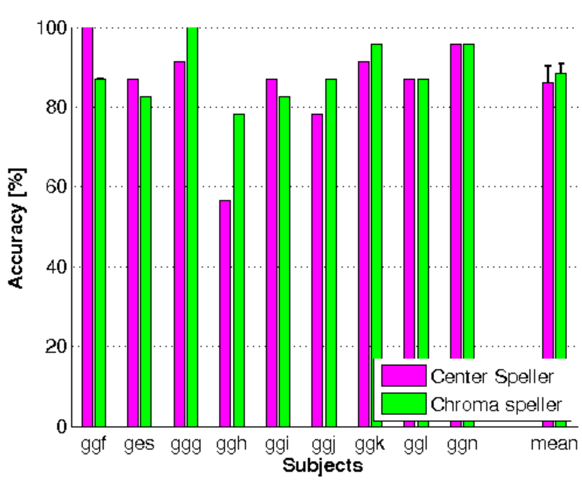

Figure 3: Mean online symbol selection accuracies. Mean accuracies of 88.4% and 86% were achieved, respectively for the Chroma and the Center Speller. Two subjects reach 100% of accuracy in one on the two sessions.

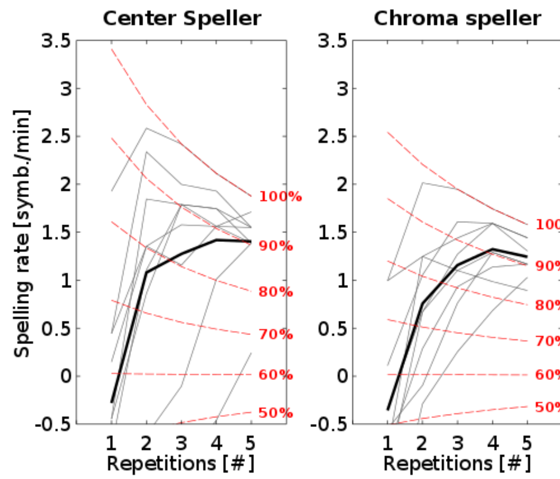

Figure 4: Theoretical spelling speed calculated offline as a function of the number of repetitions of the stimuli and accuracy (red dashed lines). In both the spellers the maximum spelling speed, which takes into account the cost of an error correction, is reached after 4 sequences with a value of 1.42 chars/min for the Center Speller and 1.32 chars/min for the Chroma Speller.

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