Focus-Sensitive Dwell Time in EyeBCI: Pilot Study

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***Abstract*—In past decades, eye-tracking (ET) became one of the most widespread communication strategies for people with severe motor impairments (as in locked-in syndromes, LIS). ET cameras enable paralyzed patients to move a cursor across a user interface (UI) by means of their gaze, and to activate a selectable UI object after looking at it for a certain dwell time. This procedure is definitely intuitive and acceptable for many users. Nevertheless, such control function of gaze can become prone to errors if the dwell time duration is too short, not customized for each specific user. Considering such issue and the potential of brain-computer interface (BCI) systems in monitoring user's parameters like attention, it is possible to design hybrid ET-BCI solutions - labeled as EyeBCI in this paper - in order to improve the performance and the usability of ET. In this paper, a novel interaction concept is introduced to adapt the duration of the dwell time to the level of mental focus of the user of EyeBCI when he/she wants to select and activate a UI item: the dwell time shortens according to the raise of the observer's concentration, improving the system precision and responsiveness. In order to evaluate this solution, a pilot study was performed to compare different control conditions in terms of task performance and user experience: 3 ET conditions (different by duration of dwell time) and 2 EyeBCI conditions (BCI-triggered activation of UI items and BCI-modulated dwell time). The results demonstrated promising levels of performance and user experience when using the tested implementation of the novel EyeBCI. In addition, the capability of this new interaction paradigm to be self-adaptable to the user's goals has the potential to greatly enhance the usability of ET solutions for patients with LIS.**

I. Introduction

Current technologies for human-computer interaction offer different strategies for augmentative and alternative communication (AAC) [1] to assist people with severe motor impairments. For instance, many patients with locked-in syndrome (LIS) [2] benefit from eye-tracking (ET) [3] cameras in order to move a cursor across a user interface (UI) by means of their gaze movements, and to activate any gaze-selected UI item by maintaining the gaze on it for a defined dwell time. This paradigm provides an intuitive control modality appreciated by many users. Nevertheless, the (unnatural) dual function of gaze (observation and control) in ET-based UIs can lead to stressful conditions, which can make the ET paradigm prone to errors and, by consequence, risk to present low performance, usability, and user experience. This typically happens when the user is not satisfied by the settings of the dwell time, which indeed should be calibrated and optimized according to the patient's skill and stamina: when the dwell time duration is shortened too much for the user, the ET control could become too challenging; when it is increased excessively, the user's engagement and motivation could decrease dramatically. Considering the potential of brain-computer interface (BCI) systems in monitoring parameters like user's attentive effort [4], it is possible to design hybrid ET-BCI solutions [5], labeled as EyeBCI in this paper. Such solutions can improve the performance and the usability of ET, modulating its functioning according to the intentions of the users to control or explore the UI.

In this paper, an interaction concept of EyeBCI is introduced to adapt the dwell time duration to the level of user's voluntary mental focus: the dwell time shortens according to the increase in concentration of the user. The result is an EyeBCI enriched by adaptive qualities that aims at decreasing the risk of errors in UI control and at improving user experience. In order to test this approach, implemented in a low-cost setup, a pilot study based on a series of comparisons between different ET and EyeBCI conditions was performed. The study considered performance metrics (correct characters per second, mean activation times, number of errors) and user experience indices (questionnaire scores). After describing the background of this investigation and the features of the novel "focus-sensitive dwell time" paradigm for EyeBCI, the experimental procedure and results are described and discussed, showing the potential of the proposed solution.

A. Background: EyeBCI Paradigms

As introduced above, ET systems offer easy and intuitive procedures of interaction by means of the detection of the user's ocular movements [6], often maintained in many cases of LIS (e.g., people with amyotrophic lateral sclerosis, ALS, can experience this kind of LIS before reaching total-LIS condition, which paralyzes also the ocular muscles [7]). Such systems are less demanding and more widely adopted solutions than BCIs, which enable paralyzed people to express thoughts and voluntary acts (decoded for instance from brainwaves [8]). BCIs require more complex calibrations and trainings than ET, making their usage a highly difficult experience for the patients. Nevertheless, it must be observed that ET has its own costs [9], which include the effort required from the user for performing repetitive eye movements during hours of activity and for maintaining the gaze on a certain UI item until the end of a dwell time to activate it without producing accidental selections and activations.

In order to overcome such limitations, the approach of hybrid BCI (hBCI) can be introduced. hBCI systems [10] are

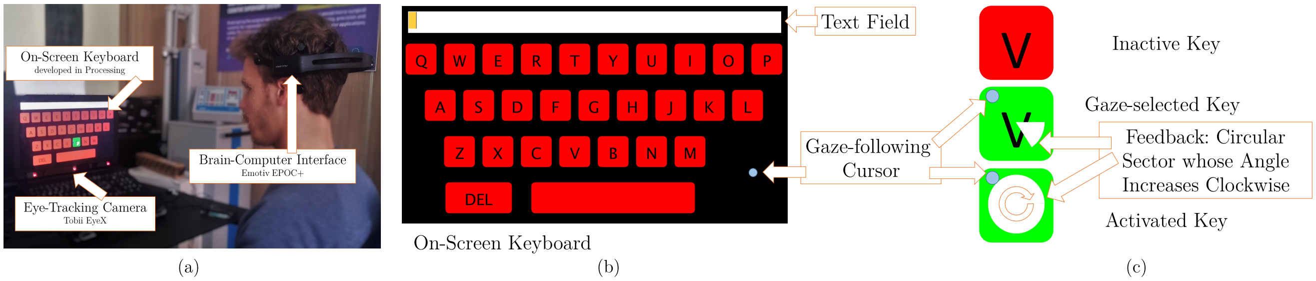

Fig. 1. (a) Experimental setup, (b) on-screen keyboard and (c) states of a key.

designed for integrating different human-machine interfaces combined sequentially (when the output of one device becomes the input of the other) or simultaneously (when their data are processed in parallel). For instance, the hBCI perspective offers the opportunity to integrate ET and BCI (e.g., [11]) obtaining an eye-brain-computer interface, a category of hBCI labeled in this paper as *EyeBCI*, designed for LIS patients who maintain a certain degree of ocular control. This solution can offer higher usability than each of its own components, improving the interaction capabilities of the users: ET can ease the pointing operation for selection, lowering the time for the calibration and training, while a BCI can ease the activation of the process triggered by the user in the observed location without a dwell time. Nevertheless, this hybrid approach can be severely influenced also by the limitations of its subcomponents, in particular the BCI [12]: the effort of triggering the activation of a UI item selected by the gaze can be affected by factors like the calibration of the BCI system or by the training of the user.

Considering such issues, this paper defines a novel potential relationship between ET and BCI, aiming at designing more user-centered ET-based interactions.

B. Introducing a Focus-Sensitive Dwell Time in EyeBCI

The adaptive EyeBCI paradigm described in this paper is based on two modalities of UI control: the ET enables the user to select an item of the UI, and the BCI enables him/her to shorten the dwell time for activating it according to his/her mental focus (representing the intention to activate the UI item). First of all, this solution fits with the natural dissociation between the activities of observation and control: when the user intends only to observe the UI, the dwell time will be long enough to avoid any accidental activation of its functions; on the other hand, if the user requires to interact with the UI, the dwell time will be reduced in order to facilitate the task.

The pilot study in this paper evaluates this adaptive EyeBCI paradigm by comparing an implementation of it with 3 ET control paradigms and with a trigger-based EyeBCI technique. The 3 ET paradigms used for comparison are characterized by different dwell times, while the trigger-based (first action: gaze to select; second action: focus to activate) EyeBCI technique uses mental focus as a mean to activate gaze-selected UI items (as in typical paradigms involving the BCI device used in this investigation). Next sections will describe the pilot study conducted to evaluate how this adaptive EyeBCI can be comparable to ET and to trigger-based EyeBCI in terms of performance and user experience, estimating its actual functioning in adapting the dwell time to user's goals (observing vs activating the UI).

II. Experimental Methodology

In order to test the interaction paradigm proposed here, an experimental setup was designed and developed. The implementation of such paradigm is based on specific hardware and software solutions, which will be addressed in this section.

A. Context

The context of the experiment was characterized by a setup in which the user controlled the selection and activation of on-screen keys either by means of ET or EyeBCI paradigms to accomplish the task of correctly writing 2 words. The experiment was performed on 14 healthy subjects (12 males, 2 females), with average age of 29.64 years (SD=3.88 years).

1) Setup: The complete setup is shown in Figure 1 (a), including an eye-tracker, a BCI, and an on-screen keyboard.

For all conditions, the consumer system Tobii EyeX[1] was used, including both hardware and software (i.e. EyeX SDK) components. The Tobii EyeX is used to track the eye movements and gaze point of the user. It is connected to the PC via USB 3.0 port, and it has to be mounted at the bottom of the screen, pointing towards the user's eyes from below. Its near infrared micro-projectors create reflection patterns on the cornea and pupil of the users eyes and two optical sensors capture images of such reflection patterns. Advanced processing algorithms are then used to estimate the position of the eye in space and the point of gaze.

In order to detect the level of mental focus of the user, the electroencephalographic (EEG) headset Emotiv EPOC+[2] is used as the BCI hardware, together with the Emotiv control panel provided by the company as processing software. The neuroheadset includes 14 electrodes located in the positions AF3, F7, F3, FC5, T7, P7, O1, O2, P8, T8, FC6, F4, F8, AF4 according to the 10-20 International system, recording EEGs at a sampling rate of 256 Hz. This low-cost neuroheadset and its features, including the placement of electrodes, were

[1] http://www.tobii.com/xperience/
[2] http://emotiv.com/epoc-plus/

extensively tested in past studies, considering also its previous version [13]. Its performance was proper for the pilot study presented here and for evaluating the chance of developing low-cost implementations of the novel EyeBCI paradigm. The Cognitiv suite of the Emotiv control panel was used to extract the Cognitiv value that represents the level of mental focus used as control signal during the experiment. The software provides a Cognitiv value from 0 to 1, corresponding to the degree of matching between a recorded calibration pattern of EEG activation (the subject was requested to focus on a UI item, recording a pattern of task-related high mental focus as in [14]) and the present one. This calibration was performed alternating neutral and active trials lasting 8 seconds each. During neutral trials the user was asked to relax without moving any muscle, while during active trials the user was asked to concentrate on the action of pushing a computer-generated moving cube within the control panel. During the experiment, the value of the Cognitiv variable used to detect subjects level of mental focus was transmitted from the Emotiv control panel to the application via the open source software Mind Your OSCs[3]. The Cognitiv variable was low-pass filtered: current and previous Cognitiv value weights were the only two parameters of the filter and they were set to 0.01 and 0.99, respectively. Update of Cognitiv value occurred each time a new sample was acquired by the Emotiv (i.e. around 4 ms). Weights were chosen to provide an acceptable user experience during previous studies. Furthermore, Cognitiv was forced to zero after each key activation, to avoid erroneous multiple selections with activation.

The UI consisted of an on-screen keyboard, with red keys, including space, shift, and delete commands, and an upper bar where the typed text was shown. It was developed by means of the Processing[4] environment, and it was presented to the subjects on the 15.6" screen of a laptop running Windows 7. A blue dot was displayed as a cursor to track the filtered users gaze across the keyboard. Each key became green while the cursor was over it, showing a white circular sector whose angle increased clockwise as feedback until becoming a full circle when the activation condition was achieved. Figure 1 (b) depicts the on-screen keyboard and Figure 1 (c) the different states of the keys, from inactive to gaze-selected, to activated. Finally, the key restored its red color after the cursor moved away. It must be noted that, after the raw gazing coordinates were transmitted from the Tobii EyeX engine to the Processing application, such coordinates were filtered to stabilize the gazing task. A simple auto-calibration feature adds an offset to current coordinates so that eventually they match the center of the currently selected key. Similarly to the case of the Cognitiv variable, the estimated offset was also slowly changed in time, with weight of 0.9 and 0.1 for previous and current estimations, respectively.

2) Task: The task consisted in correctly writing 2 words, *"cognitive robotics"*, using the ET or the EyeBCI control paradigm. The subject was warned with an error beep each time a mistake was detected. Each trial ended when the complete correct sentence was typed.

B. Experimental Conditions

Each subject performed the task in the conditions described below, according to a within-group experimental design with 5 levels of the independent variable *"UI Control"* and 5 repeated measures. The repeated measures correspond to 5 trials of writing 2 words as task using the system in each *UI Control* condition. Objective (performance) and subjective (user experience) measures were collected. All subjects performed the task under the following 5 different conditions of the independent variable *UI Control*:

1) *ET 3.0 s*, based on ET control with dwell time of 3s;
2) *ET 1.5 s*, based on ET control with dwell time of 1.5s;
3) *ET 0.5 s*, based on ET control with dwell time of 0.5s;
4) *EyeBCI trigger*, based on the BCI triggering the activation of the key highlighted via gaze;
5) *EyeBCI dwell*, based on the BCI shortening the duration of the ET dwell time.

Dwell times in ET conditions were defined after previous user trials, considering also the opinion of patients and healthcare professionals with experience with ET. In *EyeBCI trigger* the BCI triggered the activation of the key highlighted via ET by the users gaze, when the filtered Cognitiv value overcame the threshold of 0.3 (following the typical threshold-based activation paradigm used with the Emotiv EPOC+). In *EyeBCI dwell* the BCI reduced the duration of the ET dwell time according to the user mental focus. In particular, dwell time varied from 3 s to 0.75 s (a range defined based on preliminary user trials) according to the Cognitiv value and following the cumulative distribution of a beta function with B(2, 15).

C. Experimental Procedure

Before the session started, and according to the ethical protocol, the subjects of this pilot study received information about the experiment and they signed an informed consent document. After this, the calibration of both ET and BCI was performed. ET was calibrated using Tobii EyeX Engine. BCI was calibrated using Emotiv Cognitiv suite, alternating neutral and active 8 s trials, for about three-five minutes, until the subject felt confident with the Cognitiv variable control level. After calibration, and before the first session, each subject was asked to perform two short training trials, typing the word *"hello"*, under conditions *ET 1.5 s* and *EyeBCI trigger*, to understand the most typical functioning of ET and of EyeBCI with the Cognitiv threshold paradigm.

Each subject ran 2 sessions of 5 trials each one, corresponding to 3 ET-based (*ET 3.0 s*, *ET 1.5 s*, *ET 0.5 s*) and 2 EyeBCI-based (*EyeBCI trigger*, *EyeBCI dwell*) controls. In the first session (*familiarization*) the conditions were presented in the same order within their block: a block with the ordered set 1-*ET 3.0 s*, 2-*ET 1.5 s*, 3-*ET 0.5 s*, and a block with the ordered couple 1-*EyeBCI trigger*, 2-*EyeBCI dwell*. In order to

[3]https://sourceforge.net/projects/mindyouroscs/
[4]http://processing.org

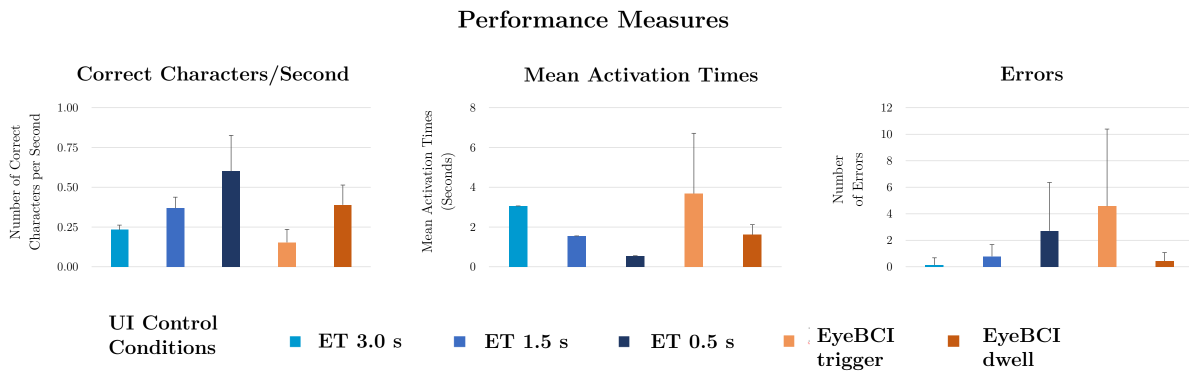

Fig. 2. Performance indices - means with upper standard deviation bars (across users in each trial, representing a condition).

control potential effects of the sequence, half of the subjects experienced the ET block before the EyeBCI block, and the other half the EyeBCI before the ET. In the second session (*evaluation*) the five conditions were presented in random order, to check the potential effects of repeated measures.

D. Measures

1) Objective Measures of Performance: From the *evaluation* session the following performance measures were extracted per each trial, that is constituted by the task of writing *"cognitive robotics"*: (a) the number of correct characters per second, computed as the total time required to accomplish the task divided by the number of correct characters activated during each trial; (b) the mean activation time, computed as the mean time elapsed between gaze moving inside a key and its activation during each trial; (c) the number of errors, i.e. erroneous activated characters during each trial.

2) Subjective Measures of User Experience: After each trial of the *evaluation* session, the subject was asked to fill out a questionnaire based on 8 statements (Figure 3) on different dimensions of user experience. Considering each completed trial, the subject was asked to mark on a continuous-like rating scale his/her level of agreement with each statement. Each scale consisted in 100 points: it was divided in 100 intervals by small lines and with increasing values from left to right. The 1st, 25th, 50th, 75th, and 100th lines are bigger than the others to provide intuitive reference points for the subject (similar to a 5-point Likert-type scale). The resulting pattern is perceptually similar to visual analogue scales [15] that allow to perform properly a wider range of analysis techniques than the discrete scales with few points.

III. Experimental Results

A. Findings

1) Performance: Since ANOVA could not be used (assumptions are violated because of high variability of the data, probably due to the small number of trials and subjects in this pilot study), Friedman's chi squared was used to compare the effects of different conditions on each performance measure, considering also the repeated measures (each condition was tested in a different trial). No effect of repeated measures was found. Table I and Figure 2 depict the results of performance measures (number of correct characters per second, mean activation time, number of errors) in terms of means and standard deviations (in each trial, across users). Table I presents also the Friedman's chi squared values in the comparisons across all conditions, with p-values with 0.01 as significance threshold. Significant differences in Friedman's chi squared were found in each comparison across all conditions. Pairwise tests allowed to evaluate further the differences between conditions in terms of preliminary observations according to the goals of this pilot study. Overall, the condition *EyeBCI trigger* showed the smallest number of correct characters per second, the longest mean activation time, and the highest number of errors. Comparing the two EyeBCI conditions, it can be observed how the BCI worked better in all performance indices when used to shorten the dwell time instead of triggering the activation of the gaze-selected UI item. *ET 0.5 s* resulted in the best overall performance in terms of number of correct characters per second, with the lowest mean activation times, but such advantages showed also costs in terms of number of errors. *EyeBCI dwell* is far less prone to error than *ET 0.5 s*. It is also slightly less fallible than *ET 1.5 s*, but this is not statistically significant. *ET 1.5 s* and *EyeBCI dwell* are similar in terms of

TABLE I
PERFORMANCE DATA - MEANS (M) WITH STANDARD DEVIATIONS (SD).

Performance Indices	Correct Characters/s		Mean Activation Times (s)		Errors	
	M	SD	M	SD	M	SD
ET 3.0 s	0.23	0.03	3.05	0.00	0.14	0.53
ET 1.5 s	0.37	0.07	1.55	0.00	0.79	0.89
ET 0.5 s	0.60	0.23	0.55	0.00	2.71	3.65
EyeBCI trigger	0.15	0.08	3.69	3.03	4.57	5.81
EyeBCI dwell	0.39	0.12	1.61	0.51	0.43	0.65
Friedman's chi squared (4)	43.26		40.97		15.67	
p<0.01	9.15e-09		2.73e-08		3.5e-03	

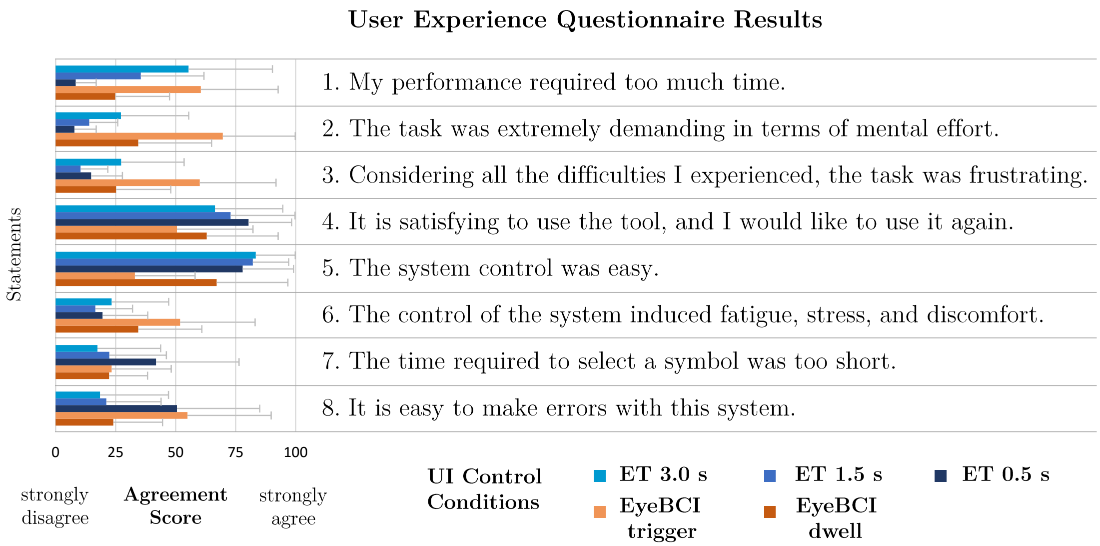

Fig. 3. Scores - means with upper standard deviation bars, across subjects - of the 8 rating scales presented in the user experience questionnaire.

TABLE II
QUESTIONNAIRE DATA - MEANS (M) WITH STANDARD DEVIATIONS (SD) - EXPRESSING THE AGREEMENT OF THE SUBJECT (FROM 0 FOR "STRONG DISAGREEMENT" TO 100 FOR "STRONG AGREEMENT") WITH THE STATEMENTS IN FIGURE 3 ABOUT DIFFERENT ASPECTS OF USER EXPERIENCE.

Scales	**1**		**2**		**3**		**4**		**5**		**6**		**7**		**8**	
	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD
ET 3.0 s	55.4	35.0	27.2	28.3	27.3	26.2	66.4	28.3	83.4	17.8	23.3	23.8	17.4	26.3	18.5	28.6
ET 1.5 s	35.5	26.3	14.0	11.9	10.4	11.3	72.9	27.0	82.1	14.9	16.6	15.4	22.4	23.8	21.1	22.8
ET 0.5 s	8.4	8.5	7.9	9.0	14.8	13.0	80.4	18.0	77.9	21.2	19.5	18.9	41.8	34.6	50.5	34.5
EyeBCI trigger	60.5	32.3	69.6	30.4	60.1	31.8	50.5	31.7	33.0	25.2	51.9	31.2	23.3	24.8	54.9	34.8
EyeBCI dwell	24.8	22.7	34.5	30.6	25.2	22.8	62.9	29.8	67.1	29.6	34.5	26.5	22.3	16.0	24.1	20.5
F(4,52)	10.9		15.18		12.03		4.05		12.45		6.46		2.13		5.03	
$p<0.01$	1.7e-06		2.8e-08		5.4e-07		6.3e-03		3.6e-07		2.7e-04		9.1e-02		1.7e-03	

correct characters per second and mean activation times. *ET 3.0 s* showed a non-significant advantage in terms of number of errors over *EyeBCI dwell*, without improving the number of correct characters per second (also because of the long mean activation times).

2) User Experience: A within-subject ANOVA (Table II) was performed (assumptions were checked) for each scale of the questionnaire about user experience, comparing the effects of control conditions on their scores. No effect of repeated measures was found. Significant effects of the different conditions in *UI Control* variable occurred in all scales but the 7th ("The time required to select a symbol was too short"). Considering also the post-hoc tests, it was possible to highlight how the *EyeBCI trigger* was the worst condition overall, while the *EyeBCI dwell* was appreciated in terms of speed, ease of use, and proneness to errors. Neverteheless, it must be noted the level of mental effort and fatigue expressed in scales 2 and 6: *EyeBCI dwell* was probably affected by the limitations in BCI control (effort in mental focus), even if they are influencing the interaction less than in *EyeBCI trigger*, where the activation of the key is completely controlled by the BCI without a dwell time.

Apparently, the most important advantage of the *EyeBCI dwell* was the low perceived proneness to errors, on the same levels of *ET 3.0 s* and *ET 1.5 s* ET conditions. The *ET 0.5 s* is perceived as quite demanding in temporal terms, and as prone to errors like the *EyeBCI trigger* probably because of the risk of selecting a word when the Cognitiv value is already over threshold.

B. Discussion

The analysis of performance and user experience data showed that the *EyeBCI dwell* condition was less prone to errors than the fastest ET condition. In addition, it has overcome, in all indices, the *EyeBCI trigger* condition, which implemented a more typical ET-BCI control. Thus, *EyeBCI dwell* offers high precision and responsiveness, similar to (and, in terms of errors number, slightly better than) an ET with average dwell time. In addition to this, *EyeBCI dwell* paradigm has the potential of obtaining even shorter mean activation times, while in typical ET they are obviously constant. The fatigue and frustration of the users in *EyeBCI dwell* is higher than in ET conditions: it depends probably on the BCI control, which requires more advanced methods of EEG interpretation than the default ones offered by the low-cost Emotiv EPOC+. Nevertheless, such fatigue and frustration are smaller than the ones produced by *EyeBCI trigger*. Such observation, alongside the ones about performance, suggests to design EyeBCI paradigms with an adaptive relationship between ET and BCI that is based on a flexible facilitation of ET according to the user's intentions (which increases the potential self-customization of ET) instead of EyeBCI paradigms with a prone-to-errors pure sequential control of gaze-selection followed by focus-activation.

IV. Conclusion and Future Work

In this paper, an interaction concept of focus-sensitive dwell time in EyeBCI (UI dual control based on ET and BCI) is introduced to adapt the duration of the dwell time to the level of mental focus of the user: the dwell time shortens according to the increase in concentration of the user in order to improve the system performance and the user experience.

This approach was evaluated by means of a series of experimental comparisons within a pilot study that considered 5 UI control conditions, 3 based on ET (differing by duration of dwell time: 3 s, 1.5 s, 0.5 s) and 2 based on EyeBCI (in one case the BCI triggers the activation of the UI item observed by the user, in the other the BCI lowers the dwell time for the activation of the observed UI item according to the level of mental focus of the user). The task was based on the selection and activation of keys on an on-screen keyboard to write 2 words. The comparisons considered performance measures (correct characters per second, mean activation times, number of errors) and user experience measures (questionnaire scores).

The tested implementation of the novel EyeBCI surpassed, in all considered aspects of user experience and performance, an EyeBCI based on a typical BCI-trigger to select the keys. It obtained selection times and performance levels similar - and slightly superior in terms of errors - to the ones of ET with medium dwell time (1.5 s). Nevertheless, the effectiveness of the novel EyeBCI is shown alongside higher fatigue than the one experienced by subjects under ET conditions. Next investigations will consider this issue while improving the capabilities of self-customization in the algorithms for EEG interpretation: a faster recognition of the user's intentions should lower his/her fatigue, maintaining the same levels of precision or raising them further. Indeed, the results of this pilot study were obtained by means of a low-cost implementation of the paradigm, which did not allow a specific study of EEG signals to customize the recognition processes. Yet, the potential of the focus-sensitive dwell time paradigm for EyeBCI was confirmed because it actually shaped the dwell times according to the requests of the user, avoiding too long or too short durations as pure ET paradigms can not do. While it is obtaining performance results similar to ET paradigms, it is also minimizing the errors that can be produced without modulating the dwell time according to the real time changes of users' goals (observing or activating the UI).

Future work will: (i) develop a novel algorithm for increasing the precision of intention detection on a professional EEG system, in order to replace the Emotiv EPOC+ and its generic focus-detection based on Cognitiv variable; (ii) collect information from more subjects in order to lower the data variability; (iii) investigate optimal functions for the self-customization and adaptation of the dwell time.

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