Speedy’O’Brain: a Neuro-Feedback Videogame driven by Electroencephalographic Signals

Luigi Bianchi

Abstract **—** In this manuscript, a simple videogame driven by electrical brain activity is described. It was designed to train people to improve their ability to maintain a high degree of concentration for some tens of seconds and to be calibrated in few minutes. It is hosted on a PC running Microsoft Windows and can be combined with several commercially available EEG systems because a simple TCP/IP based communication protocol is used to receive data from them. Preliminary results show that it can be used even in a very noisy environment and that users can be able to operate it after few minutes and by using just 4 sensors. This means that it could be of great help to people that suffers for several different diseases such as Attention Deficit Hyperactivity Disorder, epilepsy, depression, schizophrenia, dementia and even in stroke patients as it was shown in several previous works that neuro-feedback could improve their quality of life.

Keywords**—** EEG**,** Neuro-feedback, regression, rehabilitation, videogame.

I. INTRODUCTION

IN recent years, several research groups have demonstrated that neuro-feedback could support clinicians and therapists in the rehabilitation process of people affected by a wide range of neurological disorders and pathologies such as Attention Deficit Hyperactivity Disorder (ADHD), epilepsy, depression, anorexia, schizophrenia, Alzheimer’s disease and stroke, to name few [1-11].

In principle, patients are trained to self-regulate some brain signals through a system that provides a visual or acoustic feedback modulated by their ongoing neural activity. This can be done in several different ways, and several different signals can be used. For obvious reasons, noninvasive systems are preferred and among them electroencephalography (EEG) and recently functional Near Infra-Red Spectroscopy (fNIRS) are the most widely used, due their relative low costs and/or because they are easy to use.

In this paper, a videogame based on quasi real-time EEG signal processing in which spectral features are used to drive the feedback will be described. It is very easy to use and to be integrated with existing EEG and/or fNIRS systems, as it just needs few commands to operate. In practice, two computer systems are used: the acquisition system transmits the signals through a TCP socket connection to the second computer that receives the data and perform all the necessary analyses to drive and visualize the feedback to the user. In this way the acquisition device is not overloaded by signal processing and feedback providing but has just to transmit the signals to the other computer, in which the neuro-feedback application is installed and running.

Furthermore, the neurofeedback application stores another copy of the EEG/fNIRS signals in NPX file format [12], besides those of the acquisition devices, enriched with additional information such as the parameters that were used to drive the feedback, the position of the runners, the results of each single race, and all the configuration settings that are necessary to execute the application. The NPXLab Suite [13], then, can be used to perform all the offline analyses, such as spectral analyses, Independent Component Analysis (ICA), Common Spatial Patterns (CSP), also to compare progresses made by users over time across consecutive recording sessions.

The NPXLab Suite is a collection of tools and software modules - NPXLab is the first one to be released - developed to analyze EEG and MEG signals, even if it can been used for EKG, EMG, fNIRS and virtually any kind of sampled signal with constant sampling rate. Among the analyses, it provides there are Independent Component Analysis, Common Spatial Patterns, several time domain filters, either IIR or FIR, and many linear and non-linear classifiers, which have been widely, used in several Brain-Computer Interface (BCI) systems such as those described in [14-16].

The videogame itself is quite simple: there are six animated puppets that have to run on a horizontal virtual line, from the left side of a PC screen toward the right (Fig. 1). The computer controls the speed of five of them, while the other one is driven by the brain activity according to a strategy that will be discussed in the following section. The winner of a single race is the puppet that is at the rightmost position after a predetermined amount of time of the order of few tens of seconds. This kind of race is repeated several times, to complete a championship.

In the following paragraphs, the system and some design choices are described in more details. Some preliminary results will be also illustrated and discussed.

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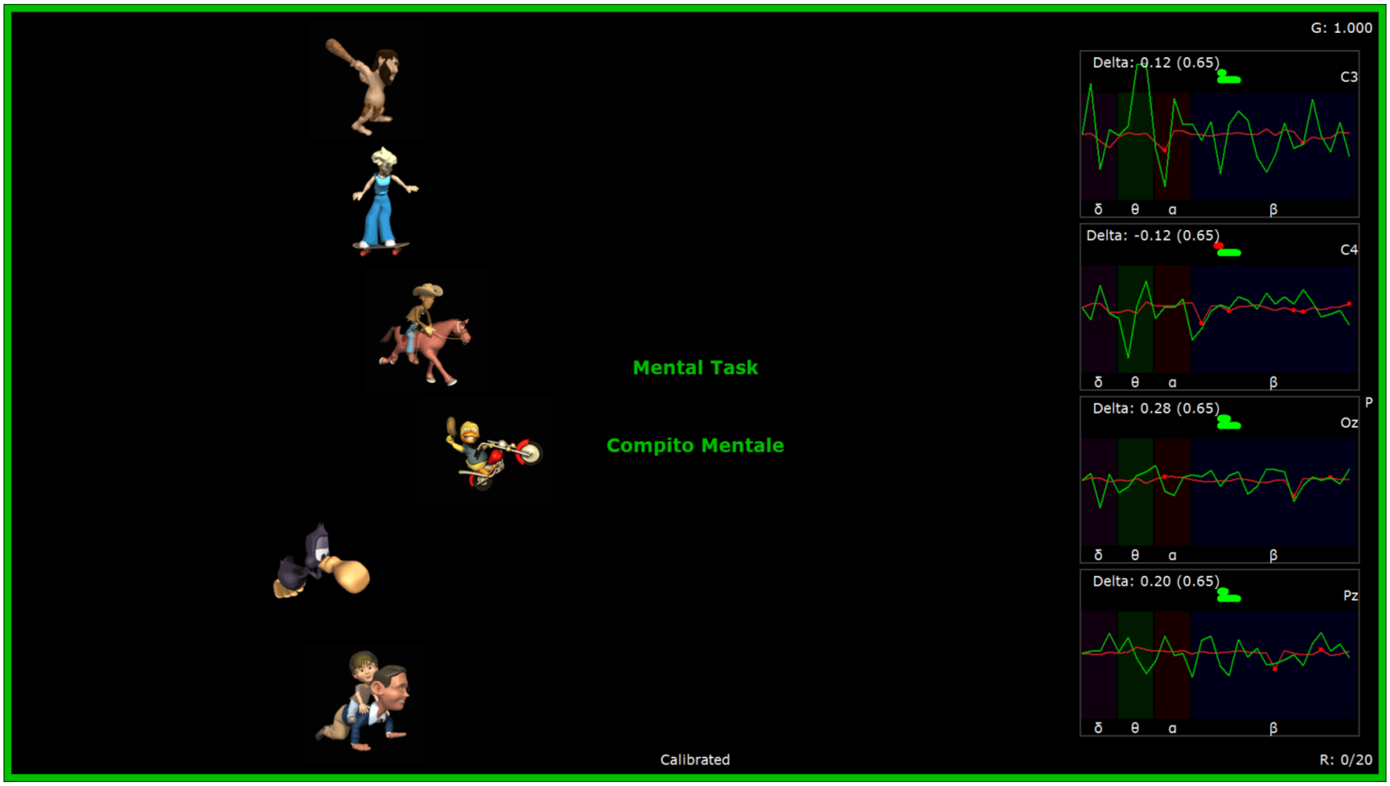

Fig. 1- A screenshot of the videogame during the Racing Modality. On the right part of the screen, features and spectra relative to the actual EEG activity are shown. The green surrounding frame indicates that the image is captured during the performance epoch.

II. Materials and Methods

The neurofeedback videogame is driven by some brain activity that is elicited by a specific mental task that was chosen and performed independently by every single user. Actually, he is asked to stay relaxed and then to perform the task. Speedy'O'Brain, then, will compute, in a manner that will be described later, the most relevant differences among the two conditions and will use them to build an internal model and drive the feedback.

A. EEG System

Speedy'O'Brain is an application written in Microsoft Visual Studio 2017 and in C++ programming language. It was designed to be hosted on a computer that receives EEG signals though a TCP socket connection from an acquisition device.

In the next paragraphs these two PCs will be also called Neurofeedback (or videogame, Speedy'O'Brain) and acquisition (or EEG, fNIRS) computers. Actually two different EEG acquisition devices were tested: a 25 channels SAM FC1 EEG system from Micromed S.p.A. (Treviso, Italy) and a 40 channels Galileo Mizar from EBNeuro S.p.A (Florence, Italy).

There is no limit to the number of EEG sensors that can be used. However, to reduce the amount of time necessary to prepare the subject to play with the game, we used just 4 EEG sensors positioned on the C3, C4, Pz and Oz locations of the 10-20 International System. Reference and ground were positioned at the Cz and Fz locations. A 512Hz sampling rate was used.

B. Communication Protocol

When two applications interchange data, both of them must use the same “language” (a.k.a. communication protocol). For simplicity, and due to the fact that processing latencies and jtterings up to 50ms were tolerated (spectral analyses were performed on 1000ms windows) the TCP protocols was used to send data and other information in a very simple format. To avoid differences in binary representation of floating point numbers it was chosen to send data in ASCII format, that is in a text readable form. This kind of transmission is not in general efficient because data need to be converted on the acquisition PC from floating point to text, then transmitted to the other PC and then reconverted into binary format. However, the overhead of this extra processing is negligible and easily handled by standard PCs.

The packet format was as defined as follows:

{ IDX message..... } (1)

that is, a sequence of characters composed of an open brace, a space, a three character message type identifier (IDX), the data (message) which varies depending on the IDX, a space and a closing brace. Actually 10 different message types are supported, but just two of them are strictly necessary:

a) the "CHN" IDX message, which describes the channels

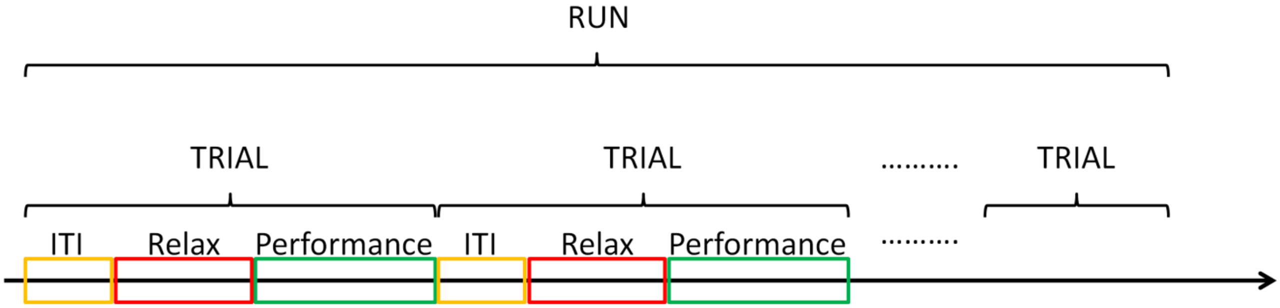

Fig. 2 - A Run is composed of a collection of trials and each trial is formed by a sequence of epochs: ITI, Relax and Performance.

whose data will be transmitted. Its message syntax is:

CHN num_chn SR labels gains (2)

where num_chn is the number of transmitted channels, SR is the sampling rate (the same for all channels), labels is a list of num_chn strings which holds the names of the sensors. Finally, gains is a list of num_chn values representing the gains of the channels and are the multiplication factor that should be applied to signals of the PKT message, described shortly after. An example of this message is:

{ CHN 4 512 C3 C4 Pz Oz 1.0 1.0 1.0 1.0 } (3)

which indicates that 4 channels (C3, C4, Pz and Oz) are sampled at 512Hz each and that the forthcoming received data will have unitary gain.

b) The "PKT" IDX message, which holds a signals data buffer. Its syntax is:

PKT abs_sample num_samples S1C1 S1C2... (4)

where abs_sample is the number of samples transmitted before this packet, num_samples is the number of samples per channel that are stored in the same packet, S1C1 is the first sample of the first channel, S1C2 the first sample of the second channel and so on. An example of this message is:

{ PKT 137 2 1.3 2.7 -1.2 0.4 1.4 2.9 -1 0.6 } (5)

which indicates that 2 samples per channel are transmitted, that 137 samples have already been sent and that the values that follow are the sample values.

These two messages are the only ones that are mandatory to operate the videogame. Among the other relevant messages, there are the "EVT", which is used to notify annotations and insert events in the data file, and the "CMD" which allows to remotely controlling the neurofeedback PC from the EEG one. This is useful to activate the different operating modalities, to show/hide some items on the feedback PC, such as the ongoing signals spectra, to reset the calibration data, to terminate the program and so on.

In the case of the EBNeuro EEG system, this protocol was directly used because the system manufacturer allowed to add some functionalities to their acquisition software in order to transmit the data in the Speedy'O'Brain format.

In the case of the Micromed system, instead, a protocol developed by the manufacturer was used, implying that Speedy'O'Brain implemented some specific functionalities in order to collect the data, because it was not possible to customize the messages sent from the EEG computer to the videogame one. This task however was relatively easy and required just a couple of days of programming.

In both cases, once the data were received and converted in the proper format by the neuro-feedback PC, the behavior of the videogame was identical and independent of the acquisition device.

C. Terminology

The Speedy'O'Brain videogame, a Windows application running Microsoft Windows 10 Operating systems, operates in 3 different modes:

a) exploring, during which a mental task suitable to drive the feedback is determined;

b) calibrating aimed at determining accurate parameters to drive the feedback;

c) racing, during which the videogame is played.

They will be defined in more details in the next section.

The completion of the execution of each of these modalities is called a run. A session is composed of several runs, usually one (optional) exploring run, one calibrating run and one or more racing runs. Each run is then formed by a collection of trials, which usually lasts from 10 to 40 seconds, each trial being divided into 3 epochs such as shown in (Fig. 2). Finally, each epoch is characterized by a color so that the user can easily identify it because a frame surrounding the screen is drawn with the color bound to the actual epoch. In particular, the three epochs are:

1) Inter-Trial Interval (ITI, yellow), during which the user can stretch and move his body. These data are not processed;

2) Relax (red), during which the user has to relax and should not move any part of the body. A spectral analysis is performed on these data;

3) Performance (green), during which the user has to execute the mental task he has chosen. A spectral analysis is also performed on these data and compared with those relative to the relax epoch;

D. Data Analysis

For each trial, the Relax and the Performance epochs were divided into 1 seconds windows and for each of them and for each sensor the power spectrum was calculated by means of FFT. For each trial, the mean spectrum of the whole Relax epoch was also computed.

E. Operating Modalities

The three modalities are defined as follow:

1) Exploring mode. In this modality, usually composed of two to six trials, the user is asked to stay relaxed for few seconds (relax epoch) and then to perform a well defined mental task (performance epoch). At the end of the last trials of this run, spectral data relative to the Relax epochs, obtained after FFTs on a 1 second consecutive windows, are compared with those relative to the Performance epochs. Then, if some spectral features (the values of the power spectrum at each sampled frequency) were statistically significantly different (after *t*-test, $p < 0.05$) and consistent with the task, then the user is allowed to enter the calibrating mode. Otherwise, if no evidence exists that the two spectra distributions are different, the procedure is repeated, eventually with a different mental task, until differences in the two spectra are detected.

2) Calibrating Mode. In this modality, composed of usually 4 to 8 trials, the user is asked to stay relaxed and to perform the mental task chosen during the Exploring mode runs. Similarly to the Exploring mode, spectra relative to the Relax and Performance epoch are compared and the n most significant features were selected to estimate, through a multiple linear regression, the A column vector of size n of the linear model:

$$Y = XA + \varepsilon \tag{6}$$

in which X is a matrix whose rows are as many as the number of spectral analyses performed, and whose columns number is n. Finally ε is a term that takes into account noise and is often called error term. The value of n corresponds to the number of features statistically different as described in the Exploring mode, but it should not exceed the square root of the number of rows of X, to try to avoid over-fitting. In this case, those features with the n lowest p-values are chosen.

The values of the X matrix are the values of the selected features after having subtracted the corresponding feature relative to the mean of the Relax spectrum of the same trial. This was done to compensate slow fluctuations in the EEG signal;

Finally, Y is a column vector whose values are equal to 0 when relative to the Relax epoch and 1 while referring to the Performance.

3) Racing Mode. In this mode the n features of the performance epochs selected at the end of the calibrating mode are the element of the x row vector (eq. 7), after having subtracted the corresponding mean features of the relax epoch. The following simple equation:

$$y = xA \tag{7}$$

will then be used to compute the scalar y that will drive the feedback and computed every time a data packet is transmitted and on the last received second.

A predefined number of trials (races) are necessary to complete a racing mode run. At the end of this run, the number of pixels "walked" by each runner was computed, by summing those of each race. This represented the recording session result.

F. Preliminary testing

Twenty-four volunteers (mean age was 35±8.3) participated to the study during the Maker Faire 2018, European Edition, held in Rome, Italy 13-15 October 2018 in a very noisy environment, as the event was attended by more than 100.000 visitors.

The different modalities settings are illustrated in the following Table I.

TABLE I
OPERATING MODE SETTINGS

Modality	Relax [ms]	Performance [ms]	Trials	Total duration [ms]
Exploring	6000	6000	3	36,000
Calibrating	8000	8000	6	96,000
Racing	6000	20000	10	260,000

These values were chosen in order to complete the whole experiment in less than 15 minutes, including the preparation phase.

The X matrix of eq. (6) was then composed of 96 rows and the maximum number of features was then set to 9. Initially, the available features were 1024 (256 for each of the sensors). However, only those in the alpha [8-12Hz] and beta [12-30Hz] bands were pre-selected for the calibration, thus reducing the number of candidates to 92 (23 for each sensor). This was done to remove either low frequency noise sources, such as eye blinks, or high frequency ones such as those induced by the environment.

III. RESULTS

All the subjects were able to complete the exploring and calibrating runs in less than 5 minutes. Usually EEG recordings are performed in silent and controlled environments. In our case, however, the EEG traces resulted contaminated by several and frequent artifacts that was not possible to remove and caused by the multitude of people moving around the stand and the environmental acoustic and electromagnetic noise (Fig. 3). Some of them, however, were filtered out because they did not belonged to the alpha or beta EEG bands, the only one considered for driving the videogame.

The quality of the signal was however considered sufficient to try to play with the videogame.

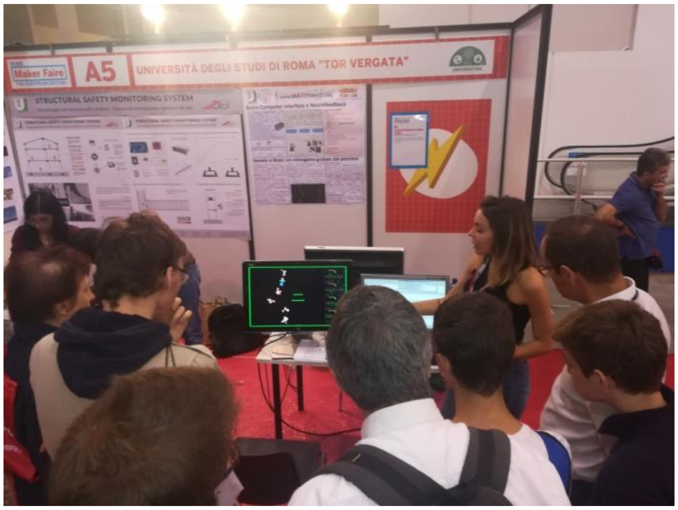

Fig. 3 - The Speedy'O'Brain stand at the Maker Faire 2018, European Edition.

For these reasons, results must be considered preliminary and should be confirmed in a laboratory environment.

However, 18 out of the 24 subjects that played with the videogame resulted the winners at the end of the recording session, thus indicating that it was possible to achieve a sufficient and reliable control over it. In case of no control, we would have expected values close to the chance level, that was just 4 winning subjects (one-sixth of the volunteers). Most of them chose to execute a motor imagery mental task during the performance epoch, such as running, swimming, rotating the arms, which are known to activate the cortex at the C3 and C4 electrode position. This was suggested by the operator to the volunteers as starting tasks to be explored. Few of them switched to other tasks such as mental calculation, singing or playing music.

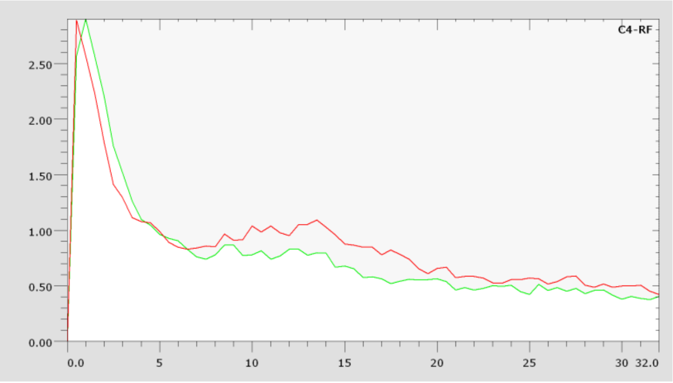

Fig. 4 - Power spectra computed on one subject during the Racing run on the C4 electrode location and relative to relax (red line) and performance (green line) epochs.

Fig. 4 represents the mean spectra computed on one subject during the Racing run on the C4 electrode location and relative to relax (red line) and performance (green line) epochs. The chosen mental task was imagining to play the piano. It can be noted a reduction of the EEG activity, as expected for a motor task, in the alpha e beta bands. The offline spectral analysis was performed with the NPXLab software [13].

Similar results are obtained at the C3 electrode location for the same subject and mental task (Fig. 5).

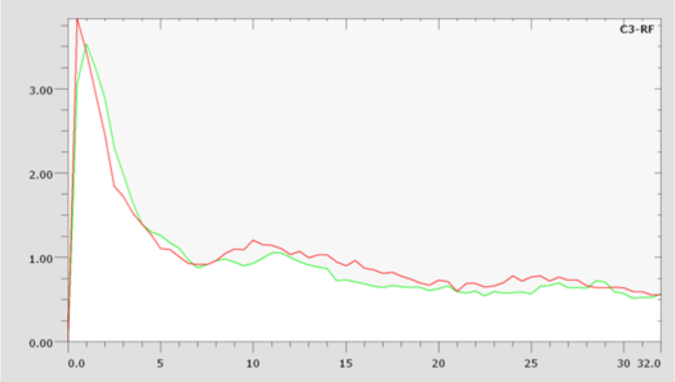

Fig. 5 - Power spectra computed on one subject during the Racing run on the C3 electrode location and relative to relax (red line) and performance (green line) epochs.

IV. FUTURE INVESTIGATIONS

As outlined, the preliminary results are very promising but further actions should be taken in the near future. First of all the observations need to be replicated in a more controlled environment and observing volunteers several time to evaluate progresses. Then, more electrodes should be used, covering the whole brain, in order to cover a wider range of mental tasks that each user could perform. It should be also very interesting to investigate other feedback driving rules, based for example on artificial neural networks and to test it when two or more players are playing simultaneously, one against the others.

V. CONCLUSIONS

Speedy'O'Brain is a videogame controlled by thought. It uses EEG signals spontaneously produced by subjects to control the speed of one specific virtual runner among other 5 that are instead controlled by a computer. Its main advantage is that it adapts to users in a very limited amount of time and that it is able to self-detect the most relevant features from brain signals that are suitable to drive the feedback.

It has been successfully used in a very noisy environment, which suggests that it can perform even better in a more controlled setting such as at home or even in a laboratory. This will be verified in the very near future even if preliminary results seems to confirm this.

It can be easily integrated with commercial systems such as EEG and fNIRS devices either using its communication protocol or using the one provided by the acquisition device manufacturer. In this last case some minimal programming effort is however required.

Its main clinical applications are relative to people affected by neurological disorders and pathologies such as ADHD, epilepsy, schizophrenia, dementia and stroke. However, even athletes can benefit from it, as demonstrated in recent studies, and this videogame, which also supports multiplayer's mode, can be used to allow disabled people to play with healthy ones such as friends and relatives, thus breaking the barriers of disability.

VI. AWARDS

Speedy'O'Brain was awarded at the Maker Faire 2018, European Edition, held in Rome, Italy 13-15 October 2018 with the Maker of Merit Blue Ribbon.

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His main interests are real-time and offline signal processing, Brain-Computer Interfaces, Human-Computer Interaction and assistive technologies and released many free tools which can be downloaded from his web site http://www.brainterface.com.

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