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Training with a Neurofeedback System for the Control of a Drone Using Electroencephalographic Signals

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***Abstract*— In the present work, a portable electroencephalography system was developed in order to monitor the attention coefficient during a neurofeedback training using a drone as a visual stimulus. A four channels EEG signal acquisition system was developed using the 10-20 international standard, positioned at FP1, FP2, F3 and F4. The Power Spectral Density was calculated using the Modified Covariance method, and the attention coefficient was calculated using the ratio of the area under the curve between the high Beta and Theta bands. With the help of the Neurofeedback system and the drone, a series of eight tests of ten minutes each was carried out with a group of eleven volunteers. Only one session per day was carried out. In each test, the attention coefficient was calculated while the subject watched the drone performing one of the 16 determined trajectories. If the attention coefficient exceeded a threshold, the drone could continue moving, otherwise the drone remained static. As a result of using this neurofeedback system, it was found an increase in sustained attention time from 7.7 to 9.4 s, as well as a reduction in inattention time from 6.0 to 4.8 s.**

Keywords—EEG, Neurofeedback, Modified Covariance, Attention Coefficient, Brainwaves, Spectral Power Density

I. INTRODUCTION

Electroencephalographic (EEG) activity is classified according to the dominant frequencies of the signal. Based on this criterion, EEG waves can be subdivided in five main groups: delta, theta, alpha, beta and gamma. They can be recorded with noninvasive electroencephalography and appear depending on the activity that is being carried out during the recording. Each group is comprised of frequencies ranging from 0.5 Hz to 50 Hz, as shown in Table 1.

TABLE I. BRAINWAVE FREQUENCY BANDS [10]

Wave	Low Frequencies (Hz)	High Frequencies (Hz)
Delta (δ)	0.50 – 3.50	N/A
Theta (θ)	4.00 – 7.00	N/A
Alpha (α)	7.50 – 9.75	10.00 – 11.75
Beta (β)	12.00 – 16.75	17.00 – 29.75
Gamma (γ)	30.00 – 39.75	41.00 – 49.75

Attention is a cognitive process that refers to the action of selectively focusing our consciousness, filtering and discarding unnecessary information [2]. Increasing attention levels is a topic of interest not only for people who have some condition that makes it difficult for them to perform this task, but also for those who want to improve that capacity. In July 2013, the FDA approved the use of the NEBA, that is an EEG-based Neuropsychiatric Evaluation Aid System for Attention-Deficit/Hyperactivity Disorder (ADHD), which uses the β-θ power ratio (TBPR) to support the classification of subjects with attention deficit hyperactivity disorder (ADHD) [3].

Neurofeedback (NF) systems implement non-invasive techniques to make electroencephalographic activity records perceptible to a subject through visual or audible stimuli, with the purpose that the person learns to concisely control their own brain activity [4]. These systems have been used for neurological treatments, with favorable results [5]. For instance, Castillo-Reyes and Cruz-Bermudez demonstrated that the NF allows a person to self-regulate their brain activity and modify cognitive processes [6]. NF systems, which have been focused on increasing the level of attention, require a visual stimulus and several studies have shown that the use of video games can improve various cognitive aspects, including increasing attention capacity [7,8]. In a study conducted in Korea, twenty-three healthy users interacted with a video game in which the speed of a car increased as the level of attention measured by beta waves (13-30 Hz) in the frontal lobe increased, and they concluded that the beta-based NF game is effective in controlling the level of attention and that this effect may be greater in the competitive mode among multiuser [9]. Balbuena-Vera and Reyes-Ramírez developed an NF system to induce the state of attention through audiovisual stimuli in a digital environment, using a binaural system as an auditory stimulus and different cognitive tests [10].

Activities performed in a virtual world have different effects. In the school environment, the results of simulations offer to satisfy conceptual needs, however, it is well known that interaction with physical objects produces a different stimulation [11]. The difference between 2D and 3D feedback has been documented in several studies [12], as they serve different needs. A study by J. C. Mercado, concluded that patients react differently to visual stimuli, but in all types of stimuli, people obtained a greater degree of attention [13].

The system described in this paper intends to use a drone as a novel stimulus, with the purpose of generating more interest of the user in the task and, therefore, causing an increase in the attention coefficient during its execution. The main characteristic of this NF system is portability, which allowed it to be transferred to an open environment where the drone routines were performed. Additionally, it is comfortable, light and ergonomic, for a better interaction between the system and the user. Finally, it has a wireless connection for a greater degree of freedom of movement during the acquisition of encephalographic records as well as the prevention of errors due to disconnection of components.

II. Methods and Materials

The neurofeedback system contains the stages of acquisition, adaptation and digitization of the EEG signals from 4 channels, which allows their transmission to a mobile device for visualization and to a laptop for signal processing.

In addition, an algorithm implemented in Python calculated the attention coefficient and sent the instructions to the drone to complete the trajectory. Fig. 1 shows a diagram of the neurofeedback system developed.

This system allowed to know if the subject had a high level of attention due to the displacement of the drone. In contrast, the drone gets a pause if the subject had a low level of attention in the task.

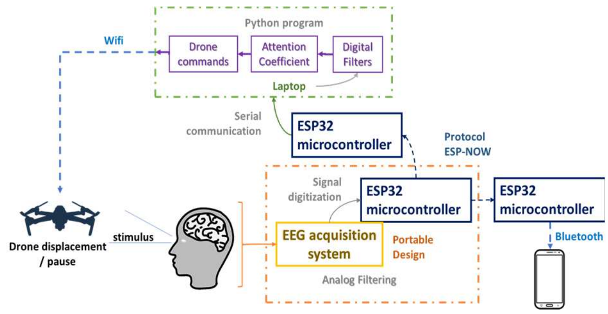

Fig. 1. Diagram of neurofeedback system developed

A. Acquisition system

Six superficial gold cup electrodes with CG-20 conductive paste for EEG and CG-Prep preparation gel for electrodes were used to collect the signals. Four of these electrodes were connected to the inputs of the acquisition system while the remaining two were connected to the reference of each input.

The system consists of 4 PCB boards with dimensions of 40 x 34 mm. Each board is an independent EEG channel module, which is made up of an instrumentation amplifier a gain of 120, then an analog filter stage: low-pass filter (cutoff frequency of 30 Hz), high-pass filter (cutoff frequency of 0.1 Hz) and band reject filter (central cutoff frequency of 60 Hz). The low-pass and high-pass filters are second order filters in Sallen-Key configuration and the band rejector is a Twin-T filter with a Q factor of 2.4, the last one in order to prevent the 60 Hz component. Finally, it has an inverting amplifier with variable gain, from 1 to 100 as well as an inverting summing amplifier where it is added a +1.5 V DC signal. In addition, there are three impedance couplers in conjunction to first order RC filters, so that the signal can be acquired with the appropriate amplitude characteristics in the next stage. Figure 2 shows the block diagram of this acquisition system.

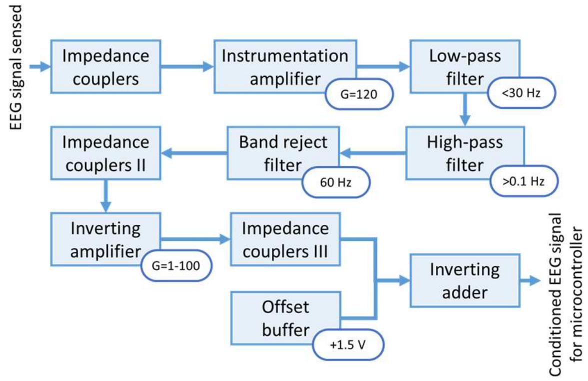

Fig. 2. System's block diagram.

The ESP32 was the microcontroller used, which has integrated Wi-Fi and Bluetooth modules, a processing speed of 240 MHz, an internal memory of 512 KB, and 18 analog inputs for measuring varying voltage levels between 0 V and 3.3 V, and an analog to digital converter with 4096 quantization levels.

In addition, three fully charged 9 V 200 mA batteries power the acquisition system for 40 minutes. The acquisition system is assembled on a 3D printed plastic structure, which can be connected to the ESP32 microcontroller and the power supplies. It is additionally placed inside an external acrylic casing; which dimensions are 200x200x50 mm. The assembly, shown in Fig. 2, is then covered by an ergonomic backpack for portability. Lastly, the system has a total weight of 0.6 kg.

Fig. 3. Assambly of the neurofeedback system

B. Communication

Concerning data communication, three ESP32 development boards were used for data communication between the acquisition, display and processing systems, one as a transmitter and two as receivers. These boards have integrated Wi-Fi and Bluetooth modules, as well as different communication protocols. The transmitter was programmed to receive the filtered analog signal, to convert the analog signal into digital and to create a 4-step data packet for sending data every 15,625 ms. Communication between the transmitting and receiving boards was through the ESP-NOW protocol, avoiding data loss during transmission within a coverage radius of 200 m. One of the receiver boards was linked with the mobile application through the Bluetooth protocol and the other receiver board was connected with the laptop and the processing program through serial communication. The programming of these microcontrollers was done in Arduino IDE.

C. Digital filtering

A Chebyshev I filter was selected to digitally filter the signals because it has a fast attenuation and therefore has a better response at frequencies near the cutoff frequency, compared to the response of other filters, however, its disadvantage is the ripple in the bandpass. In this work, after receiving the signal via serial communication, the offset was subtracted, the signal was normalized and a Chebyshev I, order 3 bandpass filter was applied with cutoff frequencies of 2 and 30 Hz.

D. Power Spectral Density

The modified covariance method with order 18 was selected for the calculation of the PSD, which allowed identifying dominant frequencies with a resolution of up to 2 Hz, as shown in Fig. 4. In this example, a signal composed of the sum of 4 sine waves, with the same amplitude and different frequency (3, 5, 10 and 16 Hz) was used. These frequencies were selected as they represent the central frequency of each of the four bands of interest: delta, theta, alpha and beta, respectively.

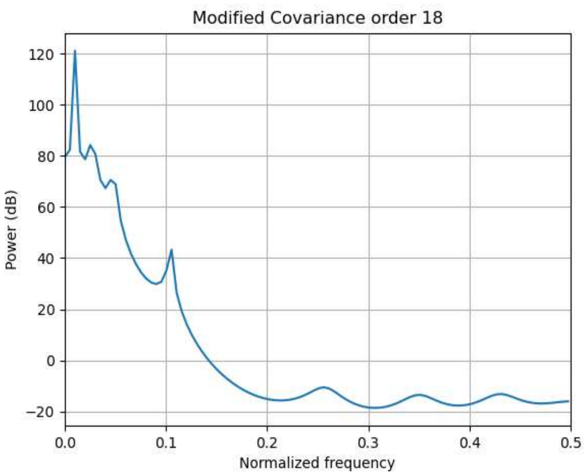

Fig. 4. Spectrum with Modified Covariance

E. Attention Coefficient

A preliminary data set was generated with volunteers while doing different activities: relaxing, doing mental arithmetic operations, listening a story, and using a mobile device. This data set contains the EEG signal, in a range of 4096 bits, obtained from FP1 with a sampling frequency of 256 Hz, each of the recordings had a duration of 10 s, for each task were made five recordings, thus twenty different recordings were stored.

The attention coefficient was calculated during the execution of last four activities with the Theta-Beta Power Rate (TBPR) calculated by the areas quotient under the curve of the Power Spectral Density, with the parametric method. Using the TBPR and normalizing the ratio, was found that when the test subjects performed activities with attention, the coefficient was greater than one. Fig. 5 shows the attentional coefficients resultant from conducting attentional and non-attentional activities.

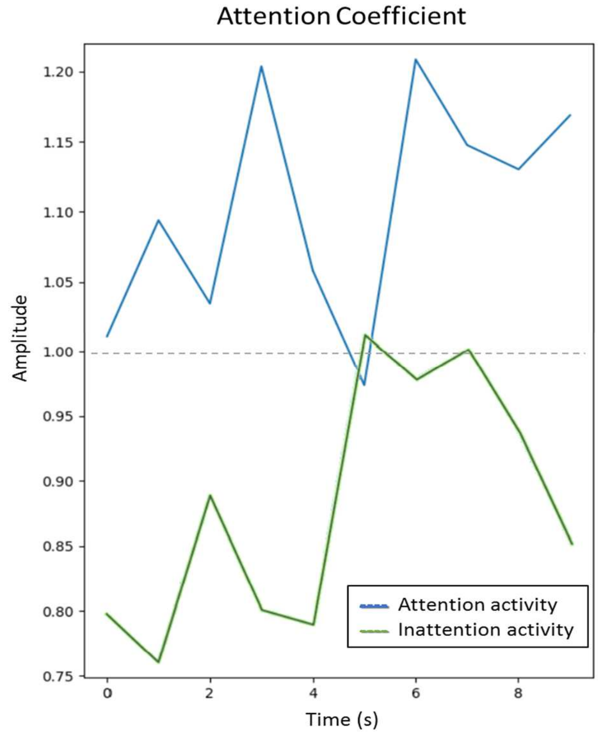

Fig. 5. Attention Coefficient get during an activity (blue) with attention, and (green) without attention. On the dotted line above 1 indicates the established threshold of attention.

F. Study Protocol

In order to evaluate our system, a study was conducted during eight neurofeedback training sessions for eleven undergraduate participants (5 women and 6 men). The protocol of the sessions describes in detail the instructions regarding each phase of the study with the purpose of informing the volunteers the aim of the experiment, its preparation (disinfection, cleaning of the scalp and placement of the EEG electrodes), the function of the drone and the task to be performed. Additionally, the SF-36 general health survey was applied to the volunteers to obtain the participant's state of mind before performing the test.

The eight sessions for each participant were scheduled every other day. In the first session, all the information described in the protocol was explained to them. The subjects signed a letter of consent if they agreed to participate in the study, according to the Declaration of Helsinki.

Thereafter at each session, a daily health survey was applied to them, in order to find out if they were stressed, if they did not sleep well or if they were taking medicine earlier on the day of the session. The user sat two meters from the drone and electrodes were placed in the four positions of the scalp: Fp1, Fp2, F3 and F4 according to the international 10-20 system. This requires placing a tubular surgical mesh, separating the hair from the area and cleaning the scalp with CG-prep gel, and finally placing the electrode filled with CG-20 conductive paste.

In each session the drone could make two figures randomly, to familiarize the user with the movement of the drone, demonstrative videos were presented with the figures of each session. Subsequently, the ballot was delivered where they selected the figure as the drone carried it out.

At first, the drone takes off, hovers 1 m above the ground and rotates 15 degrees to the left and right from its initial position, this movement is named as pause mode. This first movement produces a visual stimulus for the subject, so after recording 30 s of reference EEG, the drone begins to perform a figure in the air.

During the training, the subject must pay attention to the movement of the drone and indicate the figure it performs. If the subject maintains attention, the drone performs the movement of an edge of the figure in progress, once this displacement is finished, it checks the level of the attention coefficient again. If it is below the established threshold, the drone enters pause mode, constantly monitoring the coefficient. Up to the coefficient is higher than the threshold, the drone performs the next edge of the figure.

As soon as the subjects identified which figure was performed, they had to mark the identified figure on the ballot. As already mentioned, for each session, the drone performed two of the sixteen programmed figures. These figures are shown in Fig. 6. The number of figures that the participant performs depends entirely on the time in which he remains in a state of attention, so an increase in this time is reflected as a greater number of figures. Through the ballot filled out by each user, we followed up on how many of the figures identified were correct.

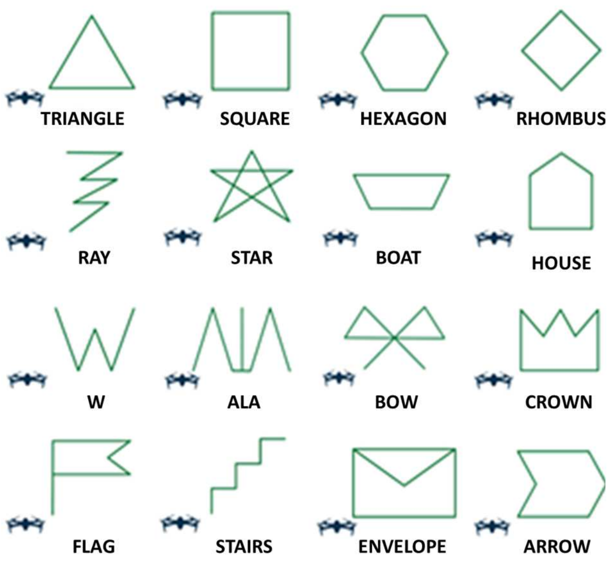

Fig. 6. Figures performed by the drone

The data that conformed the EEG signals obtained from the 4 channels, with a frequency sample of 256 Hz, was stored in a text file, whose name indicates the test subject and the session number. Likewise, the data of coefficients obtained for each 2.5 s sample of the EEG signal was stored in a text file similar. There is a data loss in the laptop records of 1 s between each sample due to the processing time taken by the algorithm.

III. RESULTS AND DISCUTION

First of all, the system was capable of acquiring and processing EEG signals for determining an attention coefficient and finally indicating to the user if he is paying attention, therefore an 8-session training with eleven undergraduate students took place.

Along the training, it was reached 88 EEG signals recordings and 88 attention coefficients recordings. In the records of the attention coefficients, periods of time can be tagged as sustained attention. The duration of these sustained attention changed during each session and for each of the test subjects. This variation was analyzed, thus obtaining the average time of sustained attention, the maximum of sustained attention and the total attention during the 10 min session.

To perform the calculation of time in seconds, it was considered that a coefficient represents the result of a sample of 2.5 s, which took 1 s to process. Therefore, each sample is equivalent to 3.5 s.

A. Average Sustained Attention

It was obtained that the average time of sustained attention for each subject is 8.444 ±3.884 s, that is, within two standard deviations of the general average.

Secondly, the average sustained attention in each session showed a continuous increase in each session, except for the fourth session, whose average is lower than in the second session, as it is shown in Fig. 7. This decay coincides with the fact that the flight time of the drone in session 4 is less than that of session 2, so it follows that the stimulation time (the flight of the drone) is directly related to the aperture of sustained attention.

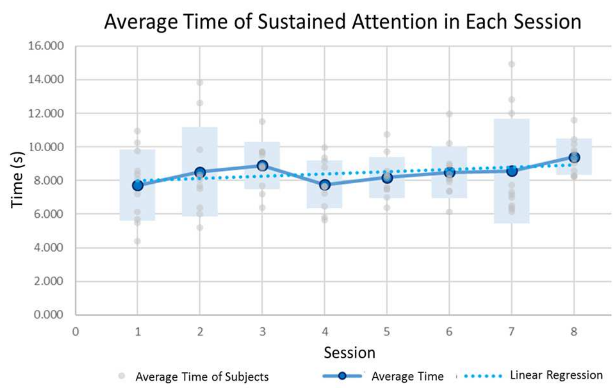

Fig. 7. Average time of sustained attention in each session.

A linear regression was obtained, which in Equation 1 indicates that the average attention time is increased by 0.134 s in each training session.

$$y = 0.1338x + 7.841 \quad (1)$$

Secondly, the average time of sustained inattention was obtained, which was 5.272±1.957 s, considering two standard deviations from the general average, and it was found that it decreased at a rate of 0.068 s in each session. In the Fig. 8 is shown the decreasing of time of sustained inattention in each session.

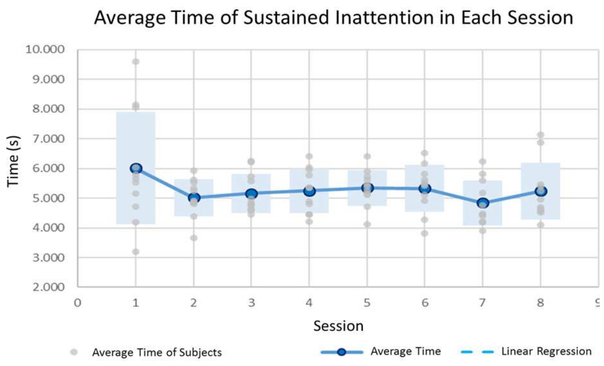

Fig. 8. Average time of sustained inattention in each session.

B. Maximum sustained attention time

Another property that was compared was the maximum duration of sustained attention among all subjects in each of the training sessions. On average, the maximum sustained attention time is 29.6±22.26 s, considering two standard deviations from the average maximum time, as shown in Fig. 9. However, it was found that the maximum recorded sustained attention time is 1 minute, which was obtained in the first session.

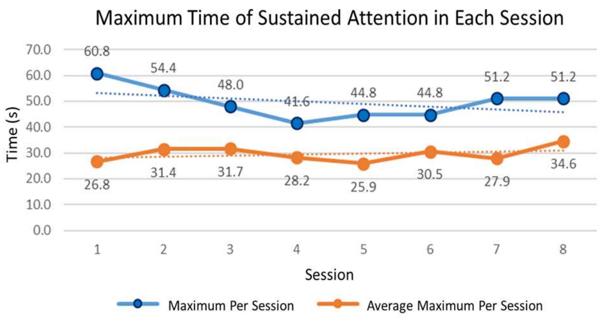

Fig. 9. Maximum time of sustained attention in each session.

In the case of sustained inattention, the average maximum time is around 16 s, as Fig. 10 shows.

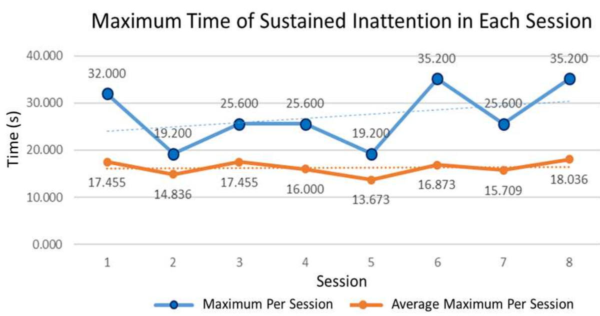

Fig. 10. Maximum time of sustained inattention in each session.

C. Total time of attention

If it is considered that each of the sessions lasts 10 minutes, the percentage of attention that the subjects presented was determined. Both individually and in general, a growing trend was observed, from which, with a linear regression, it was obtained that each session increases by an average of 4 s. Fig. 11 shows the distribution of the total attention times of the subjects, the average per session and the linear trend. The linear regression result is described in Equation 2.

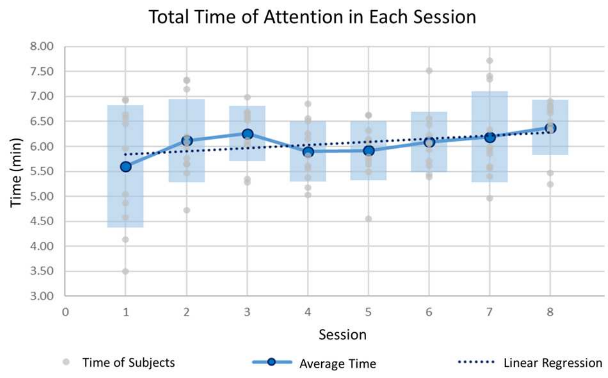

Fig. 11. Total time of attention in each session.

$$y = 0.0631x + 5.7726 \quad (2)$$

Fig. 12 shows the total average time of attention and inattention in each of the sessions. In the first session it was obtained that in 56% of the session, attention was detected, while in the remaining 44% correspond to levels of inattention. With the training for the end of the sessions, attention was shown in 64% of the session, while the time of inattention was reduced to only 36%, which correspond to only 3.6 minutes. In this way, it is observed that the total time of inattention was reduced thru training with a rate of 4 s per session on average.

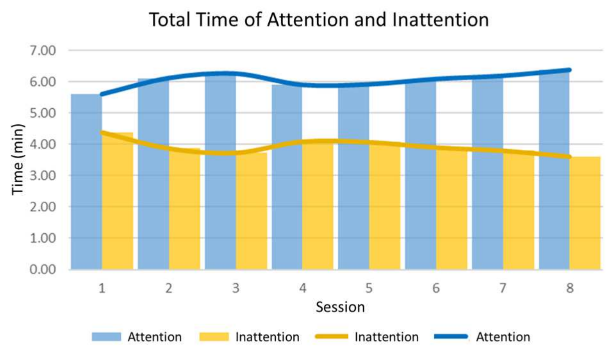

Fig. 12. Total time of attention vs Total time of inattention in each session.

D. Discusion

In general, it is observed that attention is increased, and inattention is decreased using a neurofeedback system with a drone as a visual stimulus. It was found that there was an increase of 0.11 ±0.06 in the level of attention of the subjects with respect to their first session. Similarly, the contrast between the increase in sustained attention time and the decrease in inattention time is also notable.

In comparison with previous works, it is observed that their results prove the efficiency of the NF system by means of the TOVA test, while in this work a measurable trend was obtained on the sustained attention times, and a constant growth of this, for each volunteer throughout the sessions as shown in Fig 7.

In addition, in the training sessions, important facts about this type of training were observed. Firstly, the action of marking the identified figure on the ballot not only led the users to do a cognitive process based on the information received from the stimuli, but also produced in some cases a loss of attention. Secondly, the drone works as a visual and auditory stimulus because the blades of the drone produced different sounds depending on whether the drone was moving or if it was in pause mode.

On the other hand, with the equipped wireless communication made the NF system portable, and the real-time feedback effective in such a way that subjects could identify the moment they lost attention and trained to improve their sustained attention time. But in some cases, subjects showed discomfort and disinterest in the use of the drone, so their results were not as high as the average.

IV. CONCLUSIONS

The combination of the acquisition system and wireless communication features is an option for remote acquisition of EEG signals; thus, it can be used for real-time neurofeedback training without the need to be connected to the stimulus.

In this work two data sets were obtained, the first consists of ten-second signals, with a sampling frequency of 256 Hz, obtained from Fp1 during the performance of four different tasks, which includes: relaxation with eyes closed, resolution of arithmetic operations brainstorming, listening to a story, and using a mobile device. This preliminary data set was used to stablish a threshold in the attention coefficient to be used in the real-time application.

Given the results obtained in the study with 11 subjects during their 8 training sessions, it is concluded that the use of the neurofeedback system produces gradual results with respect to sustained attention time, if its use is constant and adequate.

It was confirmed that there was an increase in the level of attention of the volunteers with respect to that obtained in their first session of 0.11 ± 0.06, however, this difference is not constant, and in some cases, it becomes almost null. in the last session. Similarly, an increase was found in the time of sustained attention individually, as well as a decrease in the time of inattention.

Drone stimulation is an innovative approach that produces positive training results, which are different from video game training. Due to the three-dimensionality of the stimulus as well as its attractiveness, it is concluded that this type of training is an option for people who are more interested in 3D stimuli.

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