Influence of a BCI neurofeedback videogame in children with ADHD. Quantifying the brain activity through an EEG signal processing dedicated toolbox

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***Abstract* — Attention Deficit Hyperactivity Disorder (ADHD) affects around 10% of children in the world and conventional therapy has proved to be insufficient to supply the resources for an effective rehabilitation. Novel approaches in attention training include the use of information technologies to complement health professional's work. Specifically, the use of neurofeedback treatments has been shown as effective for train attention's self-regulation in children with ADHD. In this paper, a pilot study using a custom-made neurofeedback videogame called *Harvest Challenge* is presented. The videogame uses a low-cost Brain Computer Interface (BCI) to measure the attention levels of players in order to use them as an input control in the videogame. We carry out $2-$sessions intervention with 7 children with ADHD attempting to find improvements in sustained attention levels. Furthermore, we recorded the EEG signals during a resting state in order to neurophysiologically characterize the children. Results revealed improvements in the sustained attention levels of players (measured by game metrics) as well as higher resting values in the power of alpha and beta bands rather than Delta and Theta. A statistical relationship between the power of the Theta band during resting and the time to accomplish the first game level was found indicating important game correlates with brain activity. Finally, we exposed the development of a software tool to simplify the EEG signal processing from low-cost BCI sensors highlighting its promising usefulness in user experience studies.**

***Index Terms*—*neurofeedback*, *videogame*, *ADHD*, *brain computer interface*, *EEG*, *physiological signals*.**

I. Introduction

In the last decade, Attention Deficit Hyperactivity Disorder (ADHD) has been investigated showing a high prevalence in Latin America and the Caribbean. The Economic Commission for Latin America estimates that around 30% of the population are children and adolescents younger than 15 years [1]. Assuming that ADHD affects 5.0% of children worldwide [2] it is estimated that there are more than 8 million children and adolescents with ADHD in Latin America and the Caribbean [3]. In some countries, some of these children received psychosocial treatment instead of medication; however, the of health coverage systems to supply the resources for an effective behavioral treatment for ADHD is limited. For instance, only the 6.6% of ADHD diagnosed children in Colombia received some treatment [4] demonstrating that it is a real public health issue.

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Conventional ADHD treatments include medications and therapeutic approaches. The therapeutic treatments embrace methodologies such as psychotherapy, behavior therapy, support groups, parenting skills training and so on [5]. More recent approaches include the use of multiple technological elements to enhance the ADHD treatments via improving motivation levels and augmenting therapeutic adherence. For instance, Information and Communication Technologies (ICT) are becoming massive and omnipresent facilitating the creation and implementation of emergent solutions for ADHD treatment [6]. Biofeedback allows the training of physiological self-regulation skills via providing feedback (mostly visual) to the users about their performances in specific tasks [7], [8]. This technology intends to unite the mind and the body to make the conscious, thinking mind more in control of what the body is doing using real-time physiological sensing [9]. Biofeedback applied with neurophysiological signals (Neurofeedback) has been effectively used to train physiological self-regulation skills in children with ADHD showing significant decreases of the ADHD core symptoms [10]. However, despite positive results in inattention and impulsiveness [11], the neurofeedback-based treatments still have limitations related with usability and treatment adherence in children. It is well-known that to produce measureable results in biofeedback therapies a mean of 30 sessions are needed [8]. This fact produces frequent mood declines in ADHD patients who lose their motivation along the time [7]. To supply solutions for these problems, ICT technologies have been playing a crucial role in maximizing the engagement level of ADHD patients during neurofeedback therapies through the use of videogames as treatment mediators.

Neurofeedback videogames are becoming popular to induce meditation and relaxation states via sensing oscillatory rhythms, specifically Theta and Beta recorded from the frontal lobe [12]; for this work, we choose the brain rhythms involved in attentional state measure by Mindwave neuroheadset [24]. Although there are an important number of works highlighting the potential of videogames to produce cognitive benefits in several fields and populations, there are also some limitations which should be addressed to improve the experience, specifically in children. For instance, the lack of personalized and realistic videogames which use 3D graphics and different game levels to produce more enjoyable experiences for ADHD children [13]. To deal with that, the development of innovative Brain Computer Interfaces (BCI) which are now wearable and minimally invasive has boosted the popularization and the commercialization of videogames with neurofeedback [14] specialized in ADHD treatment [15]. However, most of the consumer grade low-cost BCI sensors don't come with dedicated software to process the EEG signal and extract important neurophysiological parameters such as the power of each oscillatory rhythm. Thus, the low-cost BCI provides an easy way to connect the children with the neurofeedback videogames but don't provide (at least for free), good measures to evaluate the evolution of the therapies [16].

The World Health Organization Mental Health Action Plan $2013-2020$, which promotes accessible user-driven options and nonpharmacological therapies for young patients. Serious gaming is a novel action field which supports the treatment of clinical symptoms and improvement of adaptive functioning in patient groups [17], [18]. Recently, the leading Netherlands group has present two works for serious game for health, development a modular videogame "*Plan-It Commander*" that allow single and multiplayer interaction including social media (internet and local video games) to ADHD kids [19], [20], the multi-disciplinary team introduced a validation strategy for use and satisfaction are based in a play pre and post test for children, parents, and teachers. The authors concluded that videogame use teaches children and reinforce daily life skills, such as time management, planning/organizing, and cooperation movement. [21] They also put forward an extended review used a *Prisma* guide for videogames employed for rehabilitation ADHD children. In this review, the authors emphasized intervention. The principal targets were: the attention, memory work and behavior environment; the best results has been gained in cognitive and behavioral aspects after videogames intervention, although the data are very bias. Gazzaley and your group endorsement ONTRAC study (Online Neuroplasticity-based Training for the Remediation of ADHD in Children) for china ADHD early young [22], [23] Post-training cognitive assessments showed significant positive results for response inhibition and Stroop interference tests in training completers vs controls, while measures of sustained attention and short-term memory showed no significant improvement trends. Further, training-driven improvements in distractor suppression correlated with the improved ADHD symptoms. Finally the group cited open opportunity and prevalence windows of intervention nonpharmacologic in ADHD patients, due to the big problem in our country, especially in the city of Pereira where the number of reported children surpassed five thousand last year.

To tackle the limitations related with more realistic and interactive neurofeedback videogames for ADHD children which could enhance therapy adherence and long-term motivation, we developed a specialized 3D virtual reality BCI videogame which has 3 different game levels [24]. In order to assess the impact of the videogame in training sustained attention in ADHD children in Colombia, we carried out a pilot study with a $2-$sessions intervention using 9 children diagnosed with ADHD. Finally, to facilitate the neurophysiological data processing and understanding, we created a Matlab toolbox to process the EEG signals from low-cost BCI sensors such as the MindWave and the Emotiv Epoc.

This paper is considered to have the following structure: **Methodology** described the principal design component of our videogame called Harvest Challenge, as well as the EEG signal toolbox implemented and the protocol setup of children study. **Results** show the use of the personal processing toolbox and the statistics graph and descriptive time and skill training children's data. Finally are show the **Discussion** and **Conclussion** paragraph.

II. Methodology

A. Harvest Challenge serious videogame

We developed a specialized 3D virtual reality videogame called Harvest Challenge to train attention self-regulation by using a BCI system. The videogame was created using a serious games for health framework established to facilitate the design and development process for health-oriented videogames. A complete description of the design process can be found in a previous publication [24]. The Harvest Challenge videogame uses the MindWave BCI system to detect the attention levels of users using a dry electrode placed in the frontal lobe. The attention levels are mapped from 0 to 100 percent and they are shown in the user interface of the game, making the physiological feedback visually explicit. Three different interaction stages were developed:

Equipment for the Canopy

The game starts in an ecological farm which has been equipped with adventure sports such as Canopy, a hang gliding sport. The first proposed task is to collect the equipment needed for a safe ride in the canopy which is made by increasing the attention levels (more than 50%) to pickup objects from a visual panel presented on the screen. This level reinforces the idea to follow rules and elevate the attention levels in order to pass the challenge and get points. Players have to effectively choose 4 objects to complete the Canopy equipment: a helmet, a pair of gloves, a harness and the sport shoes. Once finalized, the player can continue the trip.

Repairing the pathway

In order to get the Canopy rope, the player must reach the top of a mountain. For that, a set of wood stairs were placed in a long pathway in where some ravages are presented.

Players should increase the attention levels in an incremental way to repair the pathway. A total of six path sections have to be repaired by reaching 60%, 65%, 70%, 75%, 80% and 100% of the attention levels. The last point is when the player reach the rope and can be launched in the Canopy.

Harvesting the carrots

At this point, the players has been interacting with the virtual objects via instantaneous increases of attention levels. The final challenge is placed in a large harvest field of carrots. The user is equipped with a basket to collect as many carrots as possible by elevating the attention levels and sustaining them until they are able to gather the vegetables. If the players decrease the attention levels, the carrots hide under the ground, thus they cannot be collected. The videogame finished once a total of 20 carrots has been collected or after the time limit is reached (30 minutes).

B. HCI Signal Processing Toolbox (HCI-SPT)

HCI-SPT is a computational toolboox designed under the Matlab environment v.2013a which aims to facilitate the processing of physiological and biomechanical signals acquired with low-cost sensors. This toolbox allows process signals from a set of sensors commonly used in applications in our research group such as Kinect sensor V1 and V2; BCI sensors such as Mindawave (Neurosky Inc.), Emotiv EPOC (Emotiv) and BR8 (Brain Rythms Inc.), and the Myo Armband sensor (Thalmic Labs) used for recording electromyographic (EMG) signals. Each module has different user interface guides for the individual processing of each signal.

This paper describes in detail the development of the module for EEG signal processing called NeuroRead, which allows the post-processing of the neurophysiological signal in time and frequency domains.

NeuroRead v1.1

NeuroRead v1.1 is a secondary toolbox for EEG signal processing and visualization. The NeuroRead was specially developed to read neurophysiological signals from some of the most widely used low-cost BCI systems. This graphical user interface (GUI) consists of four panels called input, signal processing, brain rhythms panel and visualization. *Figure 1* shows the NeuroRead GUI.

Input Panel: This panel allows the user to import EEG files in GDF, EDF, CSV and TXT extensions. The panel includes information related with the name and route of the EEG file and its sampling frequency. We included 4 buttons to return to the main panel (*HCI-SPT*), plot the EEG signal, restart the toolbox and exit.

Signal Processing Panel: This panel allows the user to manipulate and identify characteristics of the EEG signal as follows:

- Perform a signal-prefiltering to limit the analysis to a specific frequency bandwidth. Then, the signal can be filtered using a $N-$order Butterworth filter limiting the frequency band as well. The filter's order can be manually triggered by the user.
- Choose which signal will be visualized (*EEG signal*, *attention*, *meditation* or *all*).
- Compare the processed signal with the signal that has not been processed (*View Original*).
- Computing and show the EEG signal spectrum using the DFT (*Spectrum*), calculated by (1) for discrete values *see [25].*

$$Y(k) = \sum_{m=1}^{n} X(m) W_n^{(m-1)(k-1)} \tag{1}$$

where $W_n = e^{(-2\pi i)/n}$.

- Perform an analysis of the EEG signal using time-frequency maps by implementing windows $W_n(t-\tau)$, which can be *Blackman*, *Bartlett*, *Hanning*, *Haming*, *Gausswin* or *Kaiser*, *Tiempo-Frec*, see (2).

$$G_D(\omega,\tau) = \int_{-\infty}^{\infty} x(t)\cdot w(t-\tau)\cdot e^{-i\omega t}dt \tag{2}$$

- Adjust the range of the signal to be analyzed either *full range*, *fragment range* or by *epoch*.
- Computing the signal spectrum and the time-frequency maps using the Hilbert-Huang transform (*HHT*) which is a robust tool to track the changes in the amplitude and frequency in EEG signals.
- Computing the Theta/Beta ratio of the EEG signal, *TBR*. According to [26], Theta waves occur mainly in states of drowsiness (or daydream), also in deep meditation; on the other hand, the Beta waves are associated with waking and attentional states how there is in active thinking, namely when attention is focused on the outside world or solving concrete problems.
- Computing the area under the curve of attention module, (*ABC*).
- Given the levels of the manufacturer, computing the percentage of each level during the recorder signal, eSense (% *eSense*).

Brain Rythms Panel: This panel allows a frequency band analysis of the EEG signal associated with the oscillatory rhythms which are brain activity patterns distributed in frequency ranges as follows: Delta ($0.5-4\ Hz$), Theta ($4-8\ Hz$), alpha ($8-13\ Hz$), Beta ($13-30\ Hz$) and Gamma ($30-80\ Hz$). It has been shown that each oscillatory rhythm has specific correlations with cognitive process [27]. Finally, the toolbox allows you to export the various signals to the Matlab workspace or save them in .mat format. Moreover, users can save the obtained plots throughout the sessions in .png formats to facilitate the documentation.

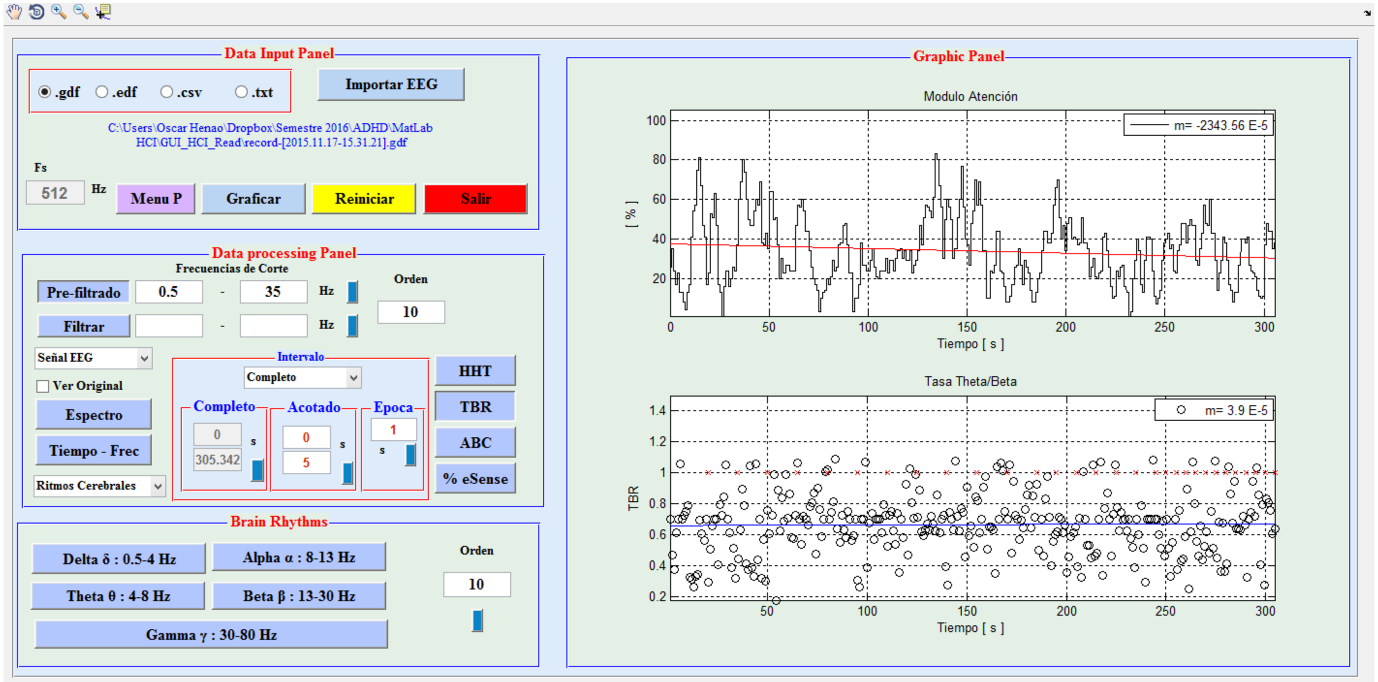

Figure 1: A screenshot of the NeuroRead Toolbox v1.1. The software includes 4 main panels to import, process and visualize the EEG signal from low-cost BCI systems.

Visualization Panel: This panel located on the right half of the window, allows the user to view the different graphs of EEG signals.

C. Pilot Study

Participants

To evaluate the usefulness of the Harvest Challenge videogame to produce sustained attention improvements in ADHD children, we carried out a 2−sessions intervention in a specialized local institution (Instituto de Audiología Integral-IdeAI). A total of 9 diagnosed children ages 5 to 12 played the videogame in 30 minute long sessions.

Protocol

A sessions of 30 minutes long was divided into two stages, the first was 5 minutes long and the second was 25 minutes long.

Stage 1**, Relax**: at this stage the child was asked to take a relaxed position seated in a chair with the eyes closed. We used earbud-headphones to isolate the ambient sounds while the child was listening a relaxing music during the 5 minutes. This stage was monitored using the MindWave device;recording the EEG signals via the opensource the opensource software OpenViBE to ensure an acquisition of 512 Hz and *.gdf* output file, see Figure 3a.

Stage 2**, Videogame**: the game *Harvest Challenge* was divided into 3 phases according to the attentional classification (*Phase 1*: selective attention, *Phase 2*: concentration-readiness engine and then impulsivity control, finally *Phase 3*: sustained attention), i.e.:

i) **Phase** 1: during this phase the children were asked to select the four elements for the Canopy equipment using the left and right computer keys and increasing the attention levels to 60%. Five minutes were programmed to complete the task and the time to equip each item was saved for further analysis, see *Figure 2*.

Figure 2: Screnshot of the *Harvest Challenge* videogame during Phase 1.

ii) **Phase** 2: here the child used a game controller to move the avatar and the MindWave sensor. The instructions for the users were: **a)** search and collect the fruits neccesary for a healthy diet (*banana*, *apple* and *pears*) and avoid the harmful ones (*chilies*), **b)** once in on stairs, increase your attention levels to repair the damaged pathway in order to successfully get the mountain top from where they have to jump in the Canopy.

(a)

(b)

Figure 3: In **3a** Child diagnosed with ADHD during stage 1, **3b** Child diagnosed with ADHD during phase 3.

iii) **Phase** 3: finally, users were challenged to train their skill to sustain the attention levels in order to collect the carrots. Once all the carrots were collected ($N = 20$) or the user exceed a 30 minutes time limit, the sessions culminated. Game metrics related with times and total scoring were saved for the analysis, see *Figure 3b*.

III. Results

In this pilot study we wanted to investigate the effects of a 2−sessions intervention using the *Harvest Challenge* videogame in children with ADHD. We carried out a users' characterization stage in which the EEG signals from the resting stage were processed in order to better understand users through an oscillatory rhythms analysis. We also explored specific game metrics which described the game performance of children for each of the proposed interactions levels. We highlight the usefulness of the *NeuroRead* toolbox to facilitate the analysis of EEG signals recorded from low-cost BCI system such as the MindWave.

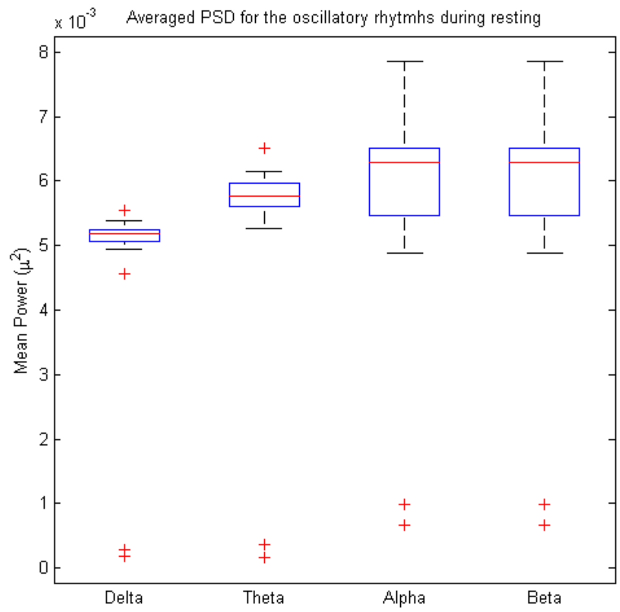

Figure 4: Brain oscillatory rhythms per resting sessions in the Delta (δ), Theta (θ), Alpha (α) and Beta (β) frequency bands.

A. Toolbox desing

To simplify the EEG signal processing analysis we developed the *NeuroRead* Matlab toolbox, a multisystem signal processing tool which has been adapted to process the neurophysiological signals from commercial-grade BCI systems. Although the *NeuroRead* was created to process the signals from low-cost sensors, the analysis could be extended to any physiological device which supports GDF, EDF, CSV and TXT files which are file formats widely used for EEG signals. The software includes 4 panels to import, process, and visualize brain patterns using EEG signals. We included time and frequency domain analysis to maximize the information recorded from BCI systems and a complete panel for oscillatory rhythms analysis was included as well. It is well-known that an analysis of brain patterns by using the oscillatory rhythms can reveal important characteristics about which neurofeedback protocol is better to each individual [28]. Thus, the software is prepared to facilitate the neurophysiological analysis of EEG signals specifically in people who are not familiar with the use of biometrics in user experience experiments such as game user researchers and software developers.

B. Brain activity patterns during resting

In order to provide a neurophysiological characterization of users, we used the *NeuroRead* toolbox to process the EEG signal recorded from the resting stage. First of all, we imported the signal using the data input panel which also inform about the sampling frequency of the file. Then, the raw data was processed using a $10-$order butterworth filter with cut frequencies in 0.5 Hz and 35 Hz. The Power Spectral Density (PSD) of the signals was computed using the FFT obtained in the signal processing panel using the Welch's method. Afterwards, we extracted the frequency bands for the oscillatory rhythm called Delta, Theta, Alpha, Beta and Gamma for each sessions. Data was averaged for each resting sessions and plotted for each oscillatory rhythm (*Figure 4*).

The averaged values for each band in the two sessions showed a higher brain activity in the alpha ($M = 6.3 \times 10^{-3}$, $SD = 6.6 \times 10^{-4}$) and Beta ($M = 6.3 \times 10^{-3}$, $SD = 6.6 \times 10^{-4}$) frequency bands rather than the Delta ($M = 5.1 \times 10^{-3}$, $SD = 2.9 \times 10^{-4}$) and Theta ($M = 5.8 \times 10^{-3}$, $SD = 1.5 \times 10^{-4}$).

C. Relationship between game performance and brain activity patterns during resting

Finally, to quantify the relationship between the game performance (measured by the game metrics in each interaction stage) and the brain activity patterns elicited during the resting, we carried out a stepwise multilinear regression model. Using this approach, we can quantify the statistical relationship between each oscillatory rhythm (Delta, Theta, Alpha and Beta) and the game metrics called time for equip, scales, carrots and final score. Results revealed significant contributions only for the Theta rhythm ($Coeff. = -1.34 \times 10^{-4}$, $p < 0.05$) contributing to the time for equipment.

D. Analysis of game performance and attention levels during gameplay

From the interaction with the videogame *Harvest Challenge* we were collecting multiple metrics in each level to evaluate the game performance. First, we computed the time each user spent collecting the 4 objects proposed in the "materials for the canopy" level. We observed that the second sessions ($M = 234$, $SD = 47$) provides a decrease in the time spent to complete the level compared with the first one ($M = 266$, $SD = 16$); due overlap time responses, we can't calculate Wiener distribution to describe the supposed aleatory data. Secondly, we collected the number of scales each user overtakes in the pathway before getting to the Canopy stage. Results do not show any difference between the 2 sessions. The same was done for the number of carrots harvested showing higher scores in the second sessions ($M = 13$, $SD = 8$) rather than the first sessions ($M = 6$, $SD = 6$). Therefore, the final game performance which is computed considering the scoring in each game level was higher in the second sessions ($M = 5757$, $SD = 1322$) compared with the first one ($M = 4585$, $SD = 2064$). Although there is no statistical difference mainly due to the small sample size, the number of sessions and the large user variability, the game performance data suggests an improvement in the attention self-regulation skill by playing the *Harvest Challenge* videogame.

IV. Discussion

The final results showed promising findings in the implementation of novel treatments using neurofeedback videogames through low-cost BCI sensors for sustained attention training in Colombian children with ADHD. The use of these BCI systems to effectively provide a communication pathway between user's attention/relaxation levels and videogame dynamics was explored in the different interaction levels of the *Harvest Challenge* videogame. To our knowledge, the *Harvest challenge* is the first neurofeedback serious videogame for ADHD treatment created in Colombia. The videogame presents remarkable features such as the use of virtual reality to represent 3D environments aiming to improve children's engagement, the utilization of a wearable and non-invasive BCI sensor to record brain activity signals and the proposal of three game levels with different physiologically-driven interaction dynamics.

Additionally, in a $2-$sessions pilot study carried out in a local health institute, we used the *Harvest Challenge* videogame to explore changes in sustained attention in children diagnosed with ADHD. First, we used a resting state to record the EEG signals from users before the gameplay to characterize them in terms of the neurophysiological activity produced. Results showed a higher activity in alpha and Beta rhythms, which have been widely associated with hyperactivity behavior [29]. Results are consistent with past findings in ADHD adults [30]. First, the power of the alpha rhythms have been shown as useful index for reflecting differences in neural communication of ADHD patients [31]. Second, it seems like increases in Beta activity in ADHD children leads to a normalization of Beta activity in adult-hood. A clear identification of these brain activity patterns not only during the task execution but also, during the resting states could untangle the role of videogame dynamics improving specific cognitive skills in ADHD patients. For instance, novel approaches could use the different band powers recorded with the BCI sensors and use them as an input control in the videogame according to the results from the resting neurophysiological characterization. Thus, this could optimize the effects of the videogame-based neurofeedback therapy.

Furthermore, we used a modelling approach to find the relationship between brain activity patterns and the game metrics. The stepwise model revealed a significant relationship between the power of the Theta band and the time spent to complete the canopy's equipment in the first game level. The Theta band has been mainly studied in the frontal brain region (in where the MindWave measured the signal) and has been linked to a decrease in specific cognitive functions such as attention [32]. A more systematic analysis has to be done in order to clearly identify the strength and the direction of the different relationships between the game metrics in the *Harvest Challenge* videogame and the oscillatory rhythms.

Finally, we explored the effects of the neurofeedback training through the videogame in the attention levels of users using embedded game metrics. Results showed that there is an improvement in the game performance reflecting an enhanced sustained attention skill during the gameplay. A future work includes the redesign of some aspects of the game in where stuck points were identified (e.g. equipment for the canopy), the inclusion of a control group to compare the results of the videogame training, amore extended intervention including at least 10 sessions of 30 minutes of interaction and a complete EEG monitoring during the intervention.

V. Conclussion

By carrying out a pilot study with the neurofeedback videogame *Harvest Challenge* in ADHD children, we emphasize the importance of creating novel methodologies based on ICT to deal with the health coverage issue in ADHD. Videogames can be a motivating method to encourage ADHD children to overcome attention problems providing highly interactive experiences attempting to create good levels of treatment adherence. Moreover, we demonstrated how physiological signals could be used not only to produce challenging videogames through the inclusion of wearable BCI sensors, but also to generate valuable medical information to better understand the complex ADHD phenomena. For that, the *NeuroRead* toolbox was shown as a simple and helpful computational system to facilitate the neurophysiological signal analysis.

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