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"A Universal Game Controller Interface (UGCI) for Neurofeedback ADHD treatment"

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Dedicated to my beloved mother

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Abstract

Attention-deficit / hyperactivity disorder (ADHD) is the most common of psychiatric disorders in children with an assessed prevalence of about 5% in school-aged children (American Psychiatric Association, 2013). Despite the fact that medical therapy is very efficacious (Lansbergen *et al.*, 2011; Arns, Heinrich and Strehl, 2014; Holtmann *et al.*, 2014; Bluschke *et al.*, 2016), due to its adverse effects, current focus has been pointed to the development of an alternative treatment for the disorder. One of the most common non-pharmacological treatment of ADHD is behavioral training using Neurofeedback (NF) (Sonuga-Barke *et al.*, 2013; Holtmann *et al.*, 2014). However, one of the drawbacks of the therapy is that the selection of the games for ADHD NF (Munoz *et al.*, 2015) is limited. The developed purpose specific games cannot follow today's standards in aesthetic domain, but also in other aspects, such as game dynamics (diversity of the tasks). Due to poorer graphical standards and periodical dynamics, after a couple of sessions, the subject's (children's) interests shifts and conceivably making the therapy less effective. Development of the new advance games are very resource demanding, and it requires the broad market to be profitable. To overcome the obstacle, in the thesis I propose an innovative design of the Universal Game Control Interface (UGCI), a device that will serve as a modulator of the game commands based on EEG measured subject's attention state. In other words, UGCI will be used as a proxy between a game controller (e.g., gamepad, joystick, etc.) and a playing console or a computer. The device exploits already standardized communication interface between computer and game controllers, therefore, allowing implicitly direct control of any existing game on the market. Consequently, the most recent games can be played without any modification. In this regard, the master thesis provides the detailed description of the conceptual and implementational design of the UGCI. Finally, a conducted empirical study has demonstrated the effectiveness of the device and its potential for NF treatment of ADHD.

Keywords: *ADHD, Biofeedback, Brain-Computer Interface (BCI), EEG, Game-based therapy, Neurofeedback, Neurotherapy*

Kurzfassung

Aufmerksamkeitsdefizit-/Hyperaktivitätsstörung (ADHS) ist die häufigste psychische Störung bei Kindern, mit einer geschätzten Vorkommnis von 5% bei Kindern im Schulalter (American Psychiatric Association, 2013). Trotz der Wirksamkeit von Therapien (Lansbergen *et al.*, 2011; Arns, Heinrich and Strehl, 2014; Holtmann *et al.*, 2014; Bluschke *et al.*, 2016) hat sich, aufgrund von Nebeneffekten, der aktuelle Fokus auf die Entwicklung von alternativen Behandlungsmethoden verschoben. Eine der häufigsten nicht-pharmazeutischen Behandlungen für ADHS ist die Verhaltenstherapie mit Neurofeedback (NF) (Sonuga-Barke *et al.*, 2013; Holtmann *et al.*, 2014), die jedoch den Nachteil hat, dass es nur eine begrenzte Auswahl an Spielen für ADHS NF (Munoz *et al.*, 2015) gibt. Die entwickelten anwendungsspezifischen Spiele können nicht nur die heutigen ästhetischen Standards nicht erfüllen, sondern liegen auch in anderen Aspekten wie der Spieldynamik (d.h. Vielfalt der Aufgaben) zurück. Aufgrund der schlechteren grafischen Standards und periodischer Dynamik verlagert sich die Aufmerksamkeit der Probanden (Kinder) nach einigen Sitzungen, wodurch die Therapie merkbar an Effizienz verliert. Die Entwicklung neuer, fortgeschrittener Spiele ist kostenintensiv und erfordert, dass ein profitabler Markt existiert. In dieser Thesis befasse ich mich mit der Problematik und präsentiere ein innovatives Design für ein Universal Game Control Interface (UCGI), das Befehle und Eingaben moduliert in dem es die Aufmerksamkeit mittels EEG misst. Das UCGI wird somit als Proxy zwischen dem Steuergerät (z.B. Gamepad, Joystick, etc.) und einer Konsole bzw. Computer dienen. Das Gerät wird dabei auf bereits standardisierte Interfaces zwischen Computer und Controller zurückgreifen, wodurch jedes beliebige Spiel direkt gelenkt werden kann. Folglich können auch die aktuellsten Spiele ohne weitere Anpassungen gespielt werden. Die vorliegende Masterarbeit präsentiert eine detaillierte Beschreibung des konzeptuellen Designs als auch der Implementierung des ersten UGCI Prototypen. Abschließend demonstriere ich die Effektivität des Geräts und dessen Potenzial in der NF Behandlung von ADHS anhand einer durchgeführten Studie.

Schlagwörter: *ADHS, Brain-Computer Interface (BCI), EEG, Game-based Therapie, Neurofeedback, Neurotherapie*

Abbreviations

ADHD - Attention-deficit/hyperactivity disorder
API - Application Programming Interface
BCI - Brain-Computer Interface
CBT - Cognitive Behavioral Therapy
CNS - Central Nervous System
DSM - Diagnostic and Statistical Manual of Mental Disorders
EEG - Electroencephalography/Electroencephalogram
HID - Human-Interface Device
I/O - Input/Output
IDE - Integrated Development Environment
LCD - Liquid-Crystal-display
LED - Light-Emitting Diode
M - Mean
NF - Neurofeedback
PoC - Proof-of-Concept
QEEG - Quantitative Electroencephalography
SD - Standard Deviation
SDK - Software Development Kit
SMR - Sensorimotor Rhythm
UGCI - Universal Game Control Interface
USB - Universal Serial Bus

1 Introduction

The Attention Deficit / Hyperactivity Disorder (ADHD) belongs to the group of behavioral and emotional disorders with onset in childhood and adolescence. It manifests through problems with attention, impulsiveness, and self-regulation and in most of the cases with physical restlessness and hyperactivity. It is being estimated that the worldwide frequency of ADHD among children and adolescents is about 5% (American Psychiatric Association, 2013). Today, it is regarded as the most frequent psychiatric disorder in children and according to the available statistics, boys are significantly more affected than girls.

Throughout the history, various names and definitions have been used to describe what we today call ADHD. At the beginning of the last century, British physician George Frederick Still outlined in his work a group of children who manifested malicious vivacity, destructiveness and a deficit of motor control (Still, 1902). More than 60 years later, for the first time in 1968, the phrase "hyperkinetic reaction" of children was used in the 2nd edition of Statistical Manual of Diagnostic of Mental Disorders published by the American Psychiatric Association. In 1980 the word "Attention Disorder" has been introduced in the Manual (Spitzer, Williams and Skodol, 1980). By that time the ADHD has been seen as an only behavioral disorder. Finally, in DSM III-R (American Psychiatric Association, 1987), the term Attention Deficit and Hyperactivity Disorder, has been reported, which stands for the current acronym ADHD.

Today, the most evidence supported theory is that ADHD has both genetic and environmental causes and that the symptoms are based on a neurobiological developmental delay of the executive functions (Curatolo, D'Agati and Moavero, 2010), causing inappropriate levels of hyperactivity, impulsiveness, and inattention.

Modern techniques, including brain imagining techniques, reveal that ADHD is linked with numerous structural and functional Central Nervous System (CNS) abnormalities (Cortese *et al.*, 2012). Furthermore, molecular-genetic research has revealed that many genes could be involved in the development of the disease causing abnormalities in the dopaminergic system. Consequently, drugs employed in the treatment induces the release of dopamine (Castle *et al.*, 2007). Other stimulant medications can also be used as a pharmaceutical treatment (Greenhill, 2001; Hansen and Hansen, 2006; Castle *et al.*, 2007).

According to the National Institute of Mental Health, USA, the main three elements of the ADHD are:

- attention deficit;
- hyperactivity;
- impulsivity.

The combination of these three elements gives rise to the definition of three subgroups:

- predominantly incapable of attention;
- predominantly hyperactive-compulsive type;
- combined type (hyperactive and incapable of attention)

Concerning the three elements, the following definitions apply:

- Hyperactivity: always in motion; talk unceasingly, unable to sit for longer periods of time, and they need to be always occupied.
- Impulsiveness: Unable to put their actions under control accompanied with inability to assess the consequences;
- Attention deficit. Lack of focus on one task at a time;

Due to various cognitive and motivational difficulties, ADHD is not a negligible disorder, and it won't resolve with age. Even though the symptoms may disappear with a teen age and subjects are no longer included in the clinical description, the affected individuals are still having considerable problems adapting to the new environments, schools, workplaces, and in general to any new social setting. Also, according to the available data, there is a high evidence that ADHD is linked to other disorders in the later ages (i.e., alcoholism, drug abuse, crime and anti-social behavior), and presumably leading to high unemployment and general degradation of life quality (Taylor *et al.*, 1996).

Today, the findings suggest that ADHD treatment should be multimodal, and depending on the severity of the disorder. It includes behavior therapy, psychoeducational input, cognitive behavioral therapy (CBT), family therapy, social skills and organizational training, and NF (MTA Cooperative Group, 2004). According to the (Pigott and Cannon, 2014), behavior modification therapy and NF have the best support.

It could be argued that genetic variables and structure cerebral alternations in children with ADHD lead to the typical attitudes associated with hyperactivity by reducing the ability to inhibit inappropriate behavior and self-control, which, in the opinion of Barkley (Barkley *et al.*, 1990) is the core deficit in ADHD. We have also seen that among non-pharmacological treatment apart from behavior therapy, NF has been evaluated as the most effective alternative treatment (Arns *et al.*, 2009). The most common type of NF protocols used for ADHD treatment utilizes video-games where the reward as a visual feedback mechanism has been established through gameplay.

However, the available NF ADHD video games cannot compete with the games children are usually playing at their homes. Due to poor graphics and monotonous tasks, children's attention shifts easily after a few attempts to play the NF video game. In most cases, that reduces the effectiveness of the NF therapy.

Consequently, this master thesis focuses on that problem, providing a solution, a device that will allow control of virtually any game on the market and enable children to play almost any available video game, including the ones they are playing at their homes. This challenging endeavor will not only put out of a question the issue about quality but also considerably increase the choice of games for ADHD NF therapy.

2 Neurofeedback and ADHD

The Neurofeedback (NF) therapy is graded as evidenced based treatment by the American Academy of Pediatrics, and most commonly used non-pharmacological treatment for ADHD. Similar findings can be found in the literature (Lansbergen *et al.*, 2011; Arns, Heinrich and Strehl, 2014; Holtmann *et al.*, 2014; Bluschke *et al.*, 2016), where the NF has been regarded as clinically meaningful and placed in the group of effective nonpharmacological therapies (Sonuga-Barke *et al.*, 2013). However, even though the history of the NF dates back to the '60's (Witek, 2007), the research in this field is still in its infancy. Initially marginalized by pharmacological studies, today due to ADHD medication adverse effects mostly on sleep, appetite, growth, and the cardiovascular system, the usefulness of NF among the other non-pharmacological treatments have been revisited.

The NF is a particular type of biofeedback that typically utilizes EEG signals. The processed EEG is presented in the form of visual or audio feedback that has the aim to teach self-regulation of brain function by advancing toward patterns of improved self-regulation and slowing or stopping as the expected brain activity regresses (Strehl *et al.*, 2006).

In the case of ADHD, the most common visual/auditory feedback are video games where the measured EEG characteristics modulate the control of a character and the game dynamics. When the subject is in an attentive, focused state, the completion of the tasks or obstacles in the game are successful, thus providing a reward, and vice-versa (Egner and Gruzelier, 2001; Bluschke *et al.*, 2016). In such way patterns of optimal brain function are fostered over sessions and the symptoms of the disorder are alleviated as the brain arranges its improvements with the long-lasting results, that continue to improve even after the training (Lansbergen *et al.*, 2011; Sonuga-Barke *et al.*, 2013; Holtmann *et al.*, 2014).

2.1 Technical overview of Neurofeedback procedures

The term biofeedback refers to a series of practices that by using certain physiological inputs allow the individual to become aware of his/her psychophysical state. It utilizes brain waves recorded via EEG as an input and generates the visual/audio output presented to the subject. Through conditioning, the subject learns to modify the signal by modulating the underlying mechanism at the neuronal level. It is critical to establish the link between behavioral, psychological and cognitive characteristics on the one hand, and the electrical activity of the brain on the other, and to familiarize the subject with the connection (*see Figure 1*).

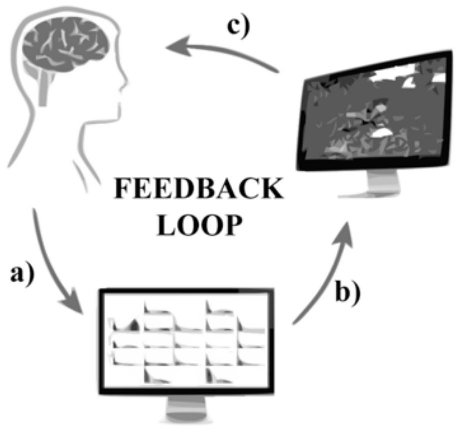

Figure 1. - A Neurofeedback loop: a) recording of a subject's physiological activity, b) real-time presentation of the recorded signal in the visual form, c) continuous visual feedback stimulates the brain to reach the maximum level of performance.

During training, cortical bioelectric signals are recorded by two or more electrodes placed on the scalp, or on the forehead, and amplified/processed in real-time by a dedicated hardware and software. The subject immediately receives feedback, which is manifested in visual or auditory form, indicating whether the electrical activity of the brain is, or not, in the fitting parameters. Through appropriate feedback, the individual can learn to drive his or her activity in a direction that brings emotional, cognitive and behavioral benefits. It is crucial to explain to the subject that the received feedback is directly determined by his or her brain activity. The subjects are never acutely aware of which mechanisms allow them to make the correct modification, but with practice, they learn to recognize visual or auditory stimuli associated with the optimal state of mind. With a regular and appropriate training, even outside of a laboratory, the subjects become able to reproduce the sensation and the right model of brain activity and, therefore, alleviate the symptoms of the disorder, or reach the desired state of mind. It is important also that the subjects are not precisely instructed how to control their EEG, but through the training, they learn the most efficient mental approach autonomously to modulate their brain activity in order to achieve the best results. Most common feedback strategies are using auditory and visual feedback. The auditory signal is represented, for example, by the sound of the sea waves or by a bubble bursting. Visual signals, on the other hand, can be simple bars, where the height of the bar is directly proportional to the magnitude of the detected EEG rhythm, or more complex, such as video games.

2.2 EEG of the brain

On the basis of their frequency, EEG waves have been divided into five categories: Delta: 0.5-4 Hz, Theta: 4-8 Hz, Alpha: 8-13 Hz, Sensorimotor (SMR): 12-15 Hz, Beta: 15-35 Hz, Gamma: 35-50 Hz *(see Figure 2)*. By experimental evidence, we know that Theta and Delta waves are low wave activities that are typically associated with a state of restiveness, drowsiness, and sleep. On the other hand, Beta waves, known as fast waves, are characterized by subjects state of high attention, focus, and concentration (Linden, Habib and Radojevic, 1996). Alternatively, the high Alpha activity corresponds to a relaxed state, where the subject is not particularly focused on anything.

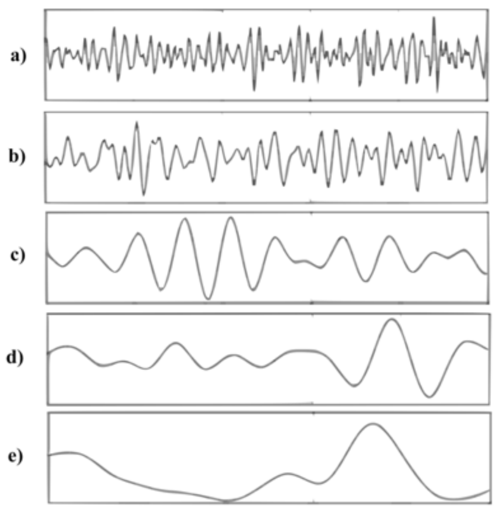

Figure 2. - Comparison of EEG Bands: a) Gamma, b) Beta, c) Alpha, d) Theta and e) Delta

According to the current scientific literature, due to functional and structural brain changes, ADHD children produce excessive Theta and lower Beta activity in comparison to the healthy individuals (Lubar, 1997; Arns, Conners and Kraemer, 2013). Therefore, these children are neurologically prone to be less focused and concentrated. EEG studies of ADHD children have highlighted that in about 70% of children the excessive Theta waves in the frontal areas are present and at the same time the activity of the Beta waves is decreased (Arns, Conners and Kraemer, 2013).

We can conclude that research of the last thirty years has confirmed that excessive slow brain activity is the most common evidence of electroencephalographic anomalies in children with ADHD.

In line with such findings, Brain Imaging analysis, both volumetric and functional, shows a dysfunction of certain parts of the brain in children ADHD, which can clarify deficits at the highest levels of arousal, motor control, attention and behavioral inhibition (Vance *et al.*, 2007; Cortese *et al.*, 2012). These dysfunctions can also be related to the measured electrophysiological differences.

With the aim to achieve the similar band ratio in comparison to the healthy individuals and based on the experimental insights, most of the NF protocols for ADHD children are focused on three frequency bands: Theta (4-8 Hz), SMR (12-15 Hz) and Beta (15-20 Hz).

2.3 ADHD and Video Games

Since ADHD is a very complex disorder, it is important to develop new approaches and techniques to treat it systematically. Perhaps we should expand our view about the treatment of any disease in general outside of a hospital or dedicated institutions to situations of our daily life. There are plenty of possibilities that our life quality can benefit just doing our everyday activities. In a very same sense, the novel approaches using video games controlled by NF had been developed. These approaches are embedded in the activities that are very popular to the target population, such as video gaming. Nowadays it is prevalent to treat ADHD using simple video games, which apart from their entertainment purposes, also help children to alleviate the symptoms and improve in their everyday life. The motivation of the children to perform therapy procedure (i.e., playing dedicated video games) is essential and furthermore, possible from their homes. Despite controversy in the media about negative effects of the video games, there are strong shreds of evidence that potential benefits can be achieved through video gameplay; of course, with the adequate tasks and time requirements, as well as with the proper cognitive and social values and demands represented in the video game (Oei and Patterson, 2013). It is very common that games require accurate judgment and action at high speed, which increases working memory capabilities, provide pro-social training, impose cognitive challenges that require focused attention and motivation. Therefore, it can be expected that positive neurological changes will happen in the brain systems that support the behaviors mentioned above. In this regard, playing a particular game that increases attention and motivation triggers physical and neurological remodeling and becomes effective in the case of ADHD treatment.

Figure 3. – "Focus-Pocus" Specially Designed Video Game for ADHD Treatment

In the last decade, there were attempts to build purpose specific games for ADHD Neurotherapy (see, for example, Figure 3). The games tightly link the game dynamics (speed) with the detected levels of attention. In that way, the game speeds up, and rewards the player when he is highly focused and in parallel fosters the neural circuitry with the hypothesis that the effect of neural remodeling will be long lasting and continue to improve even after training.

3 UGCI – A Universal Game Control Interface

In the previous chapters, we have reported that ADHD patients can benefit from the NF video game therapy. Although NF treatment might be effective, there are certain issues with this approach. Many researchers believe that motivation plays the essential role and that it is required for effective therapy (Sergeant, Oosterlaan and van der Meere, 1999; Desman, Petermann and Hampel, 2008; Modesto-Lowe *et al.*, 2013). However, the number of specially designed ADHD video games is somehow limited. The consumer market corresponds to their number, but also to their quality. We have mentioned that approximately 5% of kids show symptoms of ADHD, and only small portion of this 5% can afford NF treatment. Thus, this is a small share in comparison to the standard video game market. By informal investigation, there are no more than 20 available games on the market specially designed for ADHD treatment. Furthermore, most of them are closed-source, and license purchase is required. Since there is no standardized communication interface between the game and EEG recording equipment, most of the games are linked to only one EEG system manufacturer, and thus, purchase of the game requires the purchase of the dedicated hardware, too.

Aside from the technical obstacles, none of the specially designed games can compete with the current general purpose video games available in the market on the basis of quality and attractiveness. Most of the ADHD games have the poor graphical appearance, limited to 2-dimensional space. The dynamics of the game is rather simple, and in most games, it uses the same repetitive patterns. Therefore, in the children's eyes, the games look rather primitive and different from what they use to play at home. The motivation, and thus attention, drops after a couple of sessions and thus reducing the effectiveness of the therapy.

Due to the mentioned market obstacle (not enough potential users to cover the expenses of design and production), it is doubtful that there will be an ADHD treatment game that can compete in both graphical and game-dynamics standards with the existing general entertainment video games. Moreover, the appearance of single ADHD high-quality game would not also be a proper solution, since it is implausible that it would fit everybody's taste. Besides, most of the game-players like to change games, and thus in an ideal situation, several high-quality games would be needed to solve this matters.

The alternative solution proposed in this thesis does not target design of a new ADHD game. On the opposite, it tries to use already existing technologies, and thus, allowing general-purpose video games to be used as ADHD specialized ones. To achieve this, UGCI provides a technical solution bridging the EEG recording devices and standardized control inputs for video games.

In a nutshell, the UGCI will be by the play console or computer detected and recognized as control input devices, such as gamepad or joystick, and the input instead coming from the buttons presses will be generated by human's physiology. In that way, the gameplay can be controlled by the targeted physiological features selected by a recording device and these features can be rewarded visually by the video game.

Technically speaking, via UGCI a clean interchangeable interface will be established allowing to control almost any video game on the market without any tedious configuration and modification of the game itself.

3.1 UGCI an Endeavour Towards Interdisciplinarity

Today, we have to accept that the old division between disciplines does not apply anymore and that interdisciplinarity is required in many fields of our life. Designing and developing UGCI is a multidisciplinary endeavor, and its realization and application wouldn't be possible without synergetic collaboration between disciplines. The collaboration between disciplines in this challenging process can be best regulated through methodical knowledge transfer between the multiple domains coupled with efficient knowledge management during the design innovation process. Engineering design is a demanding and long process, challenging both inventiveness and a methodical approach to consolidating, interpreting, and using the available information. The design of the UGCI requires expanded collaboration since it relies on the most recent insights from different fields. It builds on the concepts from Neuroscience that helps us to understand the human physiology and build a link between EEG measured waveforms and the subject state of attention. Psychology supports the project with the knowledge about the content of these state and helps us to adequately and systematically study them. Finally, the realization of UGCI won't be possible without engineering skills to develop the appropriate platform for computational procedures for detection, recognition, mapping, and transformation of the signal.

With the aim to establish efficient interdisciplinary knowledge transfer, during the building process, I tried to separate conceptual design from its technical implementation, allowing different disciplines to understand, discuss and analyze the design.

Therefore, the UGCI can serve as a test, and at the same time example of a multidisciplinary piece of work on the single attempt to design, build and test the device using the novel ideas from different fields.

3.2 Conceptual Requirements and Design of UGCI

In the system design life, the conceptual system design is the first stage where the basic requirements and functional models are presented. Seeing a UGCI a black, information processing box, we have to define the inputs and the outputs first, and then to define the other internal functional components. Therefore, the UGCI must feature four main physical interfaces. Among these four, the device has two input interfaces, first for EEG signal and a second input for control commands coming from gamepad or joystick (see Figure 4, c) and d) respectively).

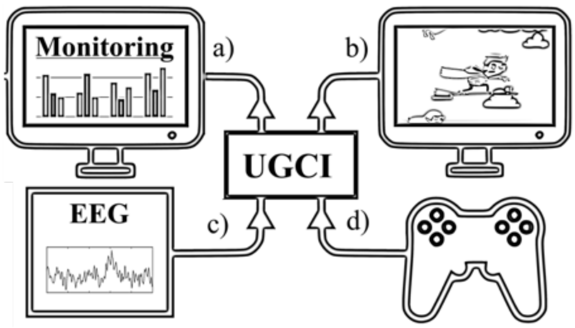

Figure 4. - Input/output UGCI Interfaces: a) output for monitoring and debugging, b) output to a computer, for game control, c) input from EEG recording device, and d) input from the gamepad or joystick

On the other hand, one among two output interfaces is dedicated for monitoring and debugging purposes (see Figure a)), whereas the second output interface serves as the connection to a computer or a gaming console (see Figure 4 b)). All the interfaces need to follow specifications if they exist. Otherwise, the communication protocol needs to be well specified and documented.

This requirement will support the universal character of the UGCI, allowing different physiological measures and different game-controllers to be used as input, as well as being compatible with most common computers and operating systems, so as to avoid the tedious installation of supporting software and configuration. Besides, it will also allow future improvement and development of the device itself.

The design approach based on functional models can bring numerous advantages for the designer: it can help in further realization, and it can serve for the establishment of the basis for comparisons of products. It also helps during interdisciplinary evaluation of the project and supports its functional extension. In that sense apart from the input/output specification, it is advantageous to have an overview of the functional modules of the device. The UGCI as a system has the aim firstly to transform EEG signal to commands, the internal representation of the reading that allow smooth functional manipulation inside the unit. This functional module also determines how the data coming from different sources will be integrated and it is linked to the operational modes of the device explained in the further text. Secondly, these internally represented commands and those originating from a game controller (i.e., gamepad or joystick) need to be merged in a way to provide an adequate control of the game *(see Figure 5)* and implicitly to form a feedback presented to a subject when the desired brain state has been reached and maintained. Figure 5 represents two operational modes and mapping functions for ADHD treatment (in the case of ADHD NF, the levels of attention will modulate or generate certain controls that will be passed to the computer or gaming console). The mapping function is marked with the f(x) and represents the core of the unit allowing integration of different inputs coming from the game controller and recording device.

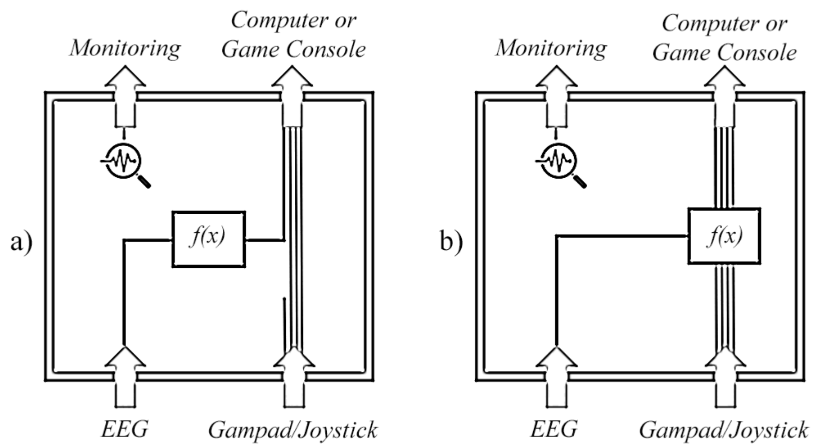

Figure 5. – Two suggested Operational modes of UGCI: a) Direct Control, b) Modulation Control

Finally, the outcome of the integration is the output signal that will be externally recognized as a standardized control input, similar to one coming from a gamepad or a joystick.

Since both ***operation modes*** and ***mapping function*** represent the core of the UGCI functional unit, they are discussed in more details in the following chapters.

3.3 Operations Modes of UGCI

Since the name of the device indicates that it is universal, it needs to be easily configured to fit the game settings and dynamics without bigger intervention. For these purposes, the device should be equipped with different modes of operation. The modes of operation depend on the game kind and type of the control. Consequently, two operational modes will be presented in this thesis in the following text.

The default operation is set to ***direct control mode***. In this mode, a certain command or group of commands is under the direct control of the EEG recording device *(see Figure 5 a))*. The direct control model prevents user push a particular button or group of buttons and sends a command, and instead generates the same command based on the detected brain state. For example, in car racing game, instead of a subject pushing acceleration button on the gamepad, the button will be pressed when the player reaches the desired brain state (in the case of ADHD it is a detected focus or level of attention). Since the attention level is not a binary phenomenon, the gradual scale can be achieved by a range of pressing frequencies leading to the constant press when the peak of the desired brain state has been detected. In such way, the car will smoothly accelerate as a subject reaches the desired state and being rewarded via a video game, he or she tries to keep the reached state. The other commands (i.e., steering, braking, etc.) will be under control of the subject. The pressing frequency can be used to create desired gradual effect.

An alternative option, called ***modulation mode***, is the mode where a subject (gamer) has complete control using a gamepad (the commands are bypassed to the computer or gaming console) only while he or she maintains the desired brain activity. Otherwise, when the subject loses its attention, in the case of ADHD, or deviates from desired brain state, chosen buttons or group of buttons are correspondingly delayed *(see Figure 5 b))*. The length of the delay is directly proportional to the subjects deviation from the desired brain state. To illustrate this situation, we can use the same example with the car racing game. In that case, a subject keeps pressed acceleration button, but his command will be modulated (delayed) if he is not in the ideal state. Therefore, the car will fully accelerate (there will be no interference of the UGCI system) when he maintains the focus. In this way, his or her neural circuitry for attention and focus will be fostered by reward from the game, potentially leading to long lasting effects.

What is noticeable from the two cases, the UGCI can be used for any car racing game, and in general with any game where the dynamics can be controlled by a subject.

3.4 Mapping Function for ADHD Treatment

In the conceptual design of the interface, we have mentioned that the device can be configured to work in different operational modes, and therefore, provide flexibility and usability with different game-designs and controlling approaches. For the development of the prototype, I have selected one of the two described methods to model and to implement. Namely, this decision has been made in parallel with the game selection elaborated in the following text. Due to characteristics of the selected game, the direct mode has been chosen with the immediate control of the acceleration command. Therefore, the idea is that when the attention is high, the acceleration of the game dynamics is high, and vice-versa, the game slows down affected by the decrease of the acceleration as the subject deviates from the desired attentive state and become unfocused. The core of UGCI is the design and implementation of the mapping (*f(x)*, *see Figure 5*), between the recorded attention value (on a scale from 0 to 100), and on the other side frequency of the sent commands (button presses). The crucial part of the design of the UGCI is to choose and model the mapping function correctly. Otherwise, the proper functioning of the device can be affected.

The parameters of the mapping function selected for the UGCI have been theoretically obtained from the description of the absolute attention values, elaborated in the further, and the ranges that correspond to the increased attention states. The mapping function has been delicately evaluated and tested empirically with the chosen game. Initially, the particular test code has been used to model the various attention levels. Using debugging interface and the provided LCD on the UGCI, the level of attention has been monitored in real-time during the game play. During this phase, the test code allowed us to set the attention value actively and follow the game dynamics.

After the test and calibration, the empirical experiment on the single subject has been performed. In this phase, the subject plays the game using full UGCI NF functionality. The outcome of this step is the final design of the mapping function that won't change in further experimentation and testing.

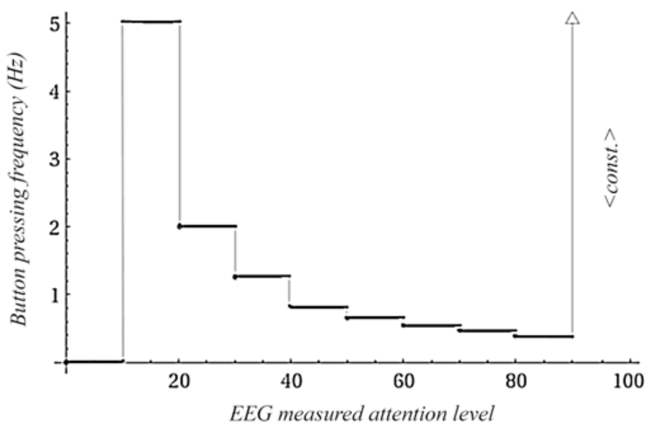

Figure 6. – Selected Mapping Function between absolute attention levels and button pressing frequency for UGCI Proof-of-Concept Experiment with Car Racing Game

We can observe on Figure 6 that the frequency of the button presses is decreasing while the attention level increases until it almost reaches the maximum where it becomes constant. This behavior is linked to the game control dynamics, and even though for most of us might sound contra intuitive, it is not this case. Since this mode of operation has been dedicated to the car simulation games (explained in the next chapter), the pressing frequency corresponds to the pressing rate of the acceleration pedal. The increasing frequency of the acceleration pedal pressing, as a matter of fact, won't increase the speed of the car, but the opposite effect will be achieved. Most of the motor vehicle simulation games by default offers to option for automatic transmission, and thus high-frequency pressing will have the contra effect, leaving the car at the low transmission rate and therefore at low speed. When the speed of the car is low due to short pressing intervals, the dynamics of the games is also slow giving the incorrect visual feedback as desired during the therapy. In the testing during the calibration phase, we have observed that the car can gradually accelerate by introducing and gradually increasing the pressing interval. During the pressed state, the car can speed up and keep the high speed. During the release period, the car can go by physical interaction and periodically refresh by the acceleration button presses. Therefore, as the attention increases, the pressing/release interval is increased according to the presented function on Figure 6. Once the attention level reaches the threshold of 90, the press becomes constant. From the point of the final deployment of the device, it very likely that multiple of mapping function will be realized, corresponding to different game kinds and categories.

3.5 Game Selection

Several conceptual requirements need to be fulfilled for the design and development of the UGCI. Game selection is critical and in many cases can predetermine the outcome of the NF therapy.

Today's video game market is very diverse, featuring a very high number of available games and, furthermore, their classification is not standardized, yet. Even though the UGCI has the word universal in its name, the game needs to fulfill certain set conditions to be used with the device. The definition of the criteria in this chapter can serve as a guideline to determine which games can be controlled by UGCI and, furthermore, be efficient in the treatment of ADHD.

The first essential criterion is that game itself needs to support control via gamepads or joysticks. This technical rule is closely related to the conceptual design of the game. Many games that require textual input from the keyboard or mouse action do not support control over the gamepad, and in thus, are not suitable for the proposed design of the UGCI. We can imply that the UGCI can be used with games that can be controlled via external devices, excluding keyboard and mouse. The second criterion is that the game dynamics need to be controlled by the player. In other words, if the player can affect the speed of the gameplay, that would be a suitable game for UGCI. The speed of the game is directly linked to a visual feedback, in that sense, the effectiveness of the treatment can be guaranteed. However, the dynamics should not be confused with a movement of the whole graphical scenery in the gameplay, but it can be limited to a certain function that character needs to perform to succeed in his or her mission.

Nevertheless, various popular games on the market can fulfill these two requirements. To help with the choice in the following text, we have selected two most compatible game categories: *(1) action games and (2) vehicle simulation games*.

Action games are included in the first group of UGCI plausible game kinds. Since action games feature physical challenges and they are centered around the player; the dynamics of the game are in direct control, too. According to the rough preliminary research, most of the existing games can be control via gamepads. In that regards, they fulfill most of the requirements to be used for NF therapy.

The second favorite category is vehicle simulation, which has the aim to provide a realist interpretation of operation of various vehicles. The most common type of vehicle simulation is racing games where the dynamics are also in full control of the player, and most of them are controllable via gamepads, too. In that regard, they fulfill two essential requirements to be potential candidates for UGCI NF protocols. The gameplay consists of the player who is placed in the driver's seat and requires to race against other drivers or to complete a race as fast as possible. The racing car games are pioneers in the field of computer gaming world, and one of the earliest games was part of this kind. Other subkinds are flight simulators, involve piloting a spacecraft and train simulators.

On the other hand, in the group of non-compatible games are the role-playing ones, in which the player is in the role of one or more "adventurers." Since many involve maneuvering these character(s) through an overworld, the mouse or a keyboard is required. For a completion of certain tasks, input text in the form of communication is needed too. These conditions do not satisfy the defined requirements, and therefore they should not be preferred in the choice for UGCI NF protocols. The second type that is not likely to work with the UGCI is the so called strategic game. These games can require careful and skillful thinking and plan to achieve victory. However, the game dynamics and speed are not directly under player's control, and also violates one of the requirements.

Furthermore, these games in most cases do not support control over the gamepad. Therefore, like role-playing games, this kind of game is not compatible with UGCI.

Unfortunately, it is not possible to list all existing types and subtypes of the games and their evaluations. In the previous chapters, I tried to point to the most common categories. Also, the presented evaluation can serve as an illustration on how to chose an adequate game for UGCI.

4 Implementation

The first phase of the project implementation is a selection of the proper hardware and software platform to realize the project. In the case of UGCI, the choice of the platform was based on predefined requirements that helped to evaluate existing solutions and select the most appropriate one. These requirements include the already mention concepts, but also extended technical ones explained in the later text. It is clear that inappropriate choice of the platform can lead to faults in later realization. Therefore, the project needs to be planned, by defining the technical requirements.

4.1 Technical Requirements for UGCI Implementation

Modularity, platform independence, and interoperability are the main requirements for implementation of the UGCI. In that sense, it is vital to specify in detail how each of these can be achieved. The prototype, hence, requires a definition of *(1) requirements for interfaces, (2) selection of the hardware and software platform and (3) requirements for an EEG recording unit.*

4.1.1 Interfaces Requirements

The chosen platform needs to be compatible both with software and hardware of existing devices and needs to support standardized communication protocols used by external EEG recording devices, as well as computers and game controllers (i.e., Bluetooth™ wireless communication, serial communication, USB, etc.). It also needs to be allowed to configure the device to work as Human-Interface Device (HID), to enable its portability and interoperability.

4.1.2 Hardware and Software Platform Requirements

Apart from mentioned interface requirements, the platform needs to be supported by a proper programming environment with cross-platform support. It is also required to have open-source and extensible software and hardware. Finally, the selected platform also needs to have a proper community support.

4.1.3 Recording Device Requirements

Technically speaking, this module is not part of the implementation, and therefore, the aim is to search for already available solutions. Even though the name says only recording, the proper recording device (recording module) needs to have implemented the whole EEG signal processing pipeline which can be represented by the following steps:

- acquisition of the EEG signal process (raw EEG)
- pre-processing (filtering, frequency analysis, etc.)
- classification the EEG signal
- sending the classified/processed signal to the UGCI in a specific range

The recording device in the processing step needs to support detection and classification of the electrophysiological features related to the ADHD (such as focus and attention).

No.	Component Name	Number of Components
1	Arduino Leonardo	1
2	Arduino Uno	1
3	Keypad LCD Shield	1
4	PS/2 Shield	1
5	HC-05	2

Table 1. – Specification of the Required Components for UGCI realization

4.2 Evaluation and System Design

In this stage, the subsystems of UGCI (i.e., a recording module, interfaces and central unit) that performed the desired functions are designed in compliance with the defined system requirements. For each of the subsystems, an already existing solution was evaluated and selected. In the following text, the selection has been presented and explained in more details. The final list of selected hardware components for UGCI realization are listed in Table 1.

4.2.1 Platform Selection

The selected platform for the realization of the project is Arduino™. During the evaluation, this platform hardware and software platform fulfilled most of the conceptual and technical requirements.

The Arduino board together with its programming language offers an inexpensive way for designing and prototyping different embedded systems. Arduino is developed as the low-cost platform to support the development of embedded computing. The hardware platform of the Arduino board is based on an ATmega microcontroller surrounded by a set of analog and digital input/output (I/O) pins, enabling easy interfacing with other hardware and modules, which is very suitable for UGCI. Arduino also features USB ports that allow users to connect a host computer running various operating systems and also has the support for the emulation of HID. Also, the company and licensed manufactured offer different hardware extensions, called shields. These are modular circuit boards that can be connected to the main Arduino board providing an extra functionality and interoperability. These additional features mainly cover interface with other devices, such as servo motors, Bluetooth, Ethernet, Serial communication, etc.

4.2.1.1 Functional Implementation – Two Boards

The UGCI has been realized using two Arduino boards: (1) *Leonardo*™ and (2) *Uno*™. The two boards were required to solve issues with independent concurrent operations needed for multiple interface design since the Arduino board alone supports only single-thread programming (a single transaction at the time). Leonardo board is the core of the UGCI, and most of the operations are handled there. The board has been chosen because it fulfills most of the predefined software and hardware requirements, thus apart from managing the operation of the UGCI, it also provides support for interfacing with computer or game console on the side, and via wireless Bluetooth connection responsible for the EEG recording. It is also involved in displaying the relevant data on the LCD. Finally, the Leonardo board also handles the communication to Uno. The function of the second board, Arduino Uno, is to manage the interface with the various game controllers. It gives an entirely independent software and hardware system that can be capable of supporting different manufacturers of game controllers as well as different connection interfaces, including the wireless ones.

4.2.1.2 Software and Integrated Development Environment

The Arduino board is programmed using its integrated development environment (IDE) and programming language, which resembles C programming language with a touch of C++. Arduino boards are programmed via Universal Serial Bus (USB) and, via their IDE and using AVR tools, the Arduino programs are translated into ATmega instructions that can be run on the microcontroller. The software may be written in their IDE, a cross-platform application written in the Java programming language. The IDE includes most of the editing features, as well as syntax highlighting.

4.2.1.3 Recording Device Selection

For the recording device, Neurosky™ MindWave[1] single electrode EEG equipment *(see Figure 7)* has been chosen. Apart from Application Programming Interface (API) for Arduino and good community support, this device features real-time EEG data processing and attention detection that is suitable for the project realization and required for the ADHD NF treatment specified in the interface design requirements.

[1] http://neurosky.com/biosensors/eeg-sensor/biosensors/, *Accessed: August 2017*

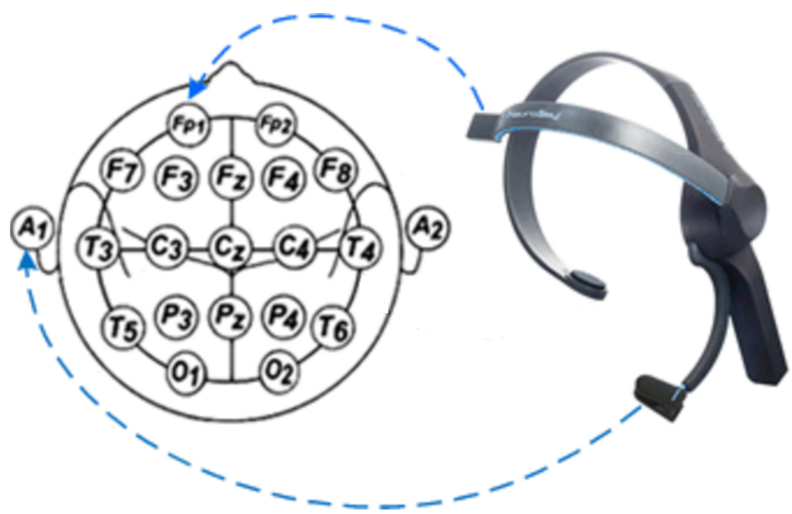

Figure 7. – Neurosky MindWave EEG Recording Device and its electrodes on 10-20 international system of electrode placement

Furthermore, this device has been used for video-game treatment of the ADHD, and the same absolute attention scale (0-100) has been used for the direct control of these specially designed games. As the same scale is used as input for UGCI, in the future the comparative analysis can be conducted to study the effectiveness of the UGCI extensively.

4.2.1.4 EEG Processing

Namely, Neurosky™ Software Development Kit (SDK) documentation shows that their devices are capable of providing attention and meditation values based on their on-chip closed-source algorithm. According to their documentation, these values are calculated with a wide range of brain waves, both in time and frequency domain. The only technical information we can get from them is that the attention value has more basis on beta waves, whereas, the meditation is founded on alpha waves. They claim that Mindwave uses dynamic adaptive algorithms to adapt to the natural variations and tendencies of each user to compensate the fact that EEG in the human brain is subject to reasonable variations and fluctuations. According to their documentation, this feature enables their sensors on their devices to work on a broad range of people under a broad range of personal and environmental conditions while still keeping good accuracy and reliability.

Using on-chip technology, the whole EEG processing pipeline has been implemented. The chip is equipped with a single processor and set of filters for noise reduction as well as EEG frequency band separation. The sampling rate of the raw EEG is 512 Hz and are later sent to the analogue to digital converter with a 12-bit resolution. The attention values are generated once per second.

4.2.1.5 Absolute Attention Scale

The attention values from 60 to 80, on their absolute scale, are considered *slightly increased* and can be interpreted as levels that may be higher than regular ones. The values from 80 to 100 are considered *increased* in the sense that they indicate the high levels attention. On the other hand, values between 20 and 40 are indicating *reduced attention levels*, while a value between 1 and 20 shows *strongly lowered* attention level. A value of 0 is a unique value indicating that Neurosky Mindwave was unable to calculate the level of attention due to a different factor, such as excessive noise.

4.2.1.6 Physical Interface

The connection to the Neurosky is realized via Bluetooth connection. The device already features Bluetooth™ inbuilt adapter, and, therefore, the UGCI requires only the other (master) communication side. This physical interface is fully compatible with the Arduino platform and for that, the HC-05 multi purpose programmable module can be used or appropriate board extension (Arduino Shield). The HC-05 *(see Figure 8)* gives the flexibility to be independently configured to establish communication with any desired Bluetooth device in the surrounding, and it's being selected for the project.

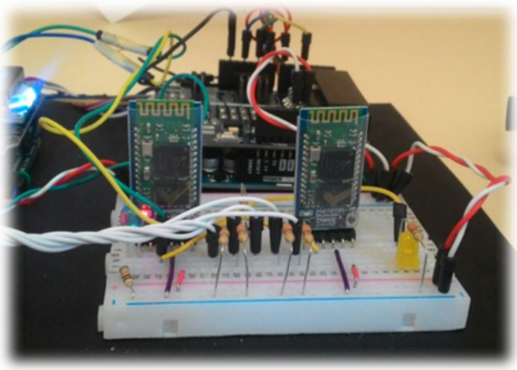

Figure 8. – Two HC-05 Modules. Communication with EEG recording device (right), Wireless connection for Monitoring and Debugging purposes (left).

To establish physical interface, the HC-05 module has been paired with the Neurosky Mindwave permanently, and thus whenever it is powered up, it will automatically establish the connection. Further improvement of the UGCI can give possibility also to add and/or remove Bluetooth devices via a provided interface, but for the prototype purposes, the device has been permanently attached only to one pair of EEG recording device.

Since there is no existing standardized interface for communication between EEG recording devices and workstations, there is a degree of freedom either to chose some of the existing ones or to develop an entirely new specification for inter-device communication. Considering that Neurosky Mindwave has been used for the recording, it is also natural to adapt the interface that is designed by the same company. It is also advantageous that device output is in the absolute scale from 0 to 100 and the conversion for UGCI won't be necessary. Therefore, if anyone in the future desires to change the recording device, it just has to make sure that the chosen recording devices convert the recorded signal to an absolute scale from 0 to 100 resembling the attention state of the subject or any other physiological feature targeted by the NF protocol.

```
switch (payloadData[i]) { // Checks if the received packet
                          //has the 0x1,0x2,0x4,0x83 and 0x80 markers
                          //that corresponds to
            case 0x1: //Battery status
                i++;
                battery = payloadData[i];
                break;
            case 0x2: //Signal Quality (i.e. impendence, noise level)
                i++;
                poorQuality = payloadData[i];
                bigPacket = true;
                break;
            case 0x4: // Detected Attention Level (0-100)
                attention = payloadData[++i];
                break;
            case 0x5:// Detected Meditation Level (0-100) -> Not used for UGCI design
                meditation = payloadData[++i];
                break;
            case 0x83: // ASIC_EEG_POWER that includes delta, theta, low-alpha
                       //high-alpha, low-beta, high-beta, low-gamma,
                       //and mid-gamma EEG band power values
                i++;

                // Extract the values
                for (int j = 0; j < 8; j++)
                       ((uint32_t)payloadData[++i] << 16) |
                       ((uint32_t)payloadData[++i]    <<    8)    |    (uint32_t)payload-
               Data[++i];
                }
                break;
            case 0x80:
                // Raw EEG Reading
               ((int)payloadData[++i] << 8) | payloadData[++i];
                break;
            default:
                // Broken packet Indication
                Serial.print("Broken package");
                break;
        }
```

Listing 1. – The source-code responsible for handling the interface to the EEG recording device

4.2.1.7 Gamepad – Computer Interface

For the prototyping purposes, due to technical characteristics and availability, PlayStation game controller has been chosen *(see Figure 9)*. One of the biggest advantages of these gamepads apart from their extensive use, ergonomics and price, are the support for vibrotactile stimulation using inbuilt servo motors. Thus, the function of UGCI and NF, in general, can be in future easily extend to the haptic feedback (e.g., activation of the motors when the subjects deviate from the desired brain state).

Figure 9. - PlayStation 2 Gamepad used in UGCI Testing and Evaluation

The device utilizes PS/2 port, and for the interface, the corresponding Arduino shield converting the data to the adequate format efficiently interpreted by Arduino Uno board *(see Figure 10)*. The interface to the gamepad has been realized through the 2nd auxiliary board - Arduino Uno and the Cytron™ PS2 Shield. Two boards communicate via digital communication pins.

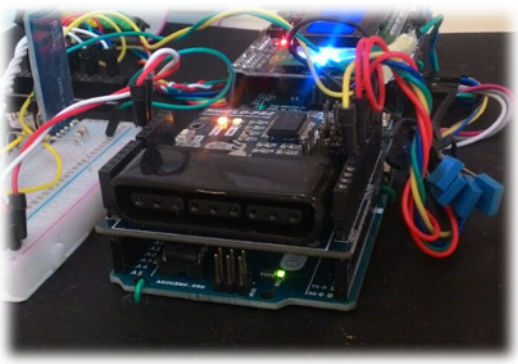

Figure 10. – Arduino Uno (below) and Cytron PS2 Shield (above)

Arduino Uno has also been equipped with the Cytron PS2 Shield[2] *(see Figure 10),* an extension that provides physical connection port to the PlayStation 2 gamepad. Initially, the PS2 interface has been chosen because it can be easily interfaced with Arduino boards using digital I/O pins. The pin specification of the PS2 port is shown in Figure 11.

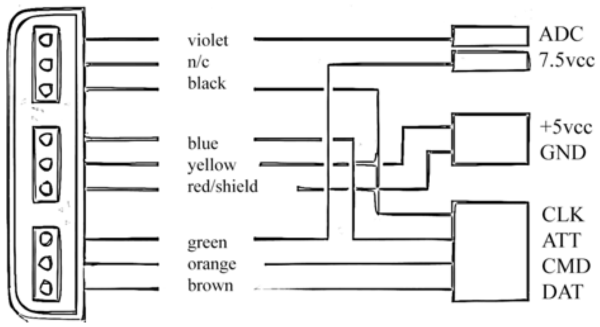

Figure 11. – Technical Specification of PlayStation 2 Communication Port

The interface to the PC has been realized using USB connection of the Arduino Leonardo. With the adequate library, Leonardo that is based on ATmega32U4[3] chipset, supports emulation of HID and thus allows easy configuration for UGCI. When connected to the computer, the device is detected as a gamepad *(see Figure 12)* and on the most modern operating systems it does not require configuration or installation of any additional software. In this virtue, the whole operation of NF is effectively hidden in the computer making the UGCI highly portable.

In order to achieve emulation, the library Joystick.h[4] has been used. Since Leonardo board is based on ATmega32u4 microcontroller, the Game Controller (Joystick.h) library will work without much effort.

[2] https://www.cytron.com.my/p-shield-ps2 *Accessed: August 2017*
[3] http://www.microchip.com/wwwproducts/en/ATmega32u4 *Accessed: August 2017*
[4] https://github.com/MHeironimus/ArduinoJoystickLibrary *August, 2017*

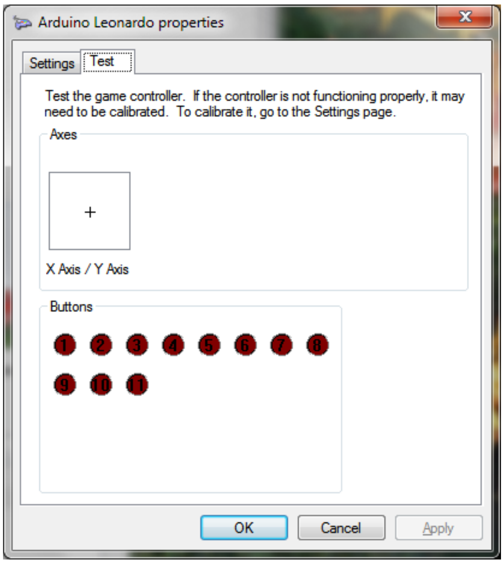

Figure 12. – Arduino Leonardo Detected as a Gamepad (Windows 7)

The Game Controller library used for UGCI provides the following:

- X, Y, and Z axis control
- X, Y, and Z axis rotation
- 32 buttons configuration
- Rudder
- Throttle
- 2 Point of View Hat Switches

Since the PlayStation 2 gamepad contains 12 buttons and two hat switches, the library has been initiated with the appropriate configuration shown in Listing 2.

```
include <Joystick.h>
Joystick_ Joystick(JOYSTICK_DEFAULT_REPORT_ID,JOYSTICK_TYPE_GAMEPAD,
  12, 2,                  // Button Count, Hat Switch Count
  true, true, true,      // X and Y, but no Z Axis
  false, false, true,    // No Rx, Ry, or Rz
  false, false,           // No rudder or throttle
  false, false, false);   // No accelerator, brake, or steering
```

Listing 2 – The soruce-code used for initial configuration of Joystick.h library

4.2.1.8 Configuration and Monitoring Display

An additional feature of the UGCI is LCD (16x2) display designed to show the essential data during EEG recording and functioning of the UGCI in general. It is also used for the configuration of the UGCI together with the set of buttons for the navigation through the menu of the device *(see Figure 14 a))*.

Figure 13. – Five LED Stripe used for an attention level visual feedback to the gamer

Furthermore, the device also features an additional simple display consisted of 5 LEDs providing a visual feedback of the subject attention state *(see Figure 13 and Figure 14 e))*. The LEDs are put together to form a bar, starting from a red color, indicating low attention, to the green showing the high state of attention. The blinking of the LEDs indicates the transitional state and provide information that the persons increases his attention.

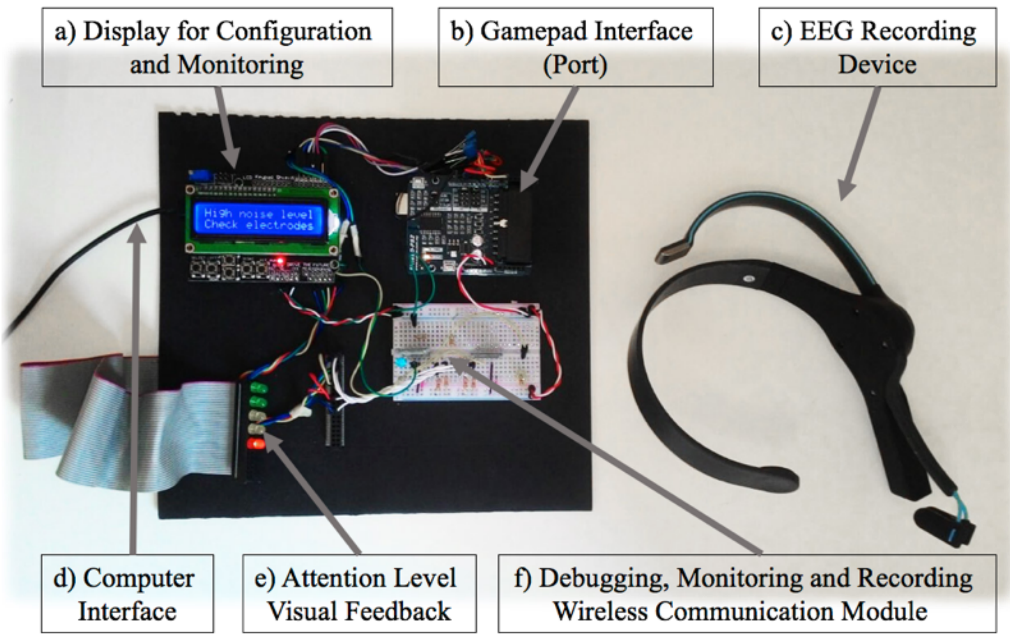

Figure 14. – UGCI Hardware Component Overview

The LEDs are fixed on the flexible cable, so that it can be placed in the visual field of the subject during gamepad.

4.2.1.9 Debugging interface

For development purposes and further experimental usage, the device needs to feature monitoring, or in more technical terms, debugging interface. During development, one needs to keep track of the proper functioning of the device, and further in the deployment stage, the recording of the action is needed for the realization of the scientific experiments and, in general, to keep track of one's states of the attention throughout sessions. To achieve mentioned functionality, the device uses a configurable serial interface, which apart, from the gamepad emulation purposes, can also serve as monitoring interface. An additional Bluetooth module has been included to increase the flexibility of the UGCI. This module serves as wireless communication to other stations (e.g., mobile phone or second computer) used for real-time monitoring and recording.

4.2.1.10 Commands Integration – UGCI Central Unit

The core of the UGCI operation is the central unit, where the mapping function has been implemented. The unit differs from the others because it is only a software entity. The appropriate methods make sure that inputs have been stored in the designed internal data structures allowing easy manipulation. Furthermore, this unit governs the selection of the operational modes, in line with the mapping function hosting.

Depending on the selected mode, the data coming from the controller are either bypassed or integrated with EEG data. The operation has been depicted in Figure 15.

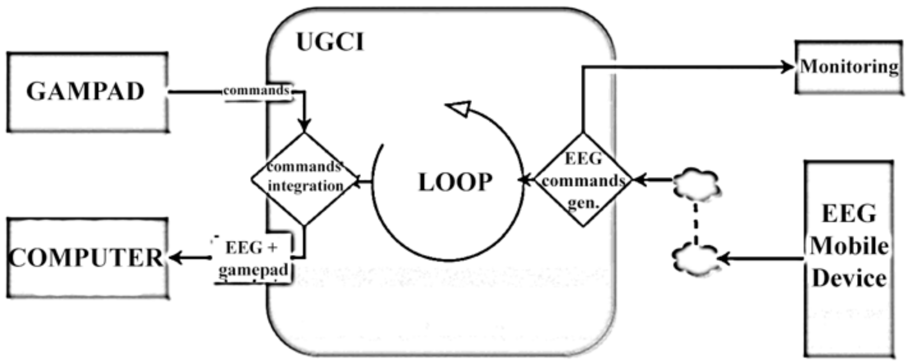

Figure 15. – UGCI Interaction Diagram

4.2.1.11 Functional Description

This chapter has the aim to illustrate in details how the UGCI functions. When connected to the computer, the UGCI is detected as a gamepad *(see Figure 12)*, and thus, in most cases it will be automatically recognized and installed. After the UGCI booting process, the device is in the sleeping mode waiting for EEG data showing the message depicted in Figure 16.

Figure 16. – Starting message is indicating that there is no Bluetooth signal and suggesting to turn on a recording device.

In the case that EEG recording device is connected, and in our case, Neurosky is turned on, the device first checks the quality indicators of the recorded data and provides a feedback if the electrodes are set correctly *(see Figure 17)*.

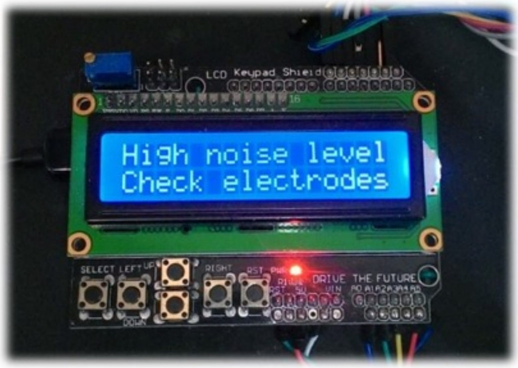

Figure 17. – The message indicates that there is a connection to the EEG recording device. However the signal quality is poor.

If not configured differently, by default the device is in the bypass mode. This mode allows the user to use a gamepad as if it is directly attached to a computer *(see Figure 18)*. This feature enables users to have immediate information if the control pipeline works correctly since the UGCI in the other stages partially modifies or modulates these control signals. The EEG acquisition device needs to be turned on during this phase to ensure data flow consistency and errorless functioning of the apparatus. However, the electrodes do not need to be set, nor data acquisition needs to be initiated: it is enough that the EEG device is turned on to provide signaling and to test the continuity of communication.

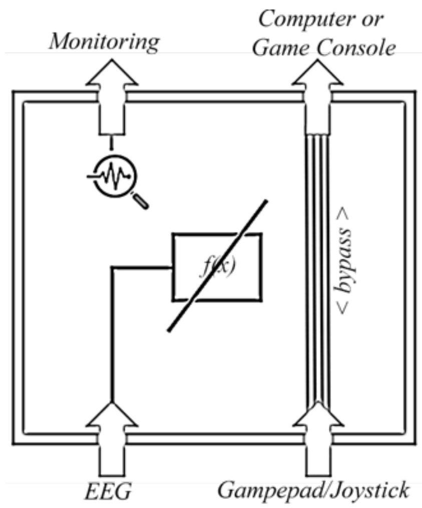

Figure 18. – Graphical depiction the bypass mode where the commands from the Gamepad are just sent without interruption to a computer or a gaming console.

For the prototype, only direct-mode has been implemented, explained in Chapter 3.3 *(see Figure **5** a).* To activate the direct operation mode, it is needed to press the select button of the UGCI.

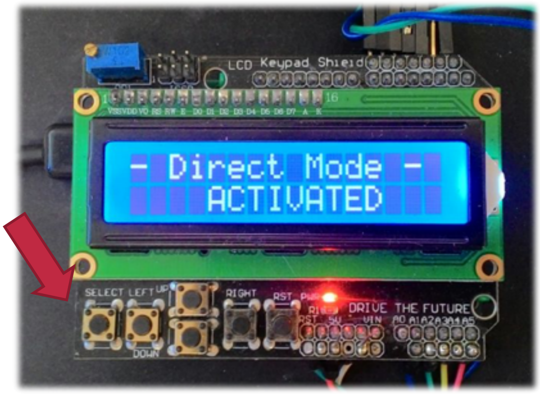

Figure 19. – The display is showing that the direct mode has been activated by pressing the select button (down-left corner).

In this mode, the user has full control of all other buttons from the gamepad, except the selected button or group of buttons that are under direct control of UGCI. To disable and to return to the bypass mode it is enough to press the select button again.

Figure 20 – UGCI connected to a computer with the Need for Speed car racing game running.

5 UGCI Evaluation and Testing

In this stage, the UGCI needs to be properly evaluated and tested. The process is separated into two phases: (1) Technical evaluation and testing, and (2) Evaluation of UGCI effectiveness. The first stage covers whether the device complies to use-cases and if the core functions work according to the idea. It includes various levels of testing to ensure that the effectiveness evaluation won't be in any sense affected by a technical error. The second phase is dedicated to the effectiveness evaluation, where a small proof of concept (PoC) study has been presented and supported by empirical findings.

5.1 Technical Evaluation and Testing

In computer science, the testing is a process which is used to identify the correctness, completeness, and reliability of the developed components. This procedure needs to be handled before evaluation of effectiveness of the device. The testing consists of running the software alone or in combination with other services and hardware with the aim to assess whether the behavior of the software meets the technical requirements.

The testing has been divided into the (1) component testing and (2) system testing. The implementational design of the UGCI allows component testing procedures. Therefore, the component testing has been further divided into interface and integration testing. The interface testing treats each input device (i.e. interface) as a separate component and ensures that UGCI has been supplied with correct input data. The integration testing phase ensures that the data coming from the various interfaces have been adequately managed. During this phase, each interface has been mocked with the corresponding data providing maximal testing coverage.

System testing is done on the complete system in the context of functional requirements of the UGCI. By system testing apart from the design, the expected user behavior has also been taken into consideration. Therefore, the test covers also the user experience of the interface (i.e., displayed messages and input possibilities).

5.2 Evaluation of UGCI Effectiveness

When building such devices as UGCI, the technical tests do not show the effectiveness of the device, and that is in most cases insufficient for the final report. For that purposes, special conceptual evaluation is required, where the usability and functionality of the equipment have been verified in the empirical study. Therefore, a Proof of Concept experimental empirical study has been conducted. The idea of PoC is to demonstrate the UGCI feasibility. It is important to keep in mind that the study does not fully verify the functionality of the UGCI, but it is here to serve as a pilot study and show its practical potential.

5.3 Theoretical Assumptions

It is known that by NF subjects can learn to alter their brain activity. Various NF protocols can elicit particular EEG changes and thus have positive effects on behavior. In the previous chapters, it was shown how NF could be used as effective therapy for ADHD. However, for the proof of concept, the idea was to use healthy individuals. Therefore, in the chapter, we will provide theoretical postulate for the implication that improvement of attention in healthy individuals can be generalized also for ADHD. In healthy subjects (Egner and Gruzelier, 2001; Gruzelier, 2014) research showed that Sensory Motor Rhythm (SMR) (12–15 Hz) was associated with improved perceptual sensitivity, were high beta (15–18 Hz) resulted in the opposite effect. Furthermore, Egner and Gruzelier (2001) concluded that increasing SMR in healthy subjects results in a general attention improving effect and changes of spectral EEG topography in healthy subjects, which is incongruent with the findings in ADHD subjects. The results of (Vernon *et al.*, 2003) revealed that following eight sessions of NF, the SMR-group of healthy individuals were able to selectively enhance their SMR activity, in relation to their theta and beta activities.

The systematic review of (Gruzelier, 2014) has covered different NF protocols based on SMR, beta ratio, alpha/theta ratio, alpha desynchronization, gamma and gamma ratio, posterior and frontal theta up-training and down-training in healthy individuals. Therefore, he concluded that there is sufficient evidence validating the role of NF in enhancing sustained attention, working memory, P300b, mental rotation, motor procedural learning, psychomotor skills, and relief of anxiety in performance.

In summary, based on several Authors (Egner and Gruzelier, 2001; Vernon *et al.*, 2003; Egner, Zech and Gruzelier, 2004; Gruzelier, 2014), we can conclude that sustained attention, together with broad encompass of cognitive and affective performance, can be improved both in healthy as in subject with ADHD. Accordingly, we can validate the implication that improvement of attention in healthy individuals can be generalized also for ADHD. Consequently, these findings provide enough support for the design of our UGCI proof of concept study with healthy subjects.

5.3.1 Implications for ADHD Subjects

The recruitment of ADHD children is a complex endeavor. Apart from the process itself, due to direct contact with children, it may be necessary to face a different ethical question that is avoided in the indirect or in research that involves adults. Furthermore, apart from confidentiality questions and the issues of the researcher's responsibility for the well-being of young subjects can always arise. More than all, the recruitment of ADHD subject is out of the scope of this thesis, that has the focus on the design and development of the UGCI, and thus requires only a proof of concept study.

5.4 Experimental Design

To ensure the effectiveness of the UGCI, we have designed a small proof of concept study that has the aim to answer if the UGCI can increase attention and therefore achieve similar results as ADHD dedicated games. The proof of concept study is not a comprehensive research that entirely validates its effectiveness, but it rather serves to show the potential of the device. The study can also be seen as a pilot one for further investigation and validations of the device effectiveness.

5.4.1 Hypothesis

The main hypothesis of the study is to validate whether the measured value of attention and the subject performance has increased after the training, hence achieve the similar results as ADHD dedicated games. Furthermore, the evidence from the NF research in ADHD subjects with Neurosky Mindwave set and dedicated games demonstrate subject's ability to voluntary modulate his brainwaves even after a couple of sessions. In general, that serves as a first indicator of the effectiveness of the NF therapy, and therefore, if subjects using UGCI after a couple of session of NF training demonstrate the same ability to modulate their brainwaves by increase of EEG measured attention, the hypothesis can be validated and effectiveness of the UGCI can be shown.

The hypothesis performed for the statistical analysis were the following:

$H1_{(0)}$: *There is no difference between mean EEG measured attention level in the first and in the last NF session.*

$H1_{(a)}$: *There is a statically significant increase of mean EEG measured attention level in the last in comparison to the first NF session.*

$H2_{(0)}$: *There is no difference between measured performance (the average time to complete the video game level) in the first and in the last NF session.*

$H2_{(a)}$: *There is a statically significant difference increase of measured performance (the average time to complete the video game level) level in the last in comparison to the first NF session.*

5.4.2 Methods

In the experiment, the participants were required to play the chosen game in 4 sessions that were recorded in four consecutive days. In each session, the subject was required to play the same game using NF with the same parameters. The chosen game for the experiment was a car racing game, and the UGCI was configured to direct control mode, controlling the acceleration of car via the press of the triangle button. The calibrated mapping function was used to map quantified attention values to the frequency of the button press. The function was explained in Chapter 4.

During each session, the EEG attention values were also recorded and stored for later offline analyses. In addition to attention values to be used as the principal measured variable for hypothesis validation, the time to complete the game levels was also noted and used for performance evaluation. In that way, we would be able to test whether the subjects (a) improved their attention in the 4th session in comparison to the 1st session, and (b) if they improved their performance in terms of time required to complete a level.

5.4.3 Game Choice

One of the tasks in the experimental design was to choose a proper game for UGCI. Following defined requirements, I have decided to experiment with a car racing game. This kind of game has been evaluated as very plausible. For the selection of the game, an additional parameter was included, which was the game popularity. In the introductory chapter, we have argued that children are not very motivated to play ADHD dedicated games since they differ a lot from the ones they have at their homes. For that reason, we have selected one of the most popular car racing game - Need for Speed Carbon *Figure 21*). According to the Metacritic[5], Need for Speed games, is among the most frequently played video racing games worldwide.

Figure 21. – Introductory disply of "Need for Speed Carbon" Gameplay

Due to its popularity, it was the first developed game for consoles such as PlayStation 3 and Wii. As in many car racing video games, the player controls a racing car in a variety of races, the goal being to win the race in competition, by achieving the best time.

5 http://www.metacritic.com/browse/games/genre/date/racing/pc *Accessed: June 2017*

5.4.4 Participants

For the proof of concept study, 8 participants were recruited, 4 women and 4 men (mean age = 27; SD = 1.41). All participants, most of them university students, had declared not to suffer from any psychiatric or neurologic disorders. Two of the male participants declared that have actively played video games in the past.

5.4.5 Procedure

In each session out of four, the subjects had to complete three different races in the first part of the session and repeat the same races in the second part (an example of a session can be seen in Figure 22). The races had various lengths, and the same races in the same order were repeated in the next consecutive sessions. The collected information can be helpful for future data analysis to examine the UGCI NF short term effect on subjects attention. However, in this study, we were interested in knowing if subjects can improve in the long run. Hence, compared the performance of the first and the last session.

The average time to complete a single race was approximately 2.5 minutes. With the setting up phase, pauses and instructions, the whole session did not last more than 40 minutes in total.

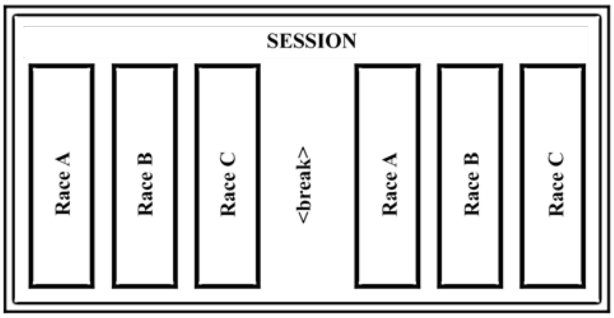

Figure 22. – Depiction of a Single Session and Race Selection

The first session for each subject begun with the introductory information about the experimental design. The subjects were also informed about the effect of the UGCI on the control and were allowed to play the first test race without NF. During this phase, the EEG of the subjects was not recorded, and the first gameplay was only done to familiarize the subject with the game. Before the recordings, each subject had an opportunity to practice and voluntary increase the attention values. Since there is a certain portion of the population who cannot modulate their brain states, the small practice also enabled us to exclude them from the experiment. None of the subjects were instructed on what technique to use to increase their attention value, but they were told that the acceleration of the car was under the direct control of their EEG attention values and that they had to investigate how to put it under control.

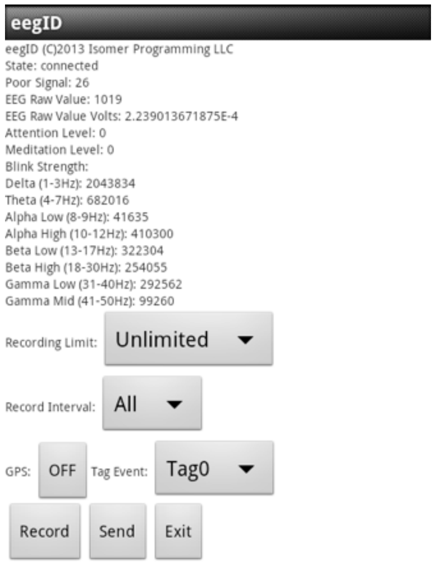

Figure 23. – Screenshot of the eegID graphical user interface used in the experiment

In the previous text, it is mentioned that for recording purposes the Neurosky Mindwave dry single electrode EEG set has been used (el. Fp_1, ground and reference A_1 on 10-20 international system of electrode placement , see Figure 7). The set communicates with the UGCI via Bluetooth. The designed prototype also features serial and additional wireless interface dedicated for data recording and debugging purposes. In our experiment, the secondary Bluetooth wireless port has been used. For the recording software, the already existing application, eegID™ has been used (see Figure 23). eegID is an application developed by Isomer Programming LLC[6] and enables connection via Bluetooth(TM) to various devices that are compatible with the Neurosky™ MindWave technology. Since for the UGCI design, the same interface technology has been adopted (see

[6] http://www.isomerprogramming.com/

Implementation chapter), the eegID application can also be used for recording the UGCI EEG incoming data. According to the specification, the application records the following fields: PoorSignal, indicator used to show when the impedance value and high noise is present, EEG Raw Value Volts, Meditation Level, Attention Level, Delta (1 - 3Hz), Theta (4 - 7Hz), Alpha Low (8 - 9Hz), Alpha High (10 - 12Hz), Beta Low (13-17Hz), Beta High (18 - 30Hz), Gamma Low (31 - 40 Hz), and Gamma Mid (41 - 50Hz). The eegID also recorded Blink Strength used for offline correction of data affected by blink artifacts. Neurosky Mindwave chip in real-time calculated the relevant attention values once per second. The data has been stored in a *.csv file marked with the time stamp allowing easy manipulation with the existing software *(see Table 2)*.

timestampMs	eegRawValueVolts	attention	blinkStrengt	delta	theta	alphaLow	alphaHigh	betaLow	betaHigh	gammaLow	gammaMid
1500472509063	1.05E-05	**51**	66	5698	24308	10660	2614	24747	14680	3928	4082
1500472509440	1.78E-05	**56**	66	1453	10030	1720	4333	5737	1938	1482	1371
1500472510397	-2.33E-05	**44**	66	2E+07	73406	2254	8773	2780	1927	2121	759
1500472511793	1.21E-05	**50**	66	4607	4539	1070	982	4480	1559	731	224
1500472512428	1.63E-05	**41**	66	91855	12057	1179	681	2472	2323	1352	1044
1500472519470	-1.49E-04	**60**	46	54595	2E+07	1.7E+07	5158	18719	30052	10164	6738
1500472514394	2.15E-05	**64**	77	106200	2E+07	19918	6010	8360	1.7E+07	8678	7293

Table 2.- A lineout of the recorded data to depict the file structure

5.5 Results

The mean value of the EEG measured attention has been calculated per subject for each session. Only the data during the gameplay have been taken into consideration. By comparison the first and the last session, the preliminary analysis showed that the subjects had improved both in measured attention values and in their performance. To test the hypothesis, we used paired or repeated measure t-test (significance level 0.05) to compare the mean in the first and the last session. Both attention values and time are approximately normally distributed, which is visible in the plot from Figure 24.

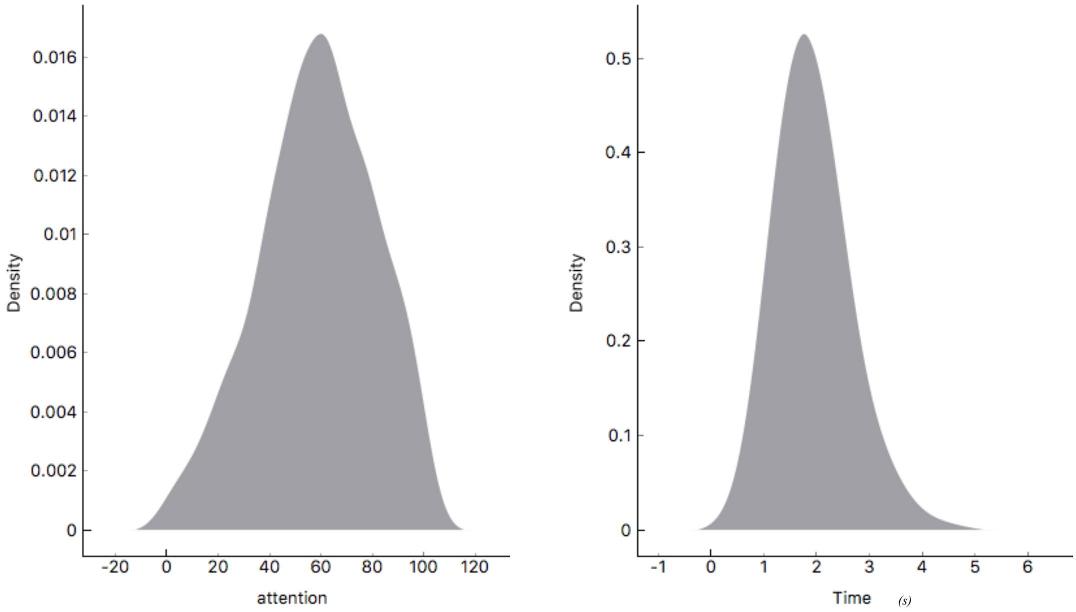

Figure 24. – Distributions of Session 1 and Session 4 joined data for attention (left) and time in seconds (right)

Using box plots, we have checked if the data contains outliers, thus making them unsuitable for the t-test. Since there were no outliers spotted, all the preconditions have been fulfilled to use this statistical method to compare the means.

Therefore, the technical form of our two hypothesis defined in the previous chapter can be expressed as follows:

H1$_{(0)}$: $\mu_{attention(session1)} = \mu_{attention(session4)}$

H1$_{(a)}$: $\mu_{attention(session1)} <> \mu_{attention(session4)}$

and

H2$_{(0)}$: $\mu_{time(session1)} = \mu_{time(session4)}$

H2$_{(a)}$: $\mu_{time(session1)} <> \mu_{time(session4)}$

In both cases, we would like to test if the mean attention and time have increased in the last session in comparison to the first one. If the mean values stayed the same, there was no effect of the NF.

		Mean (*μ*)	N	Std. Dev.	Std. Error Mean
Attention	*Session 1*	55.7250	8	5.34103	1.88834
	Session 4	59.1400	8	4.63705	1.63945
Time	*Session 1*	2.0460	8	0.38735	0.13695
	Session 4	1.8554	8	0.31456	0.11122

Table 3. - Paired Sample Statistics

The paired-samples t-test, conducted to compare attention value in the session one versus session four, shows that **there is a statically significant increase of mean EEG measured attention level in the last** *(M=59.1400, SD=4.6307)* **in comparison to the first** *(M=55.7250, SD=5.3410)* **NF session**; $t_{(7)}=-2.996$, with two tailed $p = 0.02$ *and* $\alpha=0.05$ (for more details see Table 3 and Table 5). We can reject our null $\mathbf{H1_{(0)}}$, and adopt the alternative $\mathbf{H1_{(a)}}$**.** Consequently, we can say that these results suggest that UGCI does affect the increase of measured attention.

		N	Correlation	Sig.
Attention	*Session1 & Session 4*	8	0.800	0.017
Time	*Session1 & Session 4*	8	0.802	0.017

Table 4. *- Pearson Correlation Coefficient (with a two-tailed test of significance)*

However, the paired-samples t-test, which was conducted to compare performance in the session one versus session four, shows that **there is only a marginally significant decrease in mean time (performance improvement) in the last** *(M=1.8554, SD=0.1112)* **in comparison to the first** *(M=2.0460, SD=0.13695)* **NF session**; $t_{(7)}=2.332$, with two tailed $p = 0.052$ and $\alpha=0.05$ (for more details see Table 3 and Table 5).

	Mean	Std. Dev.	Std. Error Mean	95% Conf. Interval Lower	95% Conf. Interval Upper	t	df	p
$\mu_{att.(session1)}-\mu_{att.(session4)}$	-3.41500	3.22411	1.13990	-6.11043	-0.71957	-2.996	7	**0.020**
$\mu_{t(session1)}-\mu_{t(session4)}$	0.19062	0.23124	0.08176	-0.00270	0.38395	2.332	7	**0.052**

Table 5. *- Paired Samples Hypothesis*

Observing the Pearson correlation coefficient, the results also indicate that there is a strong positive association ($r_{attenion} = 0.800$ & $r_{time}=0.802$, for more detail see Table 4) both between attention values in the first session and their pairs in the last session.

Technically speaking, the hypothesis we have tested shows that there is a significant change of the mean value for both attention and time. Observing the data, we can indeed say that there were an increase and improvement of the performance. Statistically, the significance in the case of one-tailed t-test would be $p_{attention}=0.01$ and $p_{time}=0.026$. That could sound statistically more significant, but in the one-tailed t-test it is necessary to adapt and re-estimate the alpha value, which in the end would lead to the similar findings we obtained with the t-test.

In any case what it is important is that the data show the expected trend and, hence, validate the hypothesis that both attention level and performance (measured in time) have increased.

7 Discussion

The goal of the master thesis is to present the idea of UGCI, build a prototype and give some empirical insights about the effectiveness of the device. I separated conceptual design from its implementation allowing interchangeability of the hardware and software platform in the future. Also, the clear separation allows non-technical personnel to gain insights about the concepts used to build the device. Furthermore, the thesis presents an example of a design of a modular and testable embedded system. The center of the development was also the interface design, allowing the further scalability and development of the UGCI. In the thesis, I also sought to follow the testing procedures to guarantee implementation and code quality. Finally, the effectiveness of the UGCI has been tested where its potential has been demonstrated.

7.1 Key Findings

Modeling and development of the embedded systems, such as UGCI, is a very complex process. The designer has to make sure that both hardware and software work in harmony. Apart from providing the insight in the development process, with all different stages, following the best practice of system design, it also gives the insight that NF and Brain-Computer devices can be built today even on low cost and affordable computers, such as Arduino. Apart from the system design conceptualization, I would like to present some other key insights discovered during the project realization.

Device Portability and Universality

With the UGCI we have shown that it is also possible to make portable NF devices, that does not require extensive training of the users and that work automatically without any hassle or additional configuration. Thus, it can be set up even by children, and used comfortably at their homes.

Interdisciplinary Collaborative Framework

An interdisciplinary, collaborative approach was required to plan, design, develop and verify the UGCI. Without this method, development and analysis with the aim to optimize UGCI architecture and its testability won't be possible.

Device Effectiveness

In the proof of concept study, the theoretical assumptions regarding the effectiveness of this approach have been shown. Furthermore, the study indicates that the conceptual framework and requirements defined for the UGCI game choice are valid. In other words, it shows that vehicle simulation, and in particular, car racing is effective games that can be used for ADHD NF treatment.

7.2 Limitations

From the technical perspective and, in that regard, the biggest limitation of the UGCI prototype is that it does not receive any feedback from the computer or game itself about the current situation. In other words, the UGCI is not coupled with the game dynamics, nor with the player's performance. However, to achieve this coupling, the game has to be adapted and that violetes the conceptual design of the device and its universality applied to non-dedicated ADHD games. In the further text, we present some other limitations of the system.

Recording System

Even though Neurosky(TM) Mindwave (see Figure 7) is a very portable device, some literature (Lee *et al.*, 2013; Katona *et al.*, 2014) suggests that single electrode dry EEG set is not very reliable and is very sensitive to the noise coming from the environment. Additionally, the EEG processing pipeline is realized on the closed-source chip and therefore it does not provide the insight into the internal mechanisms of the attention value calculation. Therefore, it is important to mention that the current system (UGCI) is built to fit the interface specification and also tested with this single electrode device.

Experimental Design

One might also notice that the experiment is very rudimentary and the results obtained are very questionable. Especially due to a limited number of sessions and the number of subjects participating in the study. Furthermore, the experimental design does not consider dividing participants into control and experimental group, excluding the effect of the gameplay on attention. However, it is important to understand that the focus of the thesis is design and development of the device, where the presented study serves only as a proof of concept, showing the potential of the apparatus. Designing and conducting the extensive study, including the ADHD subjects, is out of the scope of this master thesis. To alleviate the mention problems, the master thesis tried to provide a theoretical background for the implications and discuss here in detail its limitations.

Data Analysis

The used t-test is a very first step in the extended statistical analysis of data. It is a simple, but also a powerful tool for examination of the experimental sample. Even though it was a natural approach, as any other method that uses mean, a vast majority of useful information might be lost. We have seen that the standard deviation in both cases is not particularly significant. However, it would be nice to develop a different approach that will depict in more detail and explain the fluctuation of the data, that, might, in this case, have a pattern structure.

Additionally, the statistical model we used hasn't examined the trend across all sessions, and it would be nice to include such statistical analysis in the future.

Game Choice

Additional variables that can change the effectiveness of the ADHD therapy is the game choice. Despite the fact that the study provided the guidelines for the game choice, it still can not avoid the subjective interpretations of the users. Ideally, this segment can be investigated providing a more detail description of exclusion and inclusion criteria on how to chose the adequate game, and moreover, give insights on what kind of the games are the most effective. Since our proof of concept study covers car racing games, we can comfortably imply that games of this kind can be used for ADHD NF therapy.

Mapping Function Design

Usually, before NF sessions, the Quantitative EEG (qEEG) recording has been conducted. This session, also called training session, allows a system to adapt and calibrate to the physiological differences between subjects. According to the specification of the Mindwave processing unit, the deployed method has the algorithm for dynamical adaptation to the physiological diversities across subjects. In any case, the design of the recording and processing pipeline is outside the scope of the thesis, but what is in the scope is the so called mapping function. The mapping function, as explained in the implementation chapter, maps the recorded physiological measures to control signal. Since the control is not a binary phenomenon, the gradual effect is achieved using this mapping function. In the prototype design, it is being said the mapping function has been implemented and fixed. However, the conducted empirical study showed that calibration of the function per subject is in any case required. Due to physiological diversity, the dynamics and acceleration of the car were varying across subjects, but the variability stayed constant for the same subject in the consecutive session. For example, some participants were able to reach and maintain the maximum speed, while the others had a hard time even to reach it. Also, in the real-world subject need to have the possibility to play different games, and even though the principal is almost the same, the acceleration dynamics can vary, and therefore, they need to have the immediate access to configure and calibrate the device. Despite the fact that this introduces an additional variable and makes the experimental design more complex, the introduction of the calibration is required to avoid comfort reduction, since we cannot forget that the video games are fundamentally for entertainment purposes.

7.3 Future Implications

In the master thesis, I demonstrated the feasibility of the UGCI and its potential usage. During testing and evaluation, I have tried to document and present here all possible technical and operational limitations. Based on the given, the device has potential to be improved and upgraded in the future.

Testing with Different Recording Devices

It would be good to test device with different recording equipment and to avoid presented limitations of the recording device used in the proof of concept study. Perhaps, the new recording device with the improved and welcoming open-source BCI attention detection and classification algorithm could solve some of the presented issues. Perhaps, it is possible to reduce individual subject electrophysiological differences in the processing phase and keep universal the used function.

Extensive Effectiveness Study

One of the important implication for the future development of the UGCI is the extensive investigation of its effectiveness. The empirical study should involve more participants, more sessions and include experimental and control group. It would also be beneficial to include behavioral investigation and examine the congruency with the equipment used to collect measures.

Statistical Data Analysis

In the limitation chapter, I have already mentioned that the analysis of the data should be expanded to other statistical techniques. The collected data and experimental design also allow evaluation of the local NF effects, where the performance of the subject from the first and the last section of a single session can be compared. That will allow us to know if subject also improved their attention and time on the same day.

Additionally, the hypothesis can be addressed with more advanced statistical techniques, such as linear mixed model.

Development of Game Selection Framework

In the future, it would also be advantageous to classify further and review the effectiveness of presented game kinds and categories and to compile a more extensive manual for its selection.

Extension of the Feedback to the Tactile Stimulus

Initially, we have intended to include vibrotactile stimulation as a feedback path in the NF protocol. For that reason, the selected hardware was chosen to provide haptic feedback to the video game player and inform him or her about her state. The future extension with this type of stimulation would also open doors for research of NF protocols employing additional feedback strategies apart from auditory and visual ones.

Potential Treatment of Other Disorders

Additionally, the device opens a possibility for game investigation and its influence on the cognitive and emotional processing in general. With a proper game choice, the treatment can be extended to other domains where the games in combinations with NF or without shows effect.

8 Final Words

As stated in the introduction the master thesis has multiple aims. From the technical perspective, it tried to demonstrate steps in the system design necessary for a construction of a device in the interdisciplinary framework. The thesis deals with the most critical steps of the design cycle with the focus on the points that are important to achieve a good understanding of different disciplines. Additionally, from providing insights in the design practice, it also demonstrates the process of development of an innovative system using broadly available components.

Finally, the realization of the project has been followed with its testing, where the technical aspects and usability of the device has been evaluated in line with its effectiveness. With the best practice testing strategies in the embedded system design, I streamed, to my best knowledge, to ensure that the device was ready to be clinically evaluated. The small follow-up proof-of-concept study helped me to see whether I am on the right track. I have tried to mention all the noted limitations and proposed in the future implication chapter how they can improve. It is very important that the conducted study is considered only as a pilot study that indicates that the device is working and furthermore it is effective in its purpose.

9 Appendix

Code and more detailed project description available under:
https://github.com/miladinovic/UGCI
(the link is also accessible via QR code on the right)

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