Designing an Adaptive Video Game for Children with Attention Deficit Hyperactivity Disorder: Learning Proportional Reasoning through Play

by

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Declaration of Authorship

This thesis consists of material all of which I authored or co-authored: see Statement of Contributions included in the thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

Attention Deficit Hyperactivity Disorder (ADHD) is a neurodevelopmental disorder marked by symptoms of inattention and/or hyperactivity and impulsivity. Many children with ADHD suffer from poor reasoning and decision-making that impedes their readiness for learning. Proportional reasoning is an important skill in everyday decision making, and it is essential for children's academic success, which is linked to higher self-esteem, lower levels of anxiety and depression, better family and peer relationship.

Therefore, the goal of the thesis was to design an educational video game for children with ADHD that will teach them proportional reasoning through enjoyable play. The second goal of the thesis was to verify whether the designed game, which uses a low-cost mobile electroencephalogram (EEG)-based device to adapt the in-game difficulty based on players' attention, makes the learning of proportional reasoning faster through faster progression and helps players to maintain their attention span for a longer period of time.

To answer my research questions, I developed an in-game difficulty level model for the experimental game that consists of 4 designed conditions, which are a combination of the game trial win or loss with focused or not focused attention states. The faster progression is granted after at least 2 wins in the first 3 trials of the same difficulty level. To evaluate the game design and my adaptive difficulty algorithm, I performed a formal experiment. The participants (n=20), randomly assigned to two groups (ADAPTIVE and CONTROL), were asked to play the designed videos game while wearing a mobile EEG-based headset MindWave by Neurosky. During the study, I collected players' brain activity data, such as attention and meditation states, and the users' evaluations of the game experience and the difficulty of each level. I also conducted a qualitative analysis of players' in-game behavior.

The data analysis revealed a strong negative correlation between the total number of games played and the average time spent on the task in the CONTROL group, ($r(10) = -0.72$, $p = 0.02$), suggesting the presence of a learning effect that supports the ultimate goal to design a game that teaches players proportional reasoning. Although in the ADAPTIVE group we did not observe statistical difference between these parameters, the ADAPTIVE game design showed a potential to be more efficient in teaching proportional reasoning since the players were able to finish the game play in a shorter period of time having attention, meditation and flow states no different from the CONTROL group. The quantitative study findings in combination with the qualitative analysis of players' in-game behavior pointed to the necessity of the minor level design modifications that might improve the quality of game experience. Players' improved game satisfaction in combination with the already successfully implemented learning component, based on the presence of learning effect in the groups, will make the learning process an enjoyable experience.

Acknowledgement

I dedicate this work to my beloved children, Jan and Alex. You are my biggest motivators in life, my inspiration, my blessing.

It has been a period of intense learning for me, not only in the scientific arena, but also on a personal level. Therefore, I would like to extend my deepest gratitude to the people who have motivated, helped and supported me all the way through this period.

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Chapter 1

Introduction

Attention-deficit-hyperactivity disorder (ADHD) is a heritable neurodevelopmental disorder that is commonly diagnosed in childhood. According to the Canadian Attention Deficit Hyperactivity Disorder Resource Alliance (CADDRA, 2013), ADHD affects 5-12% of school-aged children and persists into adulthood in 30-50% of cases. While persons with ADHD have varying cognitive profiles, all have impaired cognitive processes. In particular, children with ADHD experience significant problems with their management of executive functions, such as difficulty staying focused and paying attention, that affects their reasoning and problem solving abilities. Consequently, children with ADHD have greater risks of low academic achievement and poor school performance, anxiety and depression, poor peer and family relations, and difficulties in adult social relationships (Anastopoulos et al., 1993).

Video games have been successfully used by scientists to help individuals with ADHD learn how to effectively manage their symptoms, develop skills, and improve their quality of life. The popularity of video game among youth inspired researchers to go beyond merely designing games for entertainment, but developing games that integrate motivational, cognitive, emotional and social domains to foster real-word psychosocial benefits and to encourage practical knowledge (Granic, Lobel, & Engels, 2014).

Thus, the ultimate goal of the thesis is to design an adaptive video game that will teach children with ADHD an essential form of mathematical reasoning – proportional reasoning – through enjoyable play. Proportional reasoning is a skill that is crucial not only for children's academic success but is also helpful in every day decision making. The secondary goal of my thesis was to verify whether using low cost EEG-based device to monitor players' attention and meditation can be effectively used to adapt the game difficulty, so that the players maintain their attention span for a longer period of time while learning proportional reasoning faster.

In order to evaluate the efficiency of the adaptive video game, I conducted a user study using a low-cost brain-computer interface (BCI) – an interface that receives, analyzes, and converts brain signals into commands – with an electroencephalogram biosensor by Neurosky. 20 participants were randomly assigned to two groups. The ADAPTIVE group played the adaptive BCI-based video game that read the brain activity profile of a player, such as attention and meditation states, and used obtained data to adapt the difficulty levels to keep the player engaged in the game. The

ADAPTIVE game design allowed participants to skip through the game trials and progress in the game faster compared to the CONTROL group based on 4 designed conditions.

The data analysis revealed a strong negative correlation between the total number of games played and the average time spent on the task in the CONTROL group, ($r(10) = -0.72$, $p = 0.02$), suggesting a presence of the learning effect and supporting the ultimate goal of the thesis to design an educational game. Although in the ADAPTIVE group we did not observe statistical difference between these parameters, the ADAPTIVE game design confirmed our expectations, based on the fact that players completed the gameplay in a shorter period of time, that proportional reasoning may be learned more quickly through adaptive progression, maintaining players' attention, meditation and flow statuses on the level with the CONTROL group.

To summarize, I designed an adaptive video game for children with ADHD to teach them proportional reasoning faster through adaptive progression. I created and tested the difficulty level methodology that incorporates 4 conditions and 3 recent trials rule, when players attention and performance statuses are used to adapt the difficulty of the game to the players' skills to maintain players' attention span for a longer period of time and to provide them with more enjoyable experience. The study revealed a possible learning effect based on the correlation between the total number of trials played and the average time spent on the task. The presence of the learning effect confirms that the educational element, in the form of proportional reasoning rules, is gradually introduced in the game play. The ADAPTIVE game design showed a potential to be more efficient in teaching proportional reasoning concept, since we did not find a difference between the attention and meditation statuses between the ADAPTIVE and the CONTROL groups, but the players of the ADAPTIVE group were able to finish the game play in a shorter period of time. The quantitative study findings in combination with the qualitative analysis of players' in-game behavior pointed to the necessity of the minor level design modifications that might improve the quality of game experience, which is an important component of the learning process incorporated into play.

1.1 Outline

To describe this thesis, I start with the literature review of the ADHD and how it affects proportional reasoning in Chapter 2. In this chapter I also discuss literature related to adaptive games and play, with examples that show how games promote improved attention in educational contexts. Chapter 3 describes the game design and its theoretical framework. Additionally, in Chapter 3, I provide the findings from the pilot that was conducted prior to the formal study. Chapter 4 details the rationale behind the study, study design and methods, and I explain how the data was collected and analyzed. Chapter 5 is focused on formal study results. In particular, I discuss how two hypotheses were addressed during the experiment, and provide a qualitative analysis of the payers' in-game behavior. Chapter 6 highlights key findings and discusses the implications of minimal design modifications on players' game experience. Finally, I talk about study contributions and directions for future research in Chapter 7.

1.2 Contributions

As a result of this master's thesis research, I made the following contributions:

1. I designed a BCI-based video game for players with ADHD, in which players' brain activity data was used to adapt the difficulty of the game to players' attention and performance statuses to improve learning and to make the game play more enjoyable,

2. I created and tested a novel difficulty progression measure. The difficulty progression is calculated based on the player's attention, and the completion results of their three previous game trials. Our method improved functionality of used in the game proportionality rules introduction recommendations by Christel et al. (2013) to enhance learning process in the ADAPTIVE game.

Chapter 2

Literature Review

Although the literature covers a wide variety of topics in the context of brain-computer interfaces (BCIs), this review will focus on the following themes: ADHD and the successful use of drug-free treatment options to improve its symptoms; the definition of BCIs and the use of EEG in BCIs; adaptive video games and neurofeedback; the definition of proportional reasoning and why this skill is important; motivation and enjoyment as cornerstones of successful learning through play.

In the first section, I describe what attention deficit hyperactivity disorder is. In the section two, literature on the use of EEG in BCIs, including human brain activity data collection using mobile EEGs is reviewed. The information discussed in this section is essential for my research in order to properly collect and analyze data. Section three examines applications of BCIs, in particular, adaptive video games and neurofeedback video games for ADHD. This part of the literature review examines the clinical and technological relevance of BCI products. In section four of the review I discuss proportional reasoning, in particular, why children with ADHD experience problems gaining this mathematical skill and how lack of this knowledge can affect other learning processes in school. The fifth section briefly examines the motivation behind playing video games or excitement behind physiological computing. I also discuss why enjoyment is an important part of successful learning process. And, finally, I summarize the reviewed literature and explain motivation behind my own research in the summary section.

2.1 Attention Deficit Hyperactivity Disorder

Attention Deficit Hyperactivity Disorder is a neurodevelopmental disorder that is usually diagnosed in childhood with symptoms, such as inattention, impulsivity and hyperactivity, often recurring in adulthood (Weiss & Hechtman, 1993). In every day life, children with ADHD understand what is expected of them but are often unable to follow through because they cannot sit still, pay attention to details, or focus on certain things (e.g. fishing, puzzle making). Although most young children act this way when they are anxious or excited, children with ADHD display symptoms over a longer period of time and in more than two settings (e.g. at home, in the schoolroom, on the playground, in the community).

Mayes and Calhoun (2006) report that 71% of children with ADHD have learning disabilities, of which 26% experience learning disabilities in mathematics. Proportional reasoning is an area where researchers (Siegler & Vago, 1978; Huizenga, Crone, & Jansen, 2007) have focused their research as it is an essential part of early mathematical skills, it is an ability to think about numbers in relative, rather than absolute terms. Combined with poor problem solving and reasoning abilities, impaired judgment of proportionality in children with ADHD can impact not only academic performance but also daily life activities in adulthood (e.g. adjusting recipes or calculating taxes). According to Kwon et al. (2000) proportional reasoning is a complex way of thinking that is influenced by many biological (e.g. working memory capacity) and environmental factors (e.g. physical experiences), however, it can be altered through training. That is, by improving proportional reasoning skill, the quality of life of children with ADHD can be improved in many ways.

The disorder usually affects the patients' lives negatively, particularly in the modern technology-driven society where a person is expected to keep pace with the advancement of knowledge and skills. However, many people with ADHD have a good attention span for tasks they find interesting. They become intrinsically motivated and start enjoying the activity. Research (Derryberry & Tucker, 1994) indicates that motivational processes employ attentional mechanisms, which are particularly unexploited in people with ADHD.

The usual intervention for managing symptoms of ADHD includes medications, such as stimulants and anti-depressants, but they provide short-term management of symptoms and do not bring benefits once the drug has been withdrawn (Swanson & Volkow, 2009). A number of studies (Lubar & Swartwood, 1995; Thompson & Thompson, 2005) confirmed that a non-medication alternative, when a person with ADHD learns to self-regulate brain wave activity in order to manage the symptoms, brings long-lasting effects (10-year follow-up). Such non-medication interventions that employ computer technology to train the brain are called neurotherapy or neurofeedback.

Scientists have conducted a number of studies (Hochberg et al., 2012) analyzing brain signals and how they can be used in computing to enable people with motor and psychological disorders to control their brain signals in order to effectively communicate with surrounding them environment. The raising interest in brain-computer interface (BCI) technology triggered a new wave of research and continue to expand into various areas of everyday life activities, for example, BCI-based video games (Krepki, Blankertz, Curio, & Müller, 2007; Pineda, Silverman, Vankov, & Hestenes, 2003; Lalor et al., 2005).

2.2 Proportional Reasoning: Learning How to Learn

Proportional reasoning is a popular topic in cognitive development. It has been investigated using different tasks such as, for example, balanced scales (Siegler & Vago, 1978). According to Siegler (1978), proportional reasoning skills require learning. Thus 10-year-old children experience difficulty inventing proportionality rules, however, children as young as 7 were found to learn these rules easily. The reason is that during the learning process children learn the relevance or importance of components in a task and its sequence or order of components. Additionally, children perform better when the tutoring process is not based on purely verbal instructions but allows children to manipulate the components of the task in order to predict answers (Kwon et al., 2000).

Students with ADHD require more time and effort to learn mathematical reasoning skills due to impaired non-verbal reasoning, attentive behavior, working memory and executive control (Zentall & Ferkis, 1993). Working memory plays an important role in the learning process as it stores information required for ongoing actions – for example, manipulations in a video game – and is related to attention and focus (Spence & Feng, 2010). Problems connected with ineffective information storage result in poor performance. Decades of research in psychology have demonstrated that many cognitive processes can be modified by training. Kwon (2000) confirmed that training which enables children to test their solutions to a problem and find them ineffective, is actually an important part of a learning process as it motivates children to look for new strategies. Therefore, this Master's project can be utilized in teaching and learning proportional reasoning skills. The users in both the ADAPTIVE game and the CONTROL group game are offered the same number of difficulty levels and tasks with different combinations of blocks in each trial. This type of training allows users to test different combinations a number of times until they grasp the concept of proportionality.

2.3 Brain-Computer Interfaces

The term "BCI" was coined by Professor Jacques Vidal (Vidal, 1973), who is widely considered as the inventor of BCIs (Miranda & Brouse, 2005). The ultimate goal of all BCIs was and is to record, analyze and translate brain wave activity. Brain wave activity can be measured using several methods, which include magnetoencephalography, functional MRI (fMRI), positron emission tomography (PET) and functional near-infrared spectroscopy (fNIRS) (Daly & Wolpaw, 2008). While most of them are not suitable for everyday use due to high costs and complex technical requirements, some of them, for example, fNIRS has smaller more portable size of equipment, compared to fMRI or PET (Ferrari & Quaresima, 2012). However, until recently, fNIRS biosensors have only been used in laboratories. It required participants to be connected to the sensor via fiber optic lines which limited the analysis and participants' mobility (Ayaz et al., 2013). The mobile battery-operated fNIRS have recently been tested by scientists, but they are not available on the market to the general population yet.

Initially, BCIs were created to enable people with severe motor impairment (e.g. people with locked-in syndrome, when a cognitively intact person cannot move or communicate verbally due to paralysis of muscles in the body) to communicate with outside environment (e.g. systems for basic word processing, operating a wheelchair or controlling television) (Lance, Kerick, Ries, Oie, & McDowell, 2012). While most existing assistive smart devices and technologies for individuals with a brain injury require at least some motor movement, BCIs decode brain activity (i.e. the goal is to understand emotions, attention state or imaginary movements), and, therefore, do not require motor output for successful use. For example, the BrainGate neural interface system, developed by Drs. Donoghue and Hatsopoulos at Brown University, enables people with tetraplegia (loss of sensation and control of nearly all voluntary muscles) to reach for and grasp objects in three-dimensional space (Donoghue, 2008).

Recently, BCIs have been used in robotic limbs (robotic prosthetics) research (Andaluz, Ortiz, & Sanchéz, 2015). Engineers at the John Hopkins University Applied Physics Lab have developed a robotic arm that has 26 degrees of freedom, can curl up to 45 pounds and is controlled with a person's brain (Burck, Bigelow, & Harshbarger, 2011). This robotic arm, known as Modular Prosthetic Limb, not only picks up brain signals but, according to Moran (2011), can potentially enable disabled people to feel some sensation.

Another important use of BCI alongside clinical applications is mentioned by Kotchetkov et al. (2010). Military training and operations are modified and optimized by neuroscientists in order to enhance performance of soldiers. For example, the Pentagon's Defense Advanced Research Projects Agency division has developed a BCI system called Silent Talk. The goal is to enable soldiers to communicate non-acoustically, without vocalization of thoughts or help of body gestures.

Next step in BCI research belongs to the usage of BCI technology in games and entertainment as it helps researchers to interpret emotional states of the player, such as motivation, flow and enjoyment, by measuring attention and meditation states. For example, Focus Pocus by Neurosky uses performance and EEG data to generate daily and end-of-training reports.

For the purpose of the experiment, I considered devices for personal use freely available on the market, such as mobile EEG-based biosensors. Therefore, in this thesis, when I discuss BCIs I actually mean EEG-based BCIs.

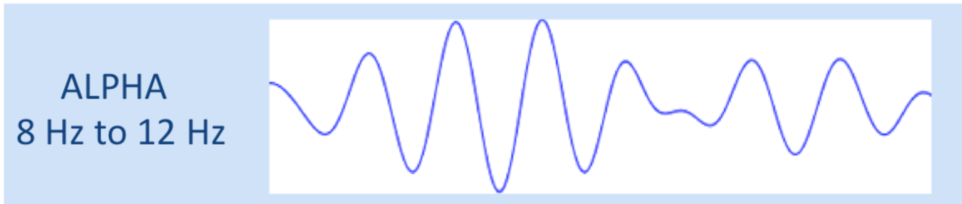

Figure 2.1: Alpha Waves

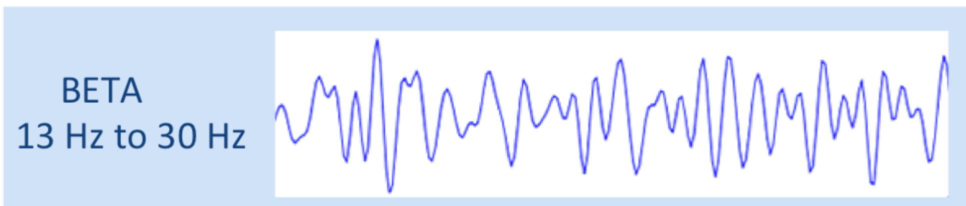

Figure 2.2: Beta Waves

2.3.1 Human Brain Activity EEG Data Collection

In the present research, we are interested in two mental states measurements, which are: attention readouts based on the beta brain wave frequency bands, and meditation readouts based on the alpha brain wave frequency bands.

- Alpha waves are slower and larger brainwaves with the frequency range from 8 Hz to 12 Hz (Figure 2.1). The posterior basic rhythm is actually slower than 8 Hz in young children (therefore technically in the theta range). It is seen normally in the posterior regions of the head on both sides, higher in amplitude on the dominant side. It emerges with closing of the eyes and with relaxation. Alpha activity has been connected to the ability to recall memories, lessened discomfort and pain, reductions in stress and anxiety. It has also been noticed in adolescents with bipolar disorder (Moeini, Khaleghi, & Mohammadi, 2015).

- Beta waves are small, faster brainwaves with frequency range above 13 Hz (Figure 2.2). Beta is seen usually on both sides in symmetrical distribution and is most evident frontally. It is associated with active, busy or anxious thinking and active concentration. Pathologically, people who lack sufficient beta activity suffer from depression, insomnia and ADHD (Egner & Gruzelier, 2004).

Neurosky eSense algorithms allow to calculate a wide range of brain waves in both time and frequency domains, summarize them and divide them into two mental states such as 'attention' with emphasis on beta waves and 'meditation' with emphasis on alpha waves. The meter values

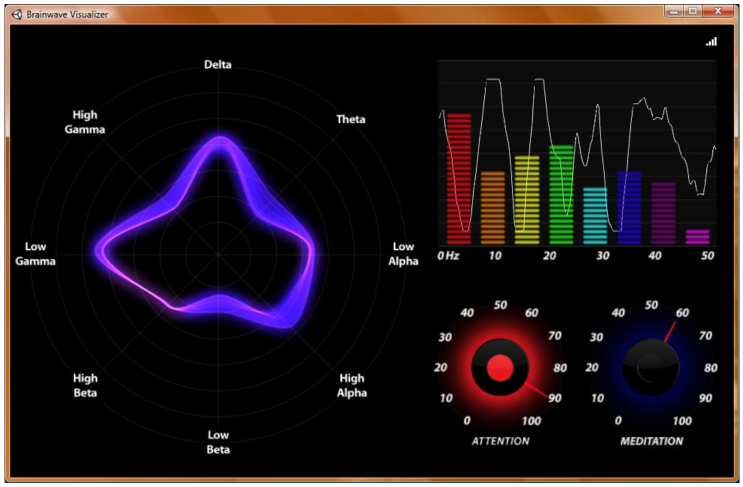

Figure 2.3: Neurosky Brainwave Visualizer

are between 1 to 100, where values between 40 to 60 are considered neutral or baseline, values between 1 to 40 show reduced levels of attention (or meditation); values from 60 to 80 and 80 to 100 show "slightly elevated" and "elevated" levels of attention (or meditation) respectively. This method of precalculating brain wave activities and assigning results into mental states can be used in BCI applications that require overall attention state during task performance to translate it into a command. For example, the difficulty level in the game can be adjusted automatically depending on the attention state of the player. Additionally, an investigator can analyze specific brain wave activity by documenting brain wave frequency bands that are shown on the monitor (Figure 2.3).

The Neurosky EEG biosensors with dry electrodes have an advantage compared to EEGs with wet electrodes, which are expensive and used only in clinical settings, as they can be used in real living environments and consumer products, and are low-cost devices.

2.4 Adaptive Video Games

It is known that video games can be powerful tools to train the brain as they improve working memory that is linked to attention and focus (Strobach, Frensch, & Schubert, 2012), in addition, video games can also be used as effective research measurement tools. According to the Vanier Institute of the Family (2013), 64% of male and 35% of female Canadians surveyed in 2013 reported that they play video games. Green and Bavelier (2003) show that video games improve players' attentional capacity, and in particular visual short-term memory and reasoning capacity. These cognitive processes play an important role in early mathematical performance in children who employ more of their prefrontal cortex (i.e the cerebral cortex that covers the front part of the frontal lobe) in math tasks.

In order to manage the user's experience during play, researchers have used different techniques, such as modification of the story line or adaptation of the game based on user-specific affections (Saari, Turpeinen, Kuikkaniemi, Kosunen, & Ravaja, 2009). For example, in first person shooter games the adaption is based upon the user's performance in games by increasing or decreasing the number of enemies. As the assumptions are based on a user's performance they are unable to depict the actual user state, and, consequently, may lead to misinterpretation of user skills, emotions and immersion in the game.

The use of biosensors in video games allows estimations of in-game experience through, for example, brain activity, respiration (Benovoy, Cooperstock, & Deitcher, 2008), heart rate (Picard, Vyzas, & Healey, 2001), electrodermal activity (electrical characteristics of the skin) (Nacke, Kalyn, Lough, & Mandryk, 2011). While physiological biosensors are subject to many factors, such as caffeine or exercise, which influence the quality of the signals, brain-computer interfaces are able to read cognitive states and even distinguish between the states (Bos et al., 2010) with reported accuracy 89-92% (Mikołajewska et al., 2014). According to Chanel (2006), electroencephalograms can provide more reliable data about the user's experience when measurements are interpreted in combination with data received from other physiological biosensor.

The challenge for BCIs comes from naturally occurring mixed emotions the user experiences while playing video games when the content of the game can, on one hand, provide relaxation, on the other hand, can become frustrating when the player cannot overcome obstacles to progress in the game (Bos et al., 2010). Video games generate different kind of emotions, such as, boredom, anxiety, engagement, arousal. The balance between these emotions, according to the flow theory (Csikszentmihalyi, 1991), can be achieved when the skills of the player meet the challenge in the game. The EEG allows researchers collect data (e.g. attention and meditation states) that reveals emotional experiences of the user at every stage of the game and adapt the game depending on that data. The data is considered to be more robust and reliable compared to self-reports in questionnaires or interviews (Mandryk, Inkpen, & Calvert, 2006).

While traditionally BCI-based video games use EEG as an additional input device (Figure 2.4), adaptive games employ data received from EEG to manipulate the player's engagement. The difficulty of the task in such games may depend on the player's attention level. Although both applications of EEG have demonstrated effective control and manipulation of brain activity, there is a number of technical issues with EEG usage in video games as an input device. The main problem of brain-computer interfaces is that transmission latency makes it difficult to adapt

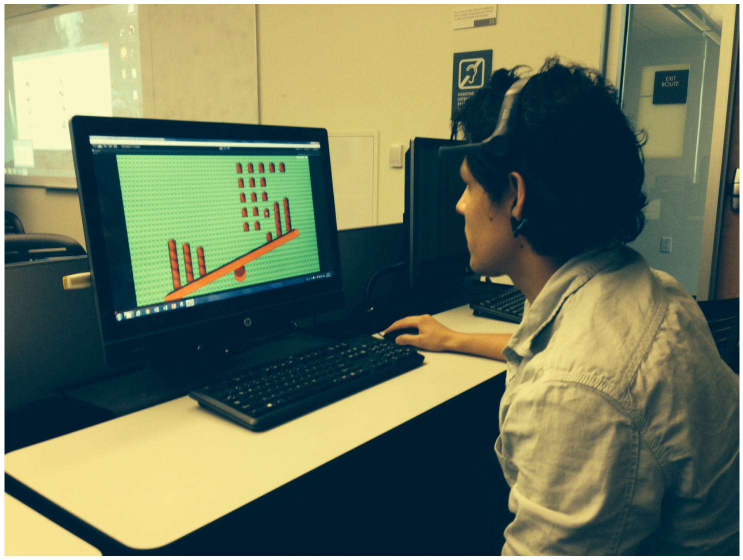

Figure 2.4: BCI-based Video Game

them to a game environment, where reaction time is usually very low. Fast-paced games require quick response, and an in-game latency of more than 100 milliseconds can be frustrating for the player (Pantel & Wolf, 2002). Whereas adaptive games do not depend on the speed of data transmission but on the characteristics of such data over a period of time to create a quick image of the attention state of the user. When the goal of the brain-controlled video games is to teach user how to control the game, the goal of the adaptive game is to learn how to control the player (i.e. to control user's state of flow) (Saari et al., 2009). For example, most recent research by Anguera et al. (2017) showed the benefit of playing adaptive video games as a part of attention interventions in children with sensory processing disorder and ADHD.

Another example of the successful manipulation of brain activity is called neurofeedback. EEG biofeedback or neurofeedback was popularized in the 1960s, and since the 1970s neurofeedback has been employed as a non-invasive treatment for children with ADHD. The neurofeedback treatment protocols for people with ADHD usually target cortical regions responsible for attention and behavioral inhibition, so that they can learn how to self-regulate brain activity effectively and avoid ADHD symptom exacerbations (Monastra et al., 2005). Rossiter and LaVaque (1995) suggest that EEG biofeedback programs are an effective alternative to medications, especially in cases where the person experiences side effects from stimulants. Researchers (Arns, de Ridder, Strehl, Breteler, & Coenen, 2009; Steiner, Frenette, Rene, Brennan, & Perrin, 2014) have demonstrated improvements in executive functions and non-verbal intelligence (i.e. the ability to analyze information and solve problems using visual, non-verbal reasoning) in chil-

Figure 2.5: NeuroSky MindWave Headset

dren with ADHD after neurofeedback sessions. Although various opinions about the long-term effectiveness of neurofeedback for children with ADHD exist in the scientific world (Vollebregt, van Dongen-Boomsma, Buitelaar, & Slaats-Willemse, 2013), researchers agree that neurofeedback is a minimal risk procedure and is attractive to children as they regard it as some kind of a game (Gevensleben et al., 2014).

A rising interest in brain-controlled interfaces has been observed in recent years. The complexity of ADHD has been a driving force for researchers and practitioners in the search for alternative treatments. A number of medical, research and commercial games have been designed to investigate the effectiveness of brain-controlled interfaces. Neurofeedback experiments with various game consoles such as Nintendo and PlayStation, have been conducted using existing video games (e.g. Spyro the Dragon) (Pope & Palsson, 2001). Motor imagery research applications have been used in Pacman (Krepki et al., 2007), Second Life, First-Person Shooter game (Pineda et al., 2003), and MindBalance game (Lalor et al., 2005). Large software companies (e.g. Microsoft), console game companies (e.g. Nintendo) and specialized companies (e.g. Neurosky) that produce low-cost EEGs (Figure 2.5) have developed neurofeedback-modulated games (e.g. Arena by Emotiv) that are interesting and challenging enough for a player to be motivated to play on a frequent basis.

It is presumed, based on the literature reviewed earlier (Bos et al., 2010; Saari et al., 2009), that the designed EEG-based ADAPTIVE game can keep the user immersed in the game as the difficulty level adjustment is done using psychophysiological measurements of the player.

2.5 Motivation

Video games have been a useful tool for researchers in the HCI field in investigating advantages and disadvantages of physiological computing (i.e. the use of real-time biosignals to interface with a computer (Fairclough, 2011)). Nacke et al. (2011) suggests that the overall experience of playing video games is more enjoyable when there is a combination of traditional game controls with physiological controls (e.g. a respiration sensor to measure breathing rate and volume). This is because players feel as though they are physically a part of the game, and therefore are more in control of the game. Additionally, players become intrinsically motivated to play such games.

Completely focused motivation of intrinsically motivated people (i.e. Flow Theory) is an important component of enjoyable and successful gameplay (Csikszentmihalyi & LeFevre, 1989). According to Watson et al. (2013), players are more likely to benefit from games when the game supports autonomy (i.e. the game is fun and a player voluntarily plays over and over again), competence (i.e. a player is challenged in the game gradually, which allows the player to acquire the necessary skills), and relatedness (i.e. a player feels connected with other players). The idea is to integrate motivation into the process by designing a software that is first fun to play and then fun to learn new skills (Denis & Jouvelot, 2005). The difficulty level in the game should adapt to the player's skill and performance to avoid boredom or frustration. For enjoyable game play, the difficulty level should be adjusted automatically based on the quality of task performance (e.g. task completion time, number of attempts, etc.). For example, Hamlet system uses statistical metrics to analyze incoming game data and estimate the player's future state from this data (Hunicke & Chapman, 2004). Such systems allow researchers to detect certain behaviours that prevent players from progressing in the game and adjust the game when necessary in order to keep the player immersed in the game. All of it suggests that there is an opportunity to help people with ADHD to learn new skills through play by designing an adaptive video game.

2.6 Summary and Implication

Attention Deficit Hyperactivity Disorder can be successfully managed without medications, and my research addresses the non-pharmacological symptoms management approach by designing the video game that uses brain signals to adapt to the player's levels of attention and meditation. This game is also a clinically relevant product as it teaches children with ADHD new skills, such as proportional reasoning. Children enjoy playtime since early age as it helps them to learn about the world around them. We used this notion to inform the design of the game, and created a video game that is Lego-based. We expect that the popularity of Lego blocks will be one of the factors behind motivation to play the game. Also, we expect participants to enjoy the process of playing as the difficulty levels adapt to the players' performance.

The customization of healthcare and education is certain and adaptive technologies, which are tailored to a particular user, will play an important role in this process. Such technologies will become essential for users suffering from psychological disorders, such as ADHD, when each subject has a different cognitive profile. The examined literature supports the idea of personalization of care in order to achieve significant long-term results. Rapid and continuous research growth in the area of physiological computing in the last twenty years reveals that ever-changing technologies are getting successfully employed by scientists not only as diagnostic tools but as treatment tools. As the focus of the thesis is on the development and validation of an adaptive video game for children with ADHD, all of these motivate my own research, and, I anticipate that the designed video game will play an important role in therapeutic and learning support.

Chapter 3

Game Design

While working on my adaptive video game design, my goal was to create a game that addresses multidimensionality of ADHD symptoms. I wanted the game interface and game mechanics to be familiar to players, so that they could intuitively know what to do. The educational element of the game in the form of proportional reasoning tasks supports and develops intuitive approach to a trial completion. The choice of Lego theme was also motivated by the fact that building with lego blocks develops creativity and encourages children to experiment with blocks independently. The lego-based learning also helps children to learn different concepts, such as shapes, sizes and numbers. The choice of colors in the game was also an important consideration, since I wanted to avoid visual overstimulation in children with ADHD, who are at risk of sensory overload.

Thus, the first thing the player is offered on the screen after they chose the game to play is a balance scale that represents of itself a made of lego blocks bridge over river that connects two highways. There are 5 positions on each side of the bridge with spare single Lego blocks resting on the Lego platform near the deck of the bridge. The spare blocks on the platform are of green color but the block changes color to yellow when the participant points with the cursor to it, and it changes color to gray once the block is dropped on the position on the bridge (Figure 3.1). The example combination of blocks is offered on the left side of the bridge. The participant's goal is to balance the bridge for the cars to cross it.

Interaction design of our experimental video game is based on concepts most children are already familiar with: "choose a lego block" and "put the lego block on top of another block" in order to "balance the bridge". The player uses the spare blocks by pointing at the block with the mouse and dragging it to a position on the right side of the bridge in order to balance it. The weight of each block is the same.

Each trial is worth 10 points. The maximum number of points the user can get in one level is 50 points. The 100 collected points give the user a mirror that can be used once (in one trial) and in more difficult levels where mirroring is blocked (levels 5,6 and 7). The number of collected throughout the game mirror powers can be seen at the top of the screen right above the bridge. The icon is clickable and the players can use collected mirror powers as soon as they reach the level 5. The red light pointing to the position on the bridge that is blocked (only one position can be blocked at a time) will disappear when the mirror power is used and the player can continue

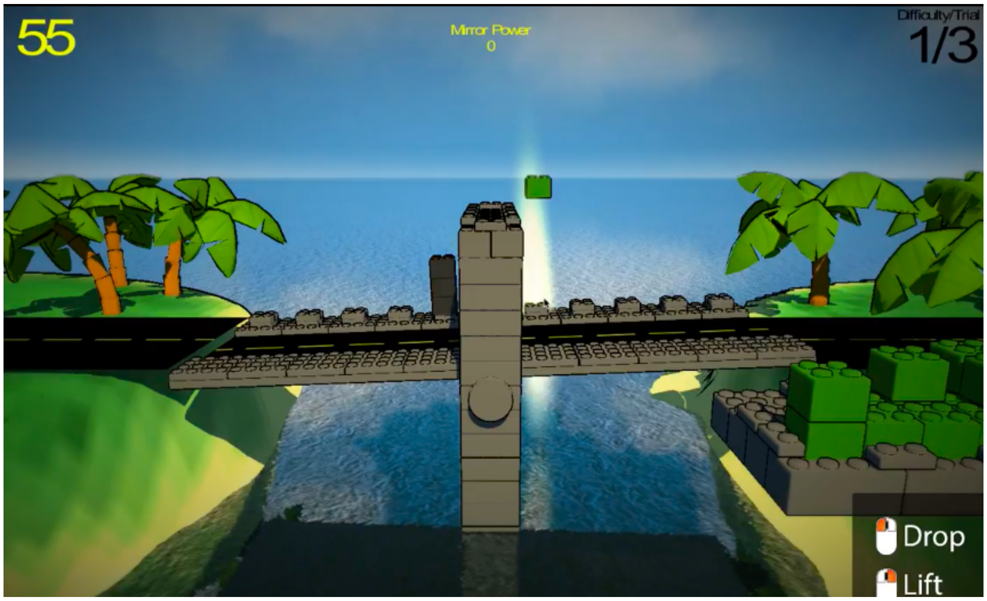

Figure 3.1: A screenshot of the game interface design

balancing the bridge. If the player failed to balance the bridge, the right number of blocks will fall on the right side of the bridge to show the player how the bridge could have been balanced in that trial.

The game trial is timed out at 60 seconds. The time conveniently counts down, so that the player does not spend time on calculating the remaining time. The timer is displayed at the top-left corner of the screen; the difficulty and trial numbers are at the top-right corner; the MindWave headset connection indicator (green color indicates connected, grey indicates no signal) is in the upper right hand corner, and the Neurosky attention and meditation (i.e stress or relaxation levels) amplifier fluctuating measurements are at the bottom-left corner of the screen.

The participant in both groups were expected to play maximum 35 trials: 5 trials per each 7 levels of difficulty. Trials within each difficulty level were assigned conditions, which are outlined in the Table 3.1, based on the prior research in user experience design in educational games (Christel et al., 2013).

While the players of the CONTROL group were supposed to play all 35 trials, the ADAPTIVE game design allowed participants to skip through the game trials and progress in the game faster compared to the CONTROL group based on their attention statuses and the trial completion status. Thus, the completion status is either ‘win’, meaning the player balanced the bridge within 60 seconds of the play time, or the completion status is ‘loss’ when the player was unable to

Table 3.1: Description of the order of trials within each difficulty level

Level	Mirroring	Description of Tasks within Level
L1	Yes	Distance constant; weight varies
L2	Yes	Weight on the left constant, distance varies, single items
L3	Yes	Weight constant, distance varies, may have multiple blocks on a single scale
L4	Yes	Weight and distance vary, may have multiple blocks on multiple scale positions
L5	No	Weight and distance vary, some positions blocked out so mirrored solution not possible
L6	No	Weight and distance vary, bigger sums of weights at different distances
L7	No	Challenge problems, blocks placed on both sides of scale fulcrum

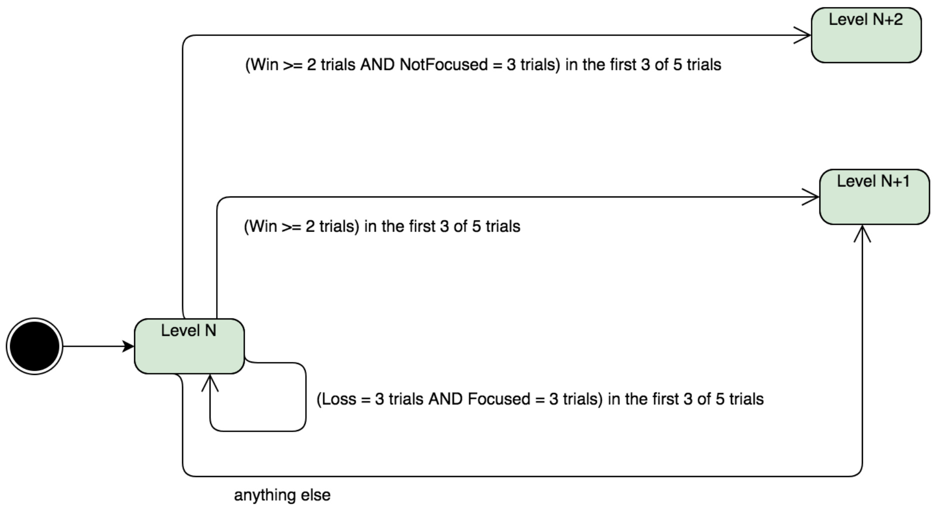

Figure 3.2: Adaptive Difficulty Level Model Diagram

balance the bridge within the given time slot. The player is supposed to win at least 2 out of 3 consecutive trials of the same level, however, in order to progress in the adaptive game the conditions described below should be satisfied. The participants in the CONTROL group played a video game with set number of trials regardless changes in attention measurements. The Neurosky MindWave headset meter was recording attention values between 1 to 100. All participants were required to rate the difficulty of the task played at the end of each trial. Also, the players were asked to fill out the Flow Questionnaire about their game experience right after finishing the game play.

The ADAPTIVE game faster progression conditions are the following (Figure 3.2):

1. Focused and winning (F/W) → go level up or progress to the next difficulty level

   If the average Neurosky meter values during time play were 60 or more and the participant balanced the bridge within the available 60 seconds time play at least two times out of three consequent trials, this is considered a F/W situation that is counted toward fastest progression.

2. Focused and losing (F/L) → the player will be shown an example 'how to balance' video and will be asked to finish playing the level.

If the average Neurosky meter values during time play were 60 or more but the participant was unable to balance the bridge within the available 60 sec time play two times out of three consequent trials, this is considered a F/L situation and is not counted toward fastest progression. The player have to play trials 4 and 5 of the same difficulty level before progression to the next level.

3. Not focused and winning (NF/W) → go two levels up or skip one difficulty level

   If the average Neurosky meter values during time play were less than 60 but the participant balanced the bridge within the available 60 sec time play at least two times out of three consequent trials, this is considered a NF/W situation that is counted toward fastest progression.

4. Not focused and losing (NF/L) → repeat the level

   If the average Neurosky meter values during time play were less than 60 and the participant was unable to balance the bridge within the available 60 sec time play three consequent trials, this is considered a NF/L situation and is not counted toward fastest progression. The player is asked to repeat the level after three trials.

The versions of the game in the ADAPTIVE (experimental game) and in the CONTROL groups are almost identical with only difference of the minimum number of trials a player can play. Thus, the participants in the experimental group were able to progress to the next difficulty level faster after successfully balancing the bridge 3 consecutive times. The experiment was created using design elements from placebo-controlled studies in order for the author to see which version of the game is more enjoyable, and, therefore, more likely to benefit children with ADHD.

3.1 Design Evaluation Framework

In order to design a video game that addresses different dimensions of ADHD, the Research Domain Criteria (RDoC) has been used to account for six major domains affected by the disorder (Benyakorn, Riley, Calub, & Schweitzer, 2016). The six domains are:

1. Reward-related processing. Children with ADHD have impaired reward-related processing in the brain and it is reflected in their motivation. In order to reinforce motivation in such players, we incorporated reward elements called 'mirrors' in the video game. The players are getting mirrors (i.e. rewards) each time they manage to balance the bridge within the time limit using different combination of blocks on the right side of the bridge.

2. Inhibition. Children with ADHD experience problems to tune out irrelevant stimuli, such as extensive sounds or idle animation, while continuing to be focused on the task. Thus, there is no unexpected sound effects in our video game, and each interactive game element is a part of the game task.

3. Sustained attention. The ultimate goal of the experiment is to keep the player focused on the task for as long period of time as possible within the given play time. The use of the EEG-based headset MindWave by Neurosky provides information about the player's attention state translated into attention meter values, which are used to adjust the difficulty of game trials to maintain the player's attention.

4. Timing. Individuals with ADHD have impaired time management skills. In other words, children with ADHD experience distorted perception of time. They easily lose interest in the activity without time frames. In our experiment, each trial has a set period of time, 60 seconds (displayed in the upper left hand corner of the game), during which the player is expected to complete the task. Also, the player is aware that the game consists of 7 difficulty levels 5 trials each. The trial and difficulty level is displayed at the top-right corner of the game, so the player knows what to expect from the game for the next while without constant time monitoring.

5. Arousal. ADHD is characterized by the spectrum of symptoms. Since some children have a combination of symptoms (e.g. a hyperactive child without attention deficit or hypoactive child with attention deficit), in our game design we tried to account for this specificity of the disorder by using color psychology (Gaines & Curry, 2011). Thus, there are three prevailing colors in our game interface, such as green, blue and gray. Blue color enhances creativity while stimulating a relaxing environment. Green is a color of relaxation, and is a good contributor to mental stability in children with ADHD. Grey color is considered a neutral, balanced, emotionless, moody color. Grey color can evoke different mood shift when used in combination with other colors.

6. Emotional lability. Emotional lability in children with ADHD affects reasoning and decision making processes. The choice of the type of the game – proportional reasoning game – was not only motivated by the fact that such games teach important reasoning concepts used in a wide range of topics in school (e.g. algebra, geometry) and in everyday day life (e.g. mix cooking ingredients, money exchange), but also by the fact that they stimulate intuitive cognition (Ben-Chaim, Keret, & Ilany, 2012) that is important in decision making.

3.2 Pilot Study

The purpose of this pilot was to verify functionality of our sum-of-blocks difficulty level model and to identify potential problems before formal study was conducted.

3.2.1 Method

This pilot study was conducted to investigate if there is a correlation between the time spent on the task, the average readout of attention state, the sum of blocks used in the task. The participants played the first version of the game without structured difficulty levels but with random number of blocks on the left scale in each trial. The goal was to test the game and the device prior to the formal study. The results have been analyzed using t-tests. All the statistical analyses were conducted using Microsoft Excel and SPSS.

3.2.2 Results

There were 7 participants aged 19 to 22 years (M=20.57, SD=1.13). The pilot results showed a moderate correlation between the sum of blocks and the attention readout for positive (successful) trials, ($r_{35} = 0.49, p < 0.002$); and, for negative trials, ($r_{15} = 0.5, p < 0.04$). There was also a moderate correlation between the completion time and the attention readout for negative (unsuccessful) trials, ($r_{15} = 0.52, p < 0.03$).

The results of the pilot also confirmed my assumption that defined trial difficulty levels together with a subjective evaluation questioner after each trial, which were not implemented at the time of the pilot study, will not only provide additional information about the task but assist in results interpretation. For example, if the difficulty of the task depends on the sum of blocks on the left (i.e. the bigger the sum the more difficult the trial is) then the increased attention state can be explained by the increased difficulty level in the game.

Chapter 4

Study Design and Methods

The Lego balanced bridge BCI-based video game has been designed to teach children proportional reasoning. The video game is inspired by the real Lego game and incorporates some key concepts to address the development of proportional reasoning.

4.1 Participants and Recruitment Process

Our experimental single player BCI-based video game is created for adolescents aged 10 to 12 years, both female and male, who have Attention Deficit Hyperactivity Disorder. Prior to study being advertised, the author prepared and submitted the ethics application to the Office of Research Ethics Committee. Following the ethics approval, the participants hiring process began. The experiment was advertised in the primary care physician offices, among students of the local colleges, and in social media groups, such as Monterey County Families, Monterey Bay Homeschool Coop, and others. The author also advertised the study during the support group meeting in Monterey for families with children with ADHD, organized by Children and Adults with Attention-Deficit/Hyperactivity Disorder (CHADD) Northern California organization. The study was also advertised in the non-profit, high-tech training and collaboration space for young people under 24 years of age called Digital Nest. Twenty participants were hired by the author in person. The details of the experiment were explained to the participants, and they were provided with the study package, which included the information letter (Appendix A), the consent to participate form (Appendix C), the demographic questionnaire (Appendix B), and the Flow questionnaire. The interested in the experiment participants were informed about the date and time of the game usability testing.

4.2 Apparatus

The game was played on a computer with a mouse used as the game controller. The physiological data (i.e. brain activity data) was collected using a mobile electroencephalogram called Neurosky

MindWave headset. The data from the EEG device was sent over Bluetooth to the computer and recorded.

4.2.1 Rationale Behind the EEG Choice

I was looking for a mobile EEG that would be characterized as:

1. Accessible. The device should have unassisted access. I excluded from consideration EEGs with wet electrodes because the placement of electrodes on a player requires assistance and cannot be used independently by a child.
2. Cost-beneficial. The device is affordable for families on a budget, and the health benefits from the device outweigh its cost.

Although there are many mobile EEG devices on the market, the Neurosky MindWave headset satisfies both conditions. The price of the device is \$119 CAD (compared to the \$400 CAD Emotiv Insight), and it has one dry EEG electrode, so the headset can easily be put on by a player without a help from a parent.

4.3 Objective

The main objective of the thesis is to conduct a study with human participants, in a real-life setting, playing the designed adaptive video game to verify whether the experimental game is faster in teaching proportional reasoning while keeping the players' attention span for a longer period of time compared to the non-adaptive video game. Our goal is to collect data before and after the experiment to understand participants' opinions on game design and hardware, and to determine whether the adaptive game play is more enjoyable compared to the non-adaptive game play.

4.4 Hypotheses

The following hypotheses will be tested:

1. Players of the ADAPTIVE game will maintain their attention span for a longer period of time while progressing faster through the game levels compared to the control group,

2. Players of the ADAPTIVE game will enjoy the game play more compared to the CONTROL group.

4.5 Data Collection and Analysis

We were interested in collecting the following data:

1. Attention and meditation measurements over 60 seconds trial play time. This data provides understanding about the amount of mental effort the player puts into the game play, in particular, task completion. Based on the attention measurements we were able to adapt the game to the player's skills (i.e. the difficulty of the subsequent trial depended on the recorded attention data and completion status). The meditation measurements gave us an idea about the stress levels of the experimental game players and the control game players. Both of these measurements also allowed us to improve the game after running the pilot study.

2. Level completion status (i.e. success or failure in the task completion). This data in combination with attention measurements allowed us to determine whether the player should progress in the game by playing more difficult tasks or she should continue practicing tasks of the same level.

3. Duration of task play. Research (Csikszentmihalyi, 1991) suggests that 60 seconds time slot is an optimal duration of a task for young learners because the children's perception of the task completion is within their reach. Consequently, it motivates kids to play over and over again.

4. Sum of weights on the left scale. Since the game's difficulty levels were made of combinations of sum of blocks and conditions assigned to that particular level (Table 3.1). Our assumption based on the pilot study results was the bigger the sum of blocks the more difficult balancing process is considered.

Each participant was asked to star rate the difficulty of the trial. The color of each star represents difficulty of a task (Figure 4.1). After the game play, the players were asked to answer the questions in the post-game flow questionnaire to measure their enjoyment experience. Flow is an optimal mental state of a player when the player is focused (attention readouts), not stressed (meditation readouts) and optimally challenged (level difficulty and flow scores). The flow questionnaire consists of 6 components (Appendix D) and it is based on the previous research by

Figure 4.1: Visual representation of the trial difficulty evaluation

IJsselsteijn et. al (IJsselsteijn, de Kort, & Poels, 2013). Each answer in the questionnaire is assigned a score, the total component scores were computed as the average value of its items.

In our experiment, the combination of brain waves data was converted into two – attention and meditation – measurements by Neurosky pre-built algorithms called eSense. The following two eSense algorithms were used: the attention meter data that indicates the intensity of mental focus or attention, and the meditation meter data that indicates the level of mental relaxation. The attention and the meditation values range from 0 to 100. When the user is focused on the task the meter values go up to over 60 indicating increased attention state. The increased meditation levels indicate that user is not stressed and is effectively relaxing the mind.

Finally, we used t-test to analyze collected data to compare means of attention, meditation, sum of blocks, task completion time and flow questionnaire scores of the ADAPTIVE game group to the CONTROL group. We also analyzed relationships between parameters using correlation and linear regression tests.

The players of the ADAPTIVE video game by design are expected to play less trials compared to the CONTROL group. To account for this fact as potentially a confounding factor, we additionally analyzed attention, meditation and average time per trial cutting off data on the trial number 12 for all players in both groups.

4.6 Method

The study was conducted to investigate whether the ADAPTIVE game teaches proportional reasoning faster than the regular video game based on time per trial over the game play and the in-game attention readouts as measured by the Neurosky MindWave mobile EEG. We also evaluated whether the players enjoyed the ADAPTIVE video game more compared to the CONTROL group based on their in-game meditation readouts as measured by the Neurosky MindWave mobile EEG, and the subjective evaluation provided by the participants in the form of Flow questionnaires.

4.7 Participants

There was a random sample of 20 participants aged 19 to 29 years (n=20, M=22.35, SD=2.43). Six participants aged 19 to 29 years (n=6, M=23.33, SD=3.39) declared in the demographic questionnaire that they were diagnosed with ADHD. One of the six participants with ADHD aged 25 years is taking medications to manage symptoms. There was also a participant whose official diagnosis is still to be confirmed by a psychiatrist. The participant has already booked an appointment. These participants' data was analyzed both with participants without ADHD, and separately. Additionally, there were two participants in the sample with Autism Spectrum Disorder (ASD). Their data was analyzed with other participants, including participants with ADHD, and we also analyzed data excluding participants with ASD from the sample.

All of the participants are undergraduate students, the demographic questionnaire data is summarized in the Table 4.1.

4.8 Experimental Procedure

First, I explained the procedure (Appendix B) of the study to the participants. I also made sure participants consented to participate. Prior to the game play, each participant was asked to fill out the demographic questionnaire (Appendix C). The participant was also reminded about the main principals of the game, and I made sure the mobile EEG device is properly placed on the head of the participant and is connected to the computer. Then, I opened the video game on the computer. The first thing the player saw on the screen was the start menu with the choice of two games, Game A and Game B. I advised the player what game to choose. The player then selected either A or B game on the screen using the mouse as a controller.The experiment was estimated to take thirty five minutes.

At the beginning of the experiment, the participants were briefed about the experiment, and a short demonstration of the game was performed. The main content of the game, starting with the choice of the ADAPTIVE or CONTROL game, was displayed on the computer screen with a mouse connected to the computer and used as a game controller. The participants were randomly assigned to the ADAPTIVE group or the CONTROL group. Then, a participant was seated in a

Table 4.1: Demographic Questionnaire - Data Summary

ADAPTIVE	Age	Gender	L/R handed	Diagnosis	Medication
A1	22	male	R	No	n/a
A2	23	male	R	No	n/a
A3	22	female	R	No	n/a
A4	21	male	R	No	n/a
A5	22	male	R	No	n/a
A6	25	male	R	Yes	Yes
A7	21	other	R	No/ASD	n/a
A8	22	male	R	Yes	No
A9	23	male	R	Yes	No
A10	24	male	R	No	n/a
CONTROL	**Age**	**Gender**	**L/R handed**	**Diagnosis**	**Medication**
B1	22	female	L	Yes	No
B2	21	female	R	No	n/a
B3	22	male	R	No	n/a
B4	21	male	R	No	n/a
B5	19	male	R	No	n/a
B6	29	male	R	Yes	No
B7	19	male	R	Yes	No
B8	26	male	R	No	n/a
B9	19	female	R	No	n/a
B10	24	female	R	No/ASD	n/a

Figure 4.2: A study participant is playing the game

chair in front of the computer. The mobile EEG-based headset (MindWave by Neurosky) with one electrode was placed on the participant's head. The headset's electrode was disinfected with an alcohol wipe prior to be put on the participant's head, and after each participant. The investigator then made sure the electrode is in proper contact with the forehead skin, and the ground-reference ear clip is properly placed on the earlobe of the participant. After the headset is in place, the investigator made sure the device is connected to the computer and the game to enable recording of brain activity. The participant then starts playing the game, beginning with the practice mode and transitioning into the experiment mode(Figure 4.2).

Chapter 5

Study Results

Generally, the study performed as expected confirming the educational aspect of the game play based on the observed learning effect in the CONTROL group ($r_{10} = -0.72, p < 0.02$). Overall, the average number of games each participant played throughout the experiment, including practices, was 29.15 (SD=10.68) with in average 15.66 seconds (SD=4.31) spent on each game completion. Specifically, in the ADAPTIVE group, participants played 19.5 games (SD=5.04) and spent 16.38 seconds (SD=4.29) on the task completion; and in the CONTROL group the average number of games was 38.8 (SD=2.94) with 14.94 seconds (SD=4.43) spent on the trial completion.

The game rules also appeared to be clear. That was supported by the participants' feedback that the game mechanics are easy to perceive and interact with, and they intuitively knew what to do. The slightly elevated average attention across groups (M=61.52, SD=8.33) in combination with players' average flow scores (M=2.38, SD=0.97) confirmed the players' positive feedback about the game.

In order to test hypotheses, we recorded and analyzed the data for 20 participants provided in the Table 5.1.

Two hypotheses were tested in the thesis. Two versions of related to hypotheses data analysis are used here. First, I examined all collected throughout the game play attention, meditation, and sum of blocks data. Second, since the players of the ADAPTIVE game by design were expected to play fewer trials compared to the CONTROL group, we decided to examine attention, meditation, and average time per trial cutting off data on the trial number 12 for all players in both groups. The choice of the cut-off trial number is based on the total minimum number of games (excluding practice trials) played by the players.

In addition to two hypotheses, and having players with ADHD in the sample, I analyzed their data separately from participants without the diagnosis. The reason we wanted to examine their data separately is that people with ADHD have altered reward-related neural processing that could result in the data differing significantly from data of participants without ADHD. Specifically, I expected the evaluations provided by the player, such as star ratings of the trial difficulty and the game experience scores, to be different in participants with ADHD because their tend to process information with high emotions.

Table 5.1: ADAPTIVE group and CONTROL group - Data Summary

ADAPTIVE	Attention	Meditation	Sum of Blocks	Rating	Flow Score	Total Trials	Time	Total Time
A1	66.39	53.33	23.29	1.95	3.4	23	17.77	168.53
A2	67.03	61.92	25.61	1.89	2.4	20	16.12	119.28
A3	63.34	60.75	25.22	2.94	1.8	22	22.33	175.81
A4	45.91	60.59	24.83	2	1.8	13	18.08	95.06
A5	57.36	64.44	18.58	1.92	2.2	13	14.28	67.14
A6	52.94	64.94	24.42	2.33	2.4	14	18	81.3
A7	60.71	62.85	23.6	1.13	2	21	13.72	77.14
A8	77.58	64.08	22.76	1.1	0.8	29	10.19	80.14
A9	67.03	57.71	20.61	2.17	3.6	21	14.91	105.98
A10	68.82	58.51	16.8	2.33	1	19	8.95	58.69
CONTROL	Attention	Meditation	Sum of Blocks	Rating	Flow Score	Total Trials	Time	Total Time
B1	59.55	45.46	23.91	2.66	3.6	41	11.86	156.87
B2	56.16	58.52	23.83	1.43	2.8	39	15.3	192.13
B3	73.97	57.42	23.46	2.66	2.6	38	14.39	188.09
B4	70.29	68.2	23.63	1	0.4	43	12.22	161.4
B5	53.27	43.91	23.71	2	1.8	38	11.78	160.45
B6	61.04	45.74	23.66	1.94	2.6	36	11.61	163
B7	67.64	61.27	23.63	1	2	44	9.77	123.06
B8	53.22	59.98	23.94	2.2	3.6	36	18.46	267.52
B9	58.26	58.33	24.03	1.71	3.8	37	22.91	275.54
B10	49.97	59.04	23.54	3.54	3	36	17.85	248.46

The following statistical symbols are used throughout this chapter: M = mean, n = sample size, p = probability value, r = correlation coefficient, SD = standard deviation, s^2 = standard error of differences, t = t-test statistic.

5.1 Qualitative Analysis

The presence of diverse group of participants in the study motivated this qualitative assessment of the experiment, evaluations, and players themselves. The information provided here rather speculative since no interviews or formal discussion with players were conducted. This section of the study results is based on observations, flow score questionnaire analysis, and players' comments interpretation.

The sample of participants consisted of 5 female players, 14 male players, and one player categorized (by the participant) as other. Among them, 4 female players were in the CONTROL group, one female and one other players were in the ADAPTIVE group. As our educational game is designed for players of all genders, in the present study we did not control the sample of participants for gender. Although some researchers (Piaw, 2014) argue there might be a difference in attention between the genders with male participants being less able to pay attention to learning stimuli compared to female.

In general, participants were trying to be focused solely on the game play. This observation is supported by the fact that none of twenty participants said in the flow questionnaire that they were "not at all" concentrated. In fact, 19 participants evaluated their in-game concentration as "moderate", "fairly" or "extremely", and only one participant in the CONTROL game assessed his concentration as "slightly". However, the noticed presence of distractions, such as when the student was checking time not to be late to a meeting, could interfere with players' attention and meditation, and consequently, influence the results.

In addition to game experience or flow evaluations players completed at the end of the game, some of the participants provided their feedback about the game in the form of remarks. For example, one of the participants with ADHD liked the idea that the game adapts to the player's attention, not the player "adapts attention" to the game (like in the brain-controlled games). Another participant with ADHD liked that the educational part of the game was well blended, and it did not not feel like "you were doing a homework".

However, there were two participants, which differed from the other players in all parameters. They had elevated, compared to players in their group, attention and meditation levels, but whose subjective evaluations in the form of flow questionnaire scores were one of the lowest. Among them, the player's attention and meditation meter values in the ADAPTIVE group were 77.58

(with average attention in the group M=62.71, SD=8.9) and 64.08 (with average meditation in the group M=60.91, SD=3.61) respectively, the game experience score was 0.8, and the player rated 19 trials out of 21 game trials played with one star (the first trial was rated with two stars) or as very easy trials. However, 21 games in total played (one of the highest total number of trials played in the ADAPTIVE group) shows that the player's in-game progression was rather slow since less trials were skipped. In the CONTROL group, the player's attention and meditation meter values were 70.29 (with average attention in the group M=60.34, SD=7.95) and 68.2 (with average meditation in the group M=55.79, SD=8.01) respectively. This player rated all 35 game trials as easy or with one star, and the player's game experience score was 0.4. Although these players are not considered to be conventional outliers (the reason we did not exclude them from the sample), their data are still rather atypical.

5.2 Hypothesis 1

The first aim of this study was to test whether players of the ADAPTIVE game will maintain their attention span for a longer period of time while progressing faster through the game levels compared to the control group. We tested the relationship between the number of trials participants played in total and the average time they spent on the trial completion. If the average time a player spent on the task completion decreased over time, it would also suggest that the player grasped the concept of proportionality. We found a strong negative correlation between the total number of trials and the average time in the CONTROL group ($r_{10} = -0.72, p < 0.02$). The same relationship trend, although statistically insignificant, was noticed in the ADAPTIVE group ($r_{10} = -0.55, p = 0.09$). (Figure 5.1). Across the groups, we have not found a significant correlation between the number of trials and average time, although a negative trend was observed ($r_{20} = -0.38, p = 0.09$).

We also compared attention levels of the participants in the ADAPTIVE group (M=62.71, SD=8.94) to the attention levels of the players in the CONTROL group (M=60.34, SD=7.95). At the current stage of the research our evidence, ($t_{18} = 0.62, p = 0.54, s^2 = 3.79$), does not give a reason to believe that there are differences (Figure 5.2) in sustained attention between the groups.

5.3 Hypothesis 2

The second goal was to determine whether players of the ADAPTIVE game will enjoy the game play more compared to the CONTROL group. We analyzed the differences in meditation statuses

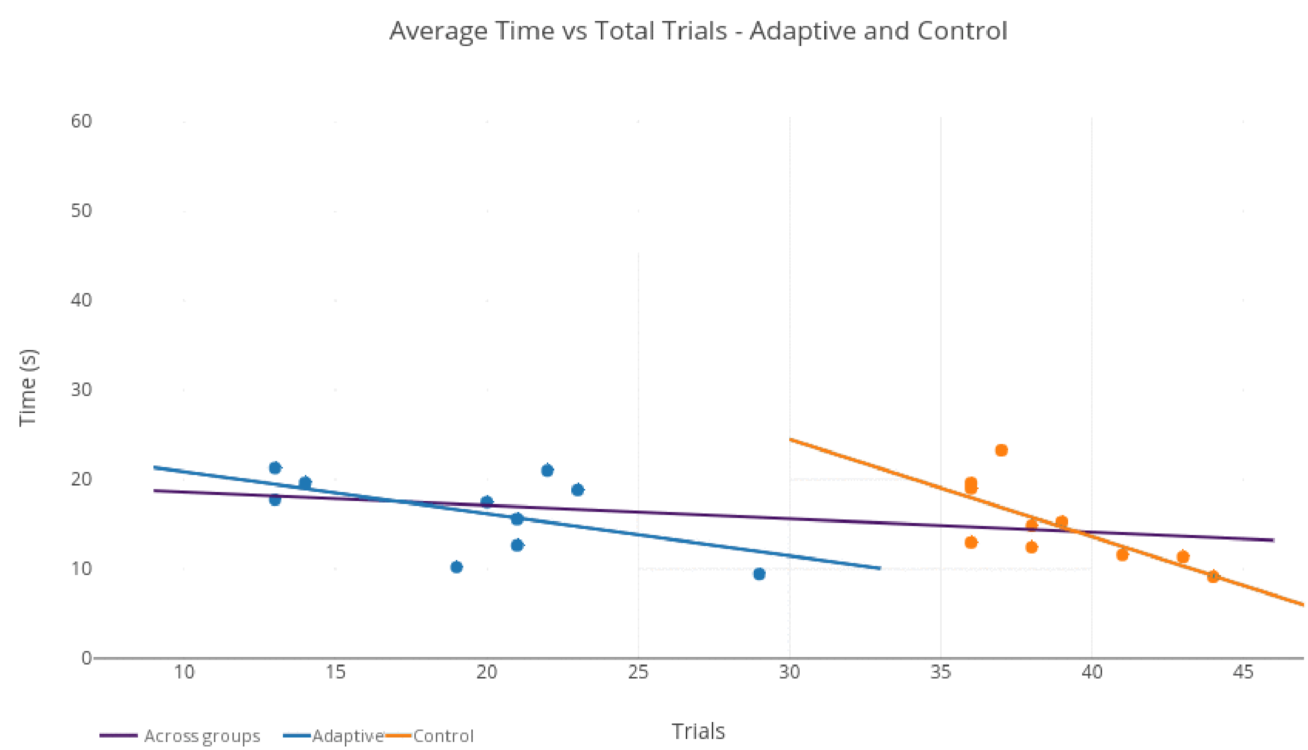

Figure 5.1: Total number of trials vs the average completion time in the ADAPTIVE, CONTROL and across groups. A strong negative correlation between the variables was revealed ($r_{10} = -0.72$, $p < 0.02$) in the CONTROL group. Negative trends, although insignificant, were observed in the ADAPTIVE group ($r_{10} = -0.55$, $p = 0.09$), and across groups ($r_{20} = -0.38$, $p = 0.09$)

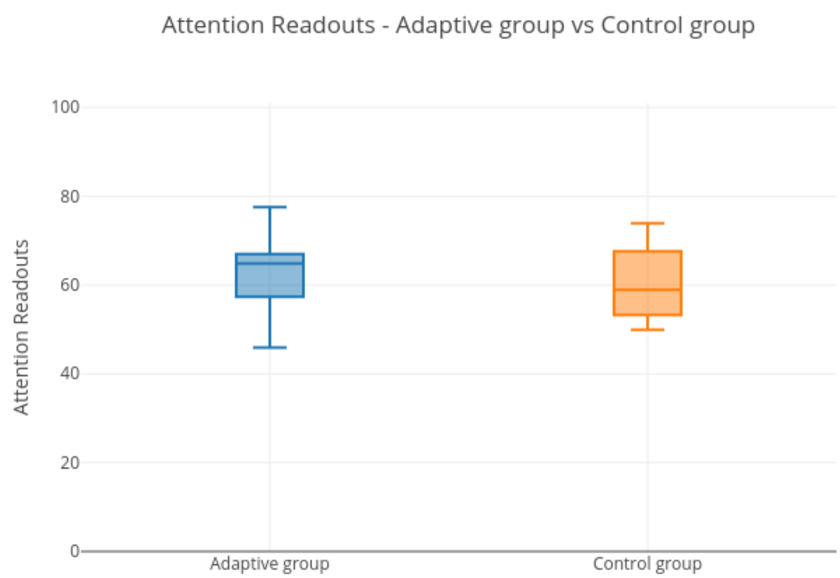

Figure 5.2: Comparison of attention readouts.
A statistical difference between the ADAPTIVE and CONTROL groups was not determined, ($t_{18} = 0.62$, $p = 0.54$).

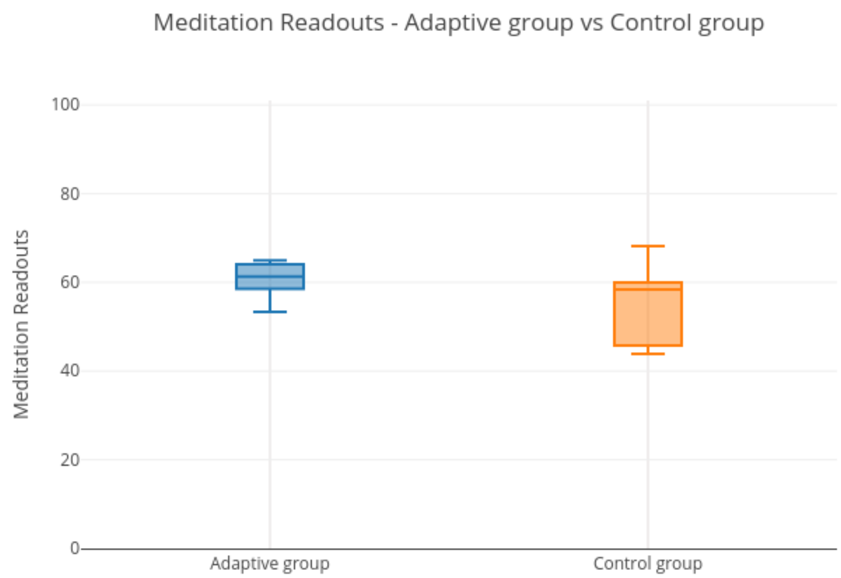

Figure 5.3: Comparison of meditation readouts.
A statistical difference between the ADAPTIVE and CONTROL groups was not determined, ($t_{18} = 1.84, p = 0.08$).

and flow scores between the groups. We also examined the relationships between the attention, meditation and flow scores, and between sum of blocks and flow score to determine whether players were optimally challenged to enjoy the game.

We found no significant difference ($t_{18} = 1.84, p = 0.08, s^2 = 2.78$) (Figure 5.3) in meditation readouts between the ADAPTIVE group (M=60.91, SD=3.61) and the CONTROL group (M=55.79, SD=8.01) groups. Also, no significant difference ($t_{18} = 1.12, p = 0.28, s^2 = 0.43$) was revealed in flow questionnaire scores between the ADAPTIVE group (M=2.14, SD=0.89) and the CONTROL group (M=2.62, SD=1.03).

To further test the hypothesis, we investigated correlations between objective brain activity measurements – meditation and attention readouts – and a subjective evaluation provided by the players at the end of the game play in the form of flow questionnaire. Since both of the measurements are determinants of flow, we wanted to supplement the t-test results by assessing the significance of the difference between two correlation coefficients. However, the results of the study revealed no correlation between meditation readouts and flow scores in the ADAPTIVE

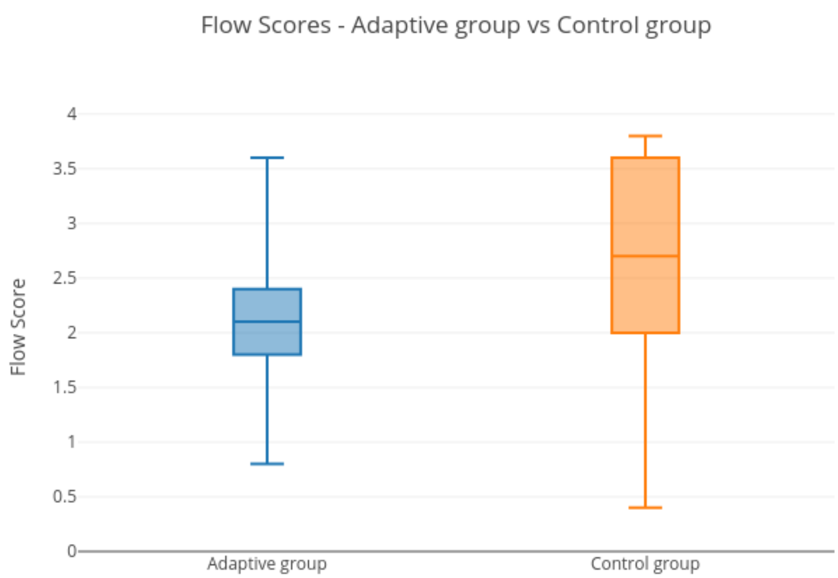

Figure 5.4: Comparison of flow questionnaire scores.
A statistical difference between the ADAPTIVE and CONTROL groups was not determined, (t_{18} = 1.12, p = 0.28).

group ($r_{10} = -0.49, p = 0.15$); and no correlation between meditation readouts and flow scores in the CONTROL group ($r_{10} = -0.3, p = 0.39$). An analysis of relationships between attention readouts and the flow scores showed no correlation in the ADAPTIVE group ($r_{10} = -0.17, p = 0.64$); and no correlation in the CONTROL group ($r_{10} = -0.49, p = 0.15$). No relationship was also determined between the sum of blocks and the flow scores in the ADAPTIVE group ($r_{10} = -0.15, p = 0.68$); and no correlation in the CONTROL group ($r_{10} = 0.58, p = 0.08$).

5.4 Analysis of Data Cut Off on 12 Trial

The difference in number of trials in each group is set by design for a number of reasons, such as the ADAPTIVE game provides players with ADHD with an incentive in the form of fastest progression and an ability to complete the game in a shorter period of time. Although the maximum number of trials participants can play is the same for both groups, the difference in the minimum number of trials in the ADAPTIVE group may look like a potential confounding factor. To account for it, I cut off attention, meditation and average time per trial data on the trial 12, and examined the differences between these variables between the groups.

No significant difference in meditation, ($t_{18} = 1.07, p = 0.29, s^2 = 3.32$), was revealed between the ADAPTIVE group (M=60.06, SD=6.03) and the CONTROL group (M=56.5, SD=8.59), as well as no significant difference was noticed in attention readouts, ($t_{18} = 0.42, p = 0.68, s^2 = 4.85$), between the ADAPTIVE group (M=64.2, SD=10.48) and the CONTROL group (M=62.16, SD=11.19). The significant difference in average time spent on the trial completion ($t_{18} = 2.88, p = 0.01, s^2 = 1.61$) was determined between the ADAPTIVE group (M=12.64, SD=4.36) and the CONTROL group (M=8.02, SD=2.6), meaning players of the ADAPTIVE game spent more time per trial balancing the bridge.

5.5 Analysis of Difficulty

The positive results of the pilot motivated the final game design modifications, which included defined difficulty levels together with a subjective evaluation (star rating) after each trial. My assumption was that if the difficulty of the task depends on the sum of blocks on the left (i.e. the bigger the sum the more difficult the trial is) then, in the context of my two hypotheses, the increased attention state and/or decreased meditation state can be explained by the increased difficulty level in the game.

The analysis of difficulty in the final study revealed a number of trends between attention levels, meditation levels, flow scores and sum of blocks. Some positive relationship between the sum of blocks and the flow scores, although insignificant, was noticed in the CONTROL group ($r_{10} = 0.58, p = 0.08$); however, no correlation was observed in the ADAPTIVE group ($r_{10} = 0.15, p = 0.68$); and across the groups, ($r_{20} = 0.19, p = 0.42$).

No correlation was observed in the CONTROL group between sum of blocks and the attention readouts ($r_{10} = -0.45, p = 0.19$); and no relationship was noticed between sum of blocks and meditation readouts ($r_{10} = -0.14, p = 0.69$). In the ADAPTIVE group no relationship was observed between sum of blocks and the meditation readouts ($r_{10} = 0.13, p = 0.72$); and the probability of the relationship between sum of blocks and attention readouts ($r_{10} = -0.25, p = 0.49$) was also not significant.

Additionally, we analyzed the relationship between the star ratings provided by the player at the end of each trial and brain wave activity. The reason we wanted to verify the relationship between the objective (attention and meditation readouts) and subjective evaluations (star ratings) is to see whether our level difficulty prediction model, when the player either repeats the level or progresses in the game faster by skipping trials based on the brain activity measurements, is working as expected. No significant correlation between the attention readouts and the star ratings was revealed across both groups, ($r_{20} = -0.34, p = 0.14$); in the CONTROL, ($r_{10} = -0.41, p = 0.24$); and in the ADAPTIVE, ($r_{10} = -0.27, p = 0.45$).

Furthermore, we analyzed relationships between sum of blocks and star ratings, since our assumption in the pilot study was that the bigger the sums of blocks the more difficult the trial will be considered by the players. However, the findings were indeterminate across the groups, ($r_{20} = -0.01, p = 0.97$), and within each group with ($r_{10} = -0.02, p = 0.96$) in the ADAPTIVE; ($r_{10} = 0.19, p = 0.6$) in the CONTROL. The pilot study assumption was not confirmed at the current stage of the experiment.

5.6 Analysis of Data of Players with ADHD

The reason we analyzed data of the participants with ADHD separately from the sample is that people with ADHD have altered reward-related neural processing that could result in the data significantly differ from data of participants without ADHD. Specifically, I might observe different patterns in EEG data and in subjective evaluations. Although the sample size of the participants with ADHD was too small to determine significant differences between the ADAPTIVE and the CONTROL groups, my observation of these players in addition to a revealed relationships between subjective evaluations provided by the participants in the form of star ratings and flow scores, and between the total number of games played and the average time spent on the trial completion, are encouraging for further investigation.

Thus, the average attention readouts in both groups were slightly elevated in the ADAPTIVE group (M=65.85, SD=12.36), and in the CONTROL group (M=62.74, SD=4.31). The average meditation status was also slightly elevated in the ADAPTIVE group (M=62.24, SD=3.95) suggesting players were relaxed while playing the game, but the average meditation values in the CONTROL group (M=50.82, SD=9.05) appeared to be neutral, and cannot be categorized into one of the mental state levels described by Neurosky. I had observed participants of both groups during the game play, and noticed a degree of impatience among players with ADHD in the CONTROL group. Two players asked similar questions, reaching 6-7 difficulty level, about how many more trials left. I suspect those players either did not feel the difference between the first four levels, or they noticed that progression in the game is slow. Since the players of the ADAPTIVE game could progress faster skipping some of the levels, consequently, their perception of difficulty progression might have been different, meaning their experience was more engaging. Although the flow questionnaire scores did not differ between the ADAPTIVE (M=2.27, SD=1.4) and the CONTROL (M=2.73, SD=0.81) groups.

Some strong correlations were observed in the group of players with ADHD between the star ratings and flow scores, ($r_6 = 0.814, p < 0.05$); and between the number of trials they played in total and the average time they spent on the trial completion, ($r_6 = -0.84, p < 0.04$). The interesting fact about the results is that the flow scores of two participants with ADHD (one participant in each group) who were not taking medications for diagnosis were identical 3.6. Both of them evaluated their in-game concentration as "extremely concentrated", and their immersion status as "extremely occupied", although meditation level values did not support their flow status self-assessment, (M=57.71 in the ADAPTIVE group, and M=45.46 in the CONTROL group).

Chapter 6

Discussion

The aim of this thesis was to design an adaptive video game to teach children with ADHD proportional reasoning through play. To test the design, I conducted an empirical study that compared the ADAPTIVE game to the CONTROL game that lacked adaptive features. In particular, I investigated whether players of the designed ADAPTIVE game learned proportional reasoning faster than players of the CONTROL game, and whether players of the ADAPTIVE game enjoyed the play more compared to the CONTROL group. My observations of the participants in combination with their feedback informed ideas for design modifications. This discussion will highlight the key findings and their implications on the design of the game.

6.1 Key Findings

We found no differences between the ADAPTIVE and CONTROL groups in attention levels, ($t_{18} = 0.62, p = 0.54, s^2 = 3.79$); meditation levels, ($t_{18} = 1.84, p = 0.08, s^2 = 2.78$); and flow scores, ($t_{18} = 1.12, p = 0.28, s^2 = 0.43$). However, observed correlations between other collected variables are very encouraging for further investigation. Among them, the observed learning effect based on the significant negative correlation between the total number of games and the average time spent on the task completion in the CONTROL group, and a moderate trend, although insignificant, in the ADAPTIVE group confirms that our game design model provided players with an appropriate interactive learning environment when they were able to successfully complete learning assignments in the form of proportional reasoning tasks. Here I report key study findings divided into four sections, which are Adaptive Learning (H1), Game Enjoyment (H2), Analysis of Difficulty, and Design Evaluation.

6.1.1 Adaptive Learning

We hypothesized that the players of the ADAPTIVE game will progress more quickly, as measured by the total number of trials played and the total time (seconds) spent playing, while maintaining their attention span for a longer period of time compared to the players of the regular video game (H1). The analysis of time players spent on the trial completion over the period of the game play revealed a strong negative correlation between the total number of trials (M=38.8, SD=2.94) and the average time (M=14.94, SD=4.43) in the CONTROL group , ($r_{10} = -0.72, p < 0.02$). The similar relationship trend between the total number of trials played (M=19.5, SD=5.04) and the average time per trial (M=16.38, SD=4.29) was noticed in the ADAPTIVE group, ($r_{10} = -0.55, p = 0.09$), although this correlation may need to be further investigated since it was not statistically significant. It is possible that the probability of the relationship between the variables in the ADAPTIVE group was not significant because participants played fewer number of trials compared to the CONTROL group, and/or since the players progressed faster in the ADAPTIVE game their adaptation period to the more difficult level was not gradual, and consequently longer in time.

The study results reveal the participants benefited from playing the game by acquiring the proportional reasoning technique toward the end of the game play. The CONTROL group participants learned quickly as shown by play times. The ADAPTIVE game players may have also developed the proportional reasoning skills as shown by the relationship trend between the variables, but to determine the significance of that correlation, if any, we would need to reassess both game designs to make them as much similar as possible (e.g. total time playing) without losing the adaptive concept. Since there was no difference in attention statuses between the groups and participants of the ADAPTIVE group completed the game play faster, I believe the adaptive game design, after the minor design modifications are implemented, will prove to be more efficient in teaching proportional reasoning to players.

As the ultimate goal of this thesis is to design a video game that can help children with ADHD to learn proportional reasoning through play, the presence of a learning effect when the participants acquire knowledge by practicing the game play over and over, are very promising and require further investigation.

6.1.2 Game Enjoyment Assessment

We hypothesized that players of the ADAPTIVE video game will enjoy the game play more than the players of the CONTROL game (H2). However, no significant differences between the groups were observed in meditation readouts, ($t_{18} = 1.84, p = 0.08, s^2 = 2.78$); and flow questionnaire scores, ($t_{18} = 1.12, p = 0.28, s^2 = 0.43$). In this study, my sample of participants was restricted to university students who were likely familiar with basic reasoning concepts, and consequently less stressed. Since I did not have access to different participants (i.e. younger participants) at the time of the study, the prior knowledge factor may need to be verified in the future by running the experiment with middle-schoolers. Overall, I consider meditation results as positive results in the context of the game design suggesting there was no striking differences between the games, and that shortening the total playtime through faster progression did not make players more anxious in the ADAPTIVE group or too relaxed in the CONTROL group.

Although no statistically significant difference was revealed, in general, player of the ADAPTIVE game looked less stressed based on my observation of them playing. Whereas the participants in the CONTROL group often asked during the game play how many more trials are left suggesting a little irritation and a feeling to finish playing. Also, given the probability of 0.08 that there is a difference between meditation readouts, and based on what is recommended in such cases in health research, I would conduct an ecological analysis to verify this result.

An analysis of relationships between meditation readouts and flow scores showed no correlation in the ADAPTIVE group ($r_{10} = -0.49, p = 0.15$); and no correlation in the CONTROL group ($r_{10} = -0.3, p = 0.39$). There was also no correlation determined between attention readouts and the flow scores in the ADAPTIVE group ($r_{10} = -0.17, p = 0.64$); and no correlation in the CONTROL group ($r_{10} = -0.49, p = 0.15$). The fact we did not observe the relationships between attention, meditation and flow scores in the experiment might be related to the multidimensionality of subjective game experiences that were partially assessed by the questionnaire consisting only related to the hypothesis flow component. In the future experiments, the extended version of the game experience questionnaire might provide more insights into participants' in-game flow state.

6.1.3 Analysis of Difficulty

With respect to analysis of difficulty that was motivated by the positive results of the pilot, we determined a strong positive correlation between the star ratings and the flow scores in players with ADHD when their data is analyzed together (i.e. as one group of players with ADHD) despite being in the ADAPTIVE or CONTROL groups, ($r_6 = 0.814, p < 0.05$). The correlation between two subjective evaluations in the players with the diagnosis – the star ratings and flow scores – can be explained by the fact that people with ADHD tend to process information with high emotions. In other words, the perception of the difficulty of the trials is influenced by the overall game experience including the interface design acceptance and clarity of game mechanics, and not by the actual difficulty in the form of increasing sums of blocks on the left side of the bridge.

We also analyzed correlations between the sum of blocks and attention, the sum of blocks and meditation, the sum of blocks and the flow scores. No relationships were observed between attention, meditation, sum of blocks and flow scores.

Table 6.1: Proposed Level Design Modifications

Level	Current Difficulty (sum of blocks)	Recommended Difficulty (sum of blocks)
1, 2, 3	2-12	7-15
4	13-24	23-31
5	25-36	39-47
6	37-48	55-62
7	49-60	70-77

6.1.4 Design Evaluation

In general, the presence of learning effect in the CONTROL group based on the strong correlation between the total number of games played and the average time spent on balancing the bridge confirmed that the game worked as designed. However, the analysis of the in-game difficulty pointed to a number of game design modifications that might positively influence the results by improving confidence levels. For example, I would modify difficulty levels by increasing the spread between the levels by the number of possible sums of blocks within the previous level (e.g. level 1,2,3 - sums of 7 to sums of 15; level 4 - sums of 23 to sums of 31; level 5 - sums of 39 to sums of 47, etc.). As can be seen in the Table 6.1, in the current trial difficulty setup the transition to more difficult levels was quite smooth. Thus, if the reason we did not observe jumps in attention and/or meditation while revealing the presence of learning effect was that players often did not feel the difference in difficulty of trials between the levels, then this level design modification in combination with my adaptive progression rules may help players to refocus their attention back on the task when its difficulty is rapidly increased. I would also ask each participant to play two games, the ADAPTIVE game and the CONTROL game, prior changing the theme of one of the games but keeping the game's mechanics. Two versions are recommended for the purpose of the experiment only to avoid mere-exposure effect (or familiarity principle when participants may develop a preference for the game they already familiar with) when players are asked to play the game second time.

The minor study modification (when each participant plays both games) together with game design improvements might not only produce different attention and meditation results, but also give us an idea about the play experience in both games from the same participant.

Chapter 7

Conclusion

As BCI-based applications become more popular, they slowly move from purely medical research to being a valuable addition to other input modalities where user satisfaction and acceptance of this technology lie at the core of human interactions with computers. The literature on brain-computer interface based educational video gaming has been steadily growing (Hwang, Kim, Choi, & Im, 2013) suggesting raising interest from scholars and practitioners. The positive trend in the research and development of portable BCIs brings new possibilities for faster commercialization of educational video games, which can restore communication, independence and control over lives for the broad range of people.

The study findings in combination with my qualitative analysis pointed to the fact that minor design modifications may not only produce significant results but also improve the quality of game experience, which is an important component of the learning process incorporated into play. The positive game experience or game enjoyment fortifies the motivation to play and learn in children with ADHD by creating an associative learning environment. Thus, the recommended game modifications are not merely changes in the game design aestetics, but, importantly, improvements of the game design dynamics. This Master's thesis is concerned with the design of an educational ADAPTIVE video game that teaches proportional reasoning to children with Attention Deficit Hyperactivity Disorder. The use of the low-cost mobile electroencephalogram, Neurosky MindWave, provided us with information about the participant's attention and meditation states while playing the game. It was also an essential part of the adaptive game difficulty level design. The collected data, such as attention and meditation readouts, time spent on the task, sum of the blocks on the left side of the scale, star ratings and flow questionnaire scores were analyzed for potential explanatory patterns (e.g. a correlation between the quality of the game experience and stress or relaxation levels) and interactions (e.g. a relationship between the star ratings and flow scores).

In the current version of the game, we did not determine significant differences in flow scores, meditation and attention readouts between the groups revealing the ADAPTIVE game allows users to complete the play in a shorter period of time while maintaining their attention and meditation levels not differing from the CONTROL group. Further investigation of potential relationships between collected variables revealed a strong correlation between the total number of games played and the average time spent on the task confirming a presence of the learning effect in the CONTROL group. This finding is important in the context of both the hypotheses analysis and the motivation behind the design of the ADAPTIVE game that teaches children with ADHD proportional reasoning.

The data of the players with ADHD was analyzed separately and with other players, as described in Chapter 5. The revealed strong correlation between the subjective difficulty evaluation or star ratings and flow scores is an interesting finding because there was no correlation found between the objective difficulty evaluation or sum of blocks and flow scores. The finding suggests that the players with ADHD rely more on their perception or intuitive evaluations of the difficulty of trials.

To summarize, the observed relationship between subjective evaluations provided by the players with ADHD points out to the fact that other HCI researchers working in the area of educational video games should focus on the user experience or behavioral design more than on the level design.

7.1 Contributions

This thesis makes the following contributions:

1. I designed a BCI-based video game for players with ADHD, in which players' brain activity data was used to adapt the difficulty of the game to players' attention and performance statuses,

2. I created and tested a novel difficulty progression measure. The difficulty progression is calculated based on the attention, meditation, and the result of three previous game trials. Our difficulty progression model supplemented the proportionality rules introduction recommendations by Christel et al. (2013) to enhance the players' learning process and game enjoyment.

7.2 Limitations

I recruited 20 participants aged 19 to 29 years, 6 of whom happened to have ADHD. Since our target population is adolescents with ADHD that entails having different prior knowledge and reasoning ability compared to participants in my sample size, it is possible that future experiments with teenage players might produce different results.

Further, in our experiment the ADAPTIVE video game incorporated flow theory elements, which consist of basic prerequisites (clarity of goals and immediate feedback, limited field of concentration, and balance between the skills and challenge) and subjective experience evaluation assessed with a help of flow questionnaire proposed by IJsselsteijn et al. (2013). The researchers recommended to administer this questionnaire right after the game. However, after running the study, based on my observation of the participants, I noticed that the time interval, although minimal, between the end of the game play and the time participants evaluated their flow state could have affected the players' perception and their flow experience was based on the most recent trials. I believe that if we were to evaluate the flow state concurrently with the game play by incorporating the flow evaluation into the game play we might observe correlations between attention, meditation and flow scores, which were not significant in the present study.

With respect to the study findings, the determined learning effect in the CONTROL group between the total number of games played and the average time spent on the trial completion, and the correlation between the star ratings and the flow scores in the group of players with ADHD, suggest that these findings may be worthy of further investigation with higher statistical power, and with potential design modifications.

I also determined that artifacts and ethical considerations are a part of limitations in my study. The EEG device I used in the experiment, although mobile, affordable and accessible, is rather restrictive in terms of the type of brain activity data that can be extracted. But having more information about the players' brain activity might affect the ethical part of the study, making the players to feel like their privacy is being invaded.

7.2.1 Artifacts

Raw EEG data are almost always contaminated by artifacts. These artifacts include biological signals, such as eye blinks, or environmental signals, such as poor grounding of the EEG electrodes. The Neurosky EEG headset with a dry electrode used in the designed video game had an advantage compared to EEGs with wet electrodes, which are expensive and used only in clinical settings, because it can be used in real living environments and consumer products, and is a low-cost device that can be purchased by anyone online.

For the purpose of the experiment, I only measured the attention and the meditation states of the participants while playing the game with the help of eSense data values that characterized the mental states. The eSense allowed me to monitor how effectively the player is engaging her attention and whether or not the player is stressed while performing the task using EEG power band values that have been pre-calculated by the chip with once per second updates.

7.2.2 Ethical Considerations

During the experiment, I collected psychophysiological measurements of each player – attention, meditation and enjoyment statuses – in order to adjust the difficulty of the game for an enjoyable game play experience. Given the personal nature of psychophysiological data study participants shared with the researcher, it was important to make sure they are informed about the research process and goals, and their personal information is protected appropriately. In times of big data and the emergence of online behavioral marketing, and in the absence of strong, well-structured data privacy protection legislation, both researchers and study subjects may find themselves in a vulnerable position. To avoid such implications, I explained participants how the brain activity data is collected (including demonstration of the recorded raw data), used and stored. I also informed players that all information provided in the demographic questionnaire is confidential and no name is attached to it. Although this study was reviewed and received ethics clearance through the Office of Research Ethics at the University of Waterloo, the final decision about participation was made by the participants. The consent from the players was obtained prior to the experiment (Appendix D).

7.3 Directions for Future Research

In the thesis, I proposed to analyze data of the players with ADHD separately and with players without the diagnosis to see if there is a difference in playing performance and difficulty level evaluations provided by the player. While working on the design of my educational video game, I learned that this category of video games requires more research on how to design the game environment that fosters knowledge acquisition. In other words, I proposed to other HCI researchers working on educational games for players with ADHD to focus on the user experience or behavioral design of the games more than on the actual level design. For example, they should employ the social-cognitive theory to create a learning environment that does not enforce behavioral changes during the game play from an individual with ADHD, but predicts and adapts to the players' in-game behaviors to keep them engaged in the learning process.

For the future research purposes, it is interesting to see if there is any difference in attention and meditation states, and, consequently, in game performance when brain activity data is recorded using mobile EEGs with more channels and better resolution. For example, it is possible that a 16-bit mobile EEG headset Emotive can provide us with data of better quality and depth of analysis compared to the 12-bit Mindwave headset we used in the study. If that is the case, the experiment would allow us to better inform design modifications.

Finally, our findings of learning effect in the CONTROL group motivate future research in educational video games design. Assuming it is possible to implement the EEG component in any other educational game of children with ADHD's choice, would we see significant differences in players' performance over time, including overall attention and meditation readouts in those games compared to my designed game? If so, it would need to be further investigated to see what it is that make the games more attractive, so that those design elements can be used by HCI designers working on educational video games for children with ADHD.

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Appendices

Appendix A

Information Letter

University of Waterloo, Canada Date:

Dear Participant(s):

I am writing to ask your permission to participate in a University of Waterloo (Canada) research project on designing an adaptive video game for children with ADHD to teach them proportional reasoning. Proportional reasoning is an important part of early math learning because children learn to compare things (e.g. quantities) multiplicatively (e.g. 3 blocks to 9 blocks is the same as 20 blocks to 60 blocks). We are interested in designing a game that will teach children to self-monitor symptoms of inattentiveness, and, consequently, help them to learn new math skill. Our project may help us understand more about how self-monitoring of ADHD symptoms can help children effectively learn new skills. Therefore, at the current stage of research, we are interested in your participation in the game testing in order to evaluate the games design. This so-called user acceptance testing is an important phase of the game testing process because the results of the testing will provide the researcher and the potential users with confidence in how the game will perform when used by children with ADHD.

The project in which you have been invited to participate is expected to be an enjoyable experience and will require less than 45 minutes of time. However, the decision about participation is yours. To help you in this decision, a brief description of the project is provided below.

Participants will meet with the researcher individually on one occasion only. In this session, your child will be assigned to a group that will play an adaptive video game (the difficulty of the task will depend on your performance in the game play including attention levels) or a group that will play regular level-by-level video game. During the game play you will be wearing a mobile electroencephalogram (EEG) headset by Neurosky. It is a noninvasive device that is approved for use in Canada and USA, and is worn like a headband. This EEG device measures your brain waves activity that is translated into attention and relaxation levels (I have attached a picture of a child wearing the Neurosky headset for your information at the end of this letter). After the EEG device is placed on your head, you are ready to start playing the video game. You will be playing the game on the computer with a mouse. The computer is equipped with a camera to video-record the game play of the participant, in particular, we will record the players reactions (e.g. facial motion). The video-recordings will be analyzed in the context of the game play. During the game play you will be offered Lego balanced bridge with a combination of Lego blocks on one side of the scales and spare Lego blocks placed on a platform beneath the other side of the bridge. You then need to use the spare blocks by clicking on a block and moving it on to the empty side of the bridge to balance the bridge. For each combination of the balanced bridge you will have maximum 60 seconds to complete the task. At the end of the task, you are asked to answer the question about the difficulty of the task by star rating it.

Thus, we will only collect six measurements during your game play, which are: duration of a game play, attention and relaxation measurements from the EEG device, positions of the blocks on the bridge, sum of blocks (weights) on the left side of the bridge, and judgment about the difficulty of the task (star rated). We will also analyze video-recordings of the game play.

All your performances are considered confidential and individual results will not be shared with university, employer or medical service providers. We will only collect your demographic data: age and gender. We will also need to know if you are right or left handed, and whether or not you are taking any medications related to diagnosis. All information obtained during the study will be secured on an encrypted hard drive for at least 5 years after which it will be erased. The video-recordings obtained during the study will only be reviewed by the researchers and will not be shown to others. Only participants who themselves agree to participate will be involved in the study. Also, you may withdraw your permission at any time during the study without penalty by indicating this decision to the researcher. There are no known or anticipated risks to participation in this study. As remuneration for the participation in this study you will receive 10 USD. The amount received is taxable. It is your responsibility to report this amount for income tax purposes.

This study has been reviewed and received ethics clearance through a University of Waterloo Research Ethics Committee (ORE 22165). If you have questions for the Committee contact the Chief Ethics Officer, Office of Research Ethics, at 1-519-888-4567 ext. 36005 or ore-ceo@uwaterloo.ca.

We would appreciate if you participate in this project, as we believe it will contribute to furthering our knowledge on how to enhance self-monitoring of inattentiveness in children with ADHD.

If you have any questions about the study, or if you would like additional information to assist you in reaching a decision, please feel free to contact me by phone at 813-920-7748 or by email ltahai@uwaterloo.ca . Thank you in advance for your interest and support of this project.

Yours sincerely,

Dr. James Wallace (Supervisor, SPHHS), Liudmila Tahai (student investigator, SPHHS)

Appendix B

Demographic and Medication Status Questionnaire

Please fill out the questionnaire. Circle correct answer.

1) What is your age?
2) What is your gender? female male other
3) Are you: left handed right handed
4) Have you been diagnosed with ADHD? Yes No
5) Are you taking any medication related to diagnosis? Yes No

Appendix C

Informed Consent

By signing this consent form, you are not waiving your legal rights or releasing the investigator(s) or involved institution(s) from their legal and professional responsibilities.

Project: Designing an Adaptive Video Game for Children with Attention Deficit Hyperactivity Disorder: Learning Proportional Reasoning through Play

I have read the information presented in the information letter about a study being conducted by Liudmila Tahai of the School of Public Health and Health Systems at the University of Waterloo (Canada) under the supervision of Professor James Wallace. I have had the opportunity to ask any questions related to this study, to receive satisfactory answers to my questions, and any additional details I wanted.

I am aware that I may withdraw my consent for any of the above statements or withdraw my study participation at any time without penalty by advising the researcher.

This project has been reviewed by, and received ethics clearance through, a University of Waterloo Research Ethics Committee. I was informed that if I have any comments or concerns resulting from my participation in this study, I can contact the Chief Ethics Officer, Office of Research Ethics, at 1-519-888-4567 ext. 36005 or oreceo@uwaterloo.ca.

Please circle one choice and put your initials. With full knowledge of all foregoing, I agree, of my own free will to participate in this study. Yes/NO

Participant Name: (Please print)

Participant Signature:

Witness Name: (Please print)

Witness Signature:

Date:

Appendix D

Game Experience Questionnaire

1. I was fully occupied with the game
   not at all 0 <> slightly 1 <> moderately 2 <> fairly 3 <> extremely 4 <>
2. I forgot everything around me
   not at all 0 <> slightly 1 <> moderately 2 <> fairly 3 <> extremely 4 <>
3. I lost track of time
   not at all 0 <> slightly 1 <> moderately 2 <> fairly 3 <> extremely 4 <>
4. I was deeply concentrated in the game
   not at all 0 <> slightly 1 <> moderately 2 <> fairly 3 <> extremely 4 <>
5. I lost connection with the outside world
   not at all 0 <> slightly 1 <> moderately 2 <> fairly 3 <> extremely 4 <>