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Development of a non-invasive game controller toolkit to study physiological responses for Game User Research

MASTER DISSERTATION

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MASTER IN COMPUTER ENGINEERING

UNIVERSIDADE da MADEIRA
A Nossa Universidade
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Thesis to obtain a master's degree in
Computer Engineering

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Thank you!

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Resumo

Os jogos afectivos usam as respostas fisiológicas do jogador para criar um ambiente adequado ao estado emocional do utilizador. A investigação destes jogos tem sido explorada nos últimos anos. Estas experiências, contudo, ainda requerem sistemas complexos e difíceis de utilizar. Nesta dissertação, é proposta a construção de um dispositivo capaz de ler dados fisiológicos de forma não invasiva e que seja de fácil utilização. Este aparelho faz a leitura do ritmo cardíaco e dos níveis de excitação do jogador, além disso foi criado um software para interligar com o dispositivo. Utilizando um comando da PlayStation 3 e um BITalino, o dispositivo é capaz de fazer a aquisição do sinal PPG e sinal EDA durante o jogo. O software analisa os sinais do comando, calcula o ritmo cardíaco e mede os níveis de excitação em tempo real. Foi realizada uma experiência utilizando biofeedback positivo e negativo, com o objectivo de testar a integração entre o software e o hardware. Não será no imediato que os dispositivos deste género sejam disponibilizados comercialmente. Os resultados são, no entanto, promissores. O cálculo do ritmo cardíaco em tempo real tem apenas uma diferença de 5 batimentos por minuto em relação ao ritmo cardíaco real do jogador. Apesar de os testes com o EDA serem inconclusivos, pode-se verificar que foi possível construir um sistema para ler os dados fisiológicos sendo mais económico do que os seus pares, sem comprometer a fiabilidade dos dados.

Palavras-chave:

Jogos afectivos, jogos adaptivos, comando biofeedback, toolkit, investigação de jogos

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Abstract

Affective games are a genre of games that use the physiological responses from the player to adapt the gameplay to a more enjoyable emotional state and experience. Physiological responses and affective games have been studied vastly over the years. However, the setups used in these interventions are very intrusive and are complex to set up. In this project, it is purposed to build a non-invasive and easy-to-set-up toolkit that records physiological data. This toolkit records the player's heart rate and arousal levels and was decomposed into software and hardware. Using a PS3 game controller replica and a BITalino, a physiological game controller which can record heart rate and arousal during gameplay was built. The software interfaces with the gamepad, processes the physiological signals and sends this information to the game. An experiment with a positive biofeedback condition and negative biofeedback condition was conducted. This experiment showed that even though more work must be done until these type of devices could be commercially available, the results are promising. This toolkit's heart rate values, when compared with other more traditional acquisition devices, were very similar, being on average only 5 BMP lower than the actual heart rate, proving that is possible to build more affordable non-invasive physiological hardware without compromising the signal's accuracy.

Keywords:

Affective games, adaptive games, biofeedback controller, toolkit, Game User research.

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Acronyms

BPM – Beats per minute

CSV – Comma separated value

DDA – Dynamic difficulty adjustment

ECG – Electrocardiogram

EDA – Electrodermal Activity

EEG – Electroencephalogram

EKG – Electrocardiogram

EMG – Electromyography

GUR – Game User Research

GSR – Galvanic skin response

IDE – Integrated development environment

IoT – Internet of things

HR – Heart rate

HRV – Hear rate variability

MAE – Mean absolute error

ME – Mean error

PPG – Photoplethysmogram

RSME – Root square mean error

S/N – Signal to noise ratio

SBL – Skin conductance baseline level

SC – Skin conductance

SCR – Skin conductance response

SUS – System usability scale

TEMP – Temperature sensor

UMa – University of Madeira

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1. Introduction

In this chapter, I will succinctly introduce the topic for this master's thesis and there are four main sections. Firstly, I start by stating the motivation for this master's thesis. Secondly, a brief introduction to the topic of research and its context in the project. In the two-remaining sections, I describe the objective of the project and the document’s structure.

1.1. Motivation

In recent years, psychophysiological information has been introduced in video games and game research. Some of these signals are Electrocardiogram (ECG) or Photoplethysmogram (PPG), both used to estimate the heart rate. Electrodermal Activity (EDA) is used to measure arousal, frustration and skin temperature. Electroencephalography is used to record the brain and is possible to assess arousal and attention. Electromyography (EMG), when placed on a muscle can detect even the slightest activation on a that muscle. The most common measures used in this genre of games are arousal and heart rate. To capture signals of this nature is, usually, required a vast and complex combination of hardware and software. Most of these systems are very intrusive, require expertise on the physiological field and are time consuming to set up. Often, research of this nature, calls for an expert to set up everything. Many intervention lack of a two way communication between the acquisition software and the game. In post analysis becomes really hard to understand which events in the game led to a certain response from the player. Thus, it is proposed the implementation of a game controller which can record physiological information in a non-intrusive and very easy to set up configuration, where the end user only needs to grab the controller and play the game. Moreover, it is also proposed to create a software to interface with the game controller, record the physiological signals and synchronise with game events.

1.2. Topic Overview

Game User Research (GUR) is a field of game development that focuses on the gameplay and how the player feels playing the game rather than finding bugs. To access the players' emotional state various methodologies, from other fields, have been implemented in GUR. Some examples are observation, questionnaires, think-aloud protocol, focus groups or recording physiological signal from the user. The majority of these methods have some kind of bias due to the interpretation of event by the player or by the researcher. Physiological signals, however, have little to no bias, because sigals are hard to control and the response is as true as possible.

Physiology has been used for many years in game development. More than just recording the signals and interpret then after a session, games have been using physiology to change the output of the game, increasing the game experience and producing unique experiences. Games that use these signals are called biofeedback games. The biofeedback can be direct or indirect. The biofeedback is direct when the player can manipulate the physiological signal such as flexing a muscle or breathing. Physiology is indirect when a player is not capable of controlling the biosignal. Examples could be the level of excitement or the heart rate. Games that have some form of physiological adaptation and the user is not able to figure out how signals is manipulating the games or does not even notices the changes are called affective games. Still, if for some reason in an affective game, the user becomes aware of the physiological changes and can manipulate the signals willingly that game becomes a simple biofeedback game.

There are vast options for signal acquisition system. Some are very accurate but very expensive also, Other are priced lower but are not so accurate. Taking this into consideration the game designer and researcher are able to compromise and choose the best hardware whilst fitting their needs. Many signals can be recorded with physiological acquisition hardware. Electrodermal Activity is used to record the emotional arousal during game play. Electrocardiogram or Photoplethysmogram are commonly used to calculate the heart rate, in beats per minute. Electroencephalography is used to record the brain and is possible to assess arousal and attention. Finally, Electromyography (EMG), when placed on a muscle can detect even the slightest activation on a that muscle.

1.3. Objectives

The main purpose of this thesis is the construction of a non-invasive game controller that records biological signals from its users using it for Game User Research and for biofeedback adaptive games. Taking this goal into consideration, the project calls for both hardware and software implementations.

Concerning hardware, the gamepad, called Physiopad, needs to be integrated with a device that can record physiological data. The Physiopad should be non-intrusive with the most natural interaction possible, easy-to-setup, and easily replicable.

Regarding the software, there is the need for an interface which manages the physiological data and can interact with video games. This software will be receiving the raw signal from the selected physiological device, will have to enable signal filtering. Also, the software will be calculating live results metrics, such as heart rate per minute (BPM) or arousal and sending these results to a biofeedback game. Finally, the software will need to collect data from the game and store it with the signals and metrics.

As a mean to validate both hardware and software, a proof of concept experiment will be implemented using a biofeedback video game.

1.4. Thesis outline

This document is structured in six different chapters. The first chapter is the introduction where the motivation and objectives, for this thesis, are. Chapter two is separated in five main topics. Starting by describing what is Game User Research and why it is used, then an overview of physiological signals and. Topic 3 and 4 are a literature review of affective gaming. A review of hardware to record physiological signals can be found on topic 5. Chapter three consist of the implementation of the hardware and software. There are described the requirements for hardware and software, the tools and materials used. The method and experiment designed to evaluate the performance of the Physiopad and its signal acquisition software can be found under Chapter four. Also, in chapter four, the results discussion is presented, and the main conclusions and future work are in chapter five.

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2. State of the art

In this literature review is possible to find a description of Game User Research and its methods, followed by an overview of the most used physiological measurements. Then, a definition of affective gaming and the difference between it and biofeedback games. How affective games are developed and the hardware devices available to record physiological data are the last two topics to be reviewed.

2.1. Game User Research

Lennart Nacke in [1] defines Game User Research is and how it is applied in the context of game development. The author describes that while Quality assurance focuses on finding the bugs and other technical problems in games, Game User Research (GUR) focuses on the game experience and how the player relates to the game. GUR uses many methods that are originally from different domains. Human factors, human-computer interaction, and psychology are some domains that inspired the Game User Research field. When a game designer creates a game, there are multiple experiences that he is trying to transmit to the player, accordingly to the author. Game user researchers use various techniques to observe and understand how the player interacts with the game and which are the players' responses through the gameplay. Note that the aim in GUR is not to evaluate the user but to analyse the game and then report back to the game designer the changes needed to meet the game designer expectations. Figure 1 shows how the game designer and GUR team communicate between each other.

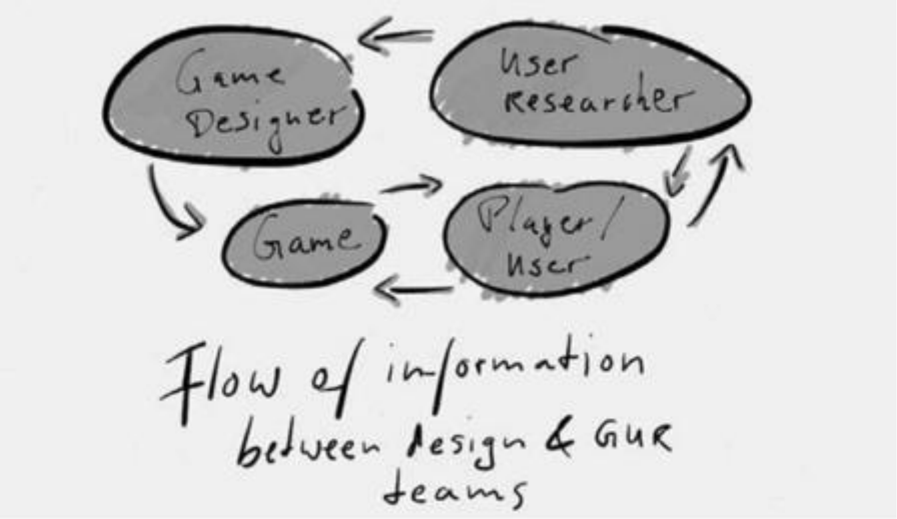


Figure 1 – Game development flow using GUR [1]

Meanwhile the user is playing the game, the researcher is observing both. Then an interview can happen to get the user's opinions and experience during the gameplay. After, researchers report back to game designers the results and observations, who iterates the game and adapts it, to, according to the author, a more compelling game.

The author presents some methods being used by researchers that also aim to retrieve the emotional state of the player and confirm whether is was the emotion which the game designer was trying to emulate. The methods described by the Nacke are (1) behavioural observation, (2) think-aloud protocol, (3) interviews, (4) questionnaires, (5) focus groups, (6) heuristic evaluation, (7) game metrics and (8) physiological game evaluation. A summary of each protocol follows below.

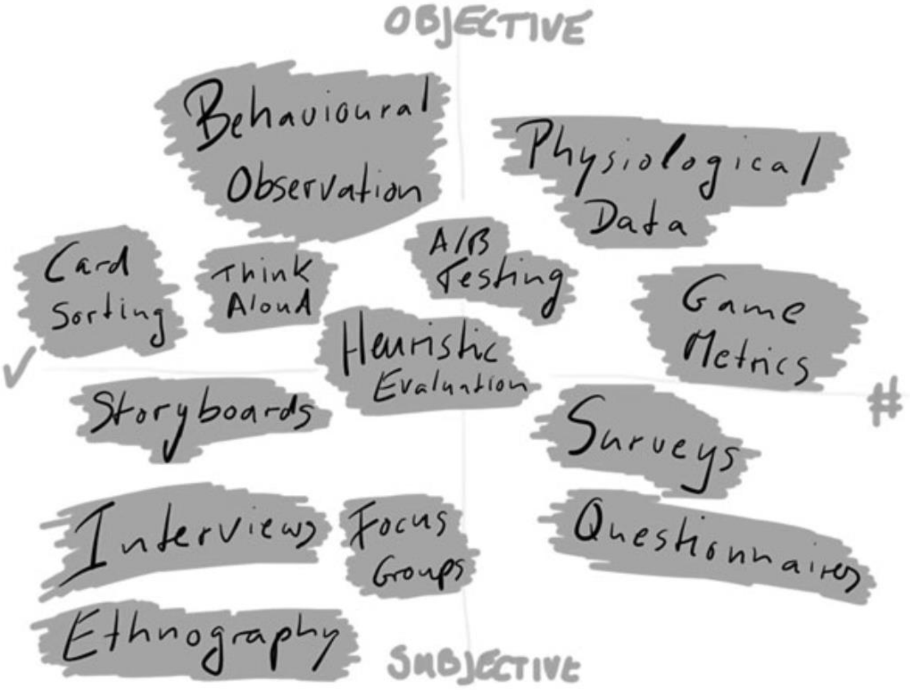


Figure 2 – Methods used in game user research [2]

Behavioural observation

Nacke states that, for many, this is one of the best methods available because of its simple nature, the game designer or researcher can simply observe the player and his gameplay. Much more complex environments are possible to accomplish such as using various cameras to record the session. One of the downfalls of this technique is that the observer must make assumptions and infer what the user is feeling and why he reacts in that manner. Another benefit is that the game designer can see the reactions (body language and expressions) in real time.

Think-Aloud Protocol

This methodology was initially used to test the usability of a product and can be seen as adding a new layer to the behavioural observation. This approach adds a narrative from the player. The author states that the user is supposed to speak out-loud what he is thinking and feeling during the interaction. This narrative is often recorded to be analysed after the session. This will require some expertise from the player and he has to feel comfortable to speak what he is feeling during gameplay. Also, this is not a natural activity so an additional moderator might be required to help the player narrate the events. This could add some bias as the narrative may interrupt the player's thought process.

Interviews

The interviews' quality is dependent on the quality of the interviewers. This method allows a deep understanding of the emotions, reactions and opinion of the user and can have an even deeper understanding using follow-up questions. Data is usually hard to analyse and sometimes common themes do not emerge from the interviews. Furthermore, the author defends that there is some bias associated with the answer given by the user.

Questionnaires

This method is described by Nacke as being widely used in GUR to collect a large volume of reports from various players. Metrics can rise from questionnaires, and data is usually much easier to analyse than Interviews. It is time efficient because multiple testers can be filling the questionnaire simultaneously. On the other hand, it lacks the depth that interviews have since there are no follow-up questions.

Focus Groups

Focus groups consist in gathering various players and let them talk about the game experience. They are allowed to speak about whatever they feel like, but there is a moderator trying to convey to more important matters. Nacke suggests that focus groups should, preferably, be used in early phases of the game development rather than final versions of games. A disadvantage of this method is that some of the players may pick on the others feedback and not be completely honest. Also, if there are more dominant users the others might not have an opportunity to express their experience.

Heuristic Evaluation

Nacke describes this method as the "discount usability method" because it is applied to a few GUR experts. They play the game and evaluate the game experience based on a bunch of parameters. With this approach, the experts determine if the game fits the designer's intentions and figure out which issues may arise from non-compliance. There are many heuristics proposed and each fit a certain kind of game. There is no common set of heuristic so it may be difficult to choose the best for the game in question. Also, an expert may miss a problem that only novice players experience, so this method should be complemented with another method that includes novice players.

Game metrics

Nacke [1] states that game metrics are one of the most recent methods to be embraced by GUR. This approach is essentially logging all the player interaction. Game variables, player position and other information that may be relevant to the gameplay. All these metrics are saved for analysis and are very complete. The issue is that the researcher will need software to go through all this data fast. This is an interesting approach because for every event happening a lot of information is recorded and the researcher and game designer can make more informed decisions.

Physiological game evaluation

The author describes physiological game evaluation as the process of acquiring data from the player, directly. This information is collected from the surface of our body and is collected as energy measures. Usually, these sensors are placed on the skin surface. Whilst manipulating elements inside the game the measures are recorded and later the designer can rearrange the gameplay to fit the desired response from the player. These responses are usually hard to control, hence they are as true to the player emotion or state as possible. Since there is no bias from the player opinion or researcher interpretation this method seems to have a big potential to help evaluating players' responses to gameplay. A downside is that this method is not fully explored and data may be hard to analyse and interpret if the researcher is not familiar with physiological data. Plus, extracting emotions from this kind of information can be very difficult and there is still no full proof method to extract emotions.

To conclude, Game User Research has various methodologies that can be implemented to evaluate how the player is interacting and reacting to a game. So, a combination of these methods should be used. Physiological game information is an interesting approach that can remove the bias factor that most of the other approaches suffer. Due to the difficulty of extracting emotions through physiology, it should not be used alone. Other, more traditional methods, as observation, should be applied at the same time to get the full picture of gameplay and players’ emotions.

2.2. Physiological signals

There are plenty of physiological measures that can be recorded or extracted from signals. Some are easy and intuitive to use, others require some expertise on the field or an intense amount of processing and analysis.

Electroencephalography

Commonly recognized as EEG, Electroencephalography is one of the most used methods to study the human brain. EEG usually uses some sensors placed on certain areas of the head. One configuration of sensor used is the 10-20 system [3]. EEG has various bands based on the frequency of the signals. The delta band is linked to sleep and increases near tumour locations. The Theta frequencies are linked with attention and mental demand. The Beta band is also associated with attention and vigilance. Finally, the Gama band is linked, again, with attention, object recognition and arousal. [4]

Cardiovascular measures

The more traditional method to record the heart's health is Electrocardiogram, ECG or EKG. ECG shows the changes in electrical potential of the heart.

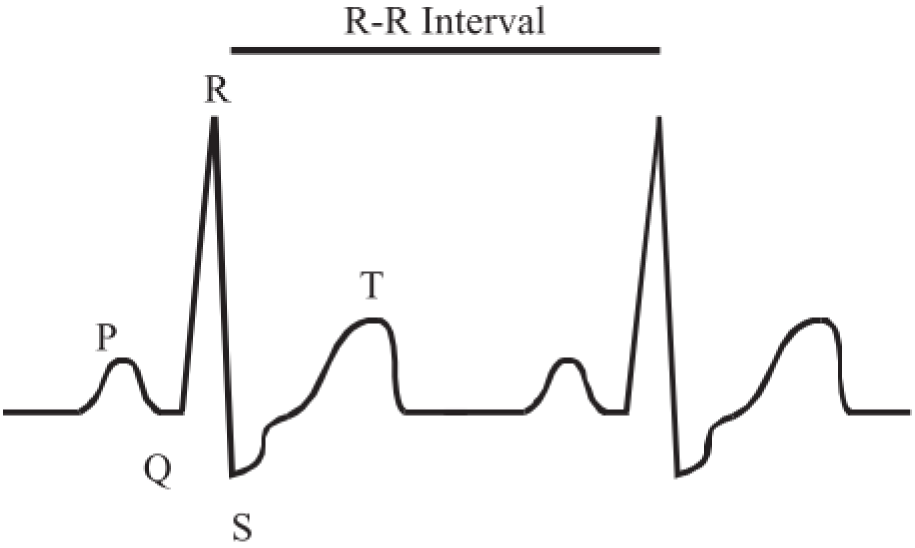


Figure 3 - Example of a perfect ECG signal[5]

The peaks represented by the letter R, in Figure 3 ,occur when the ventricles contract [5]. The difference between each consecutive peak is called heart rate variability (HRV) [6]. ECG usually is recorded using 3 electrodes: Positive, negative and neutral. Another form of calculating heart rate is using Photoplethysmogram (PPG). PPG measures the blood flow and is usually placed on a ear lobe or tip of a finger [7].

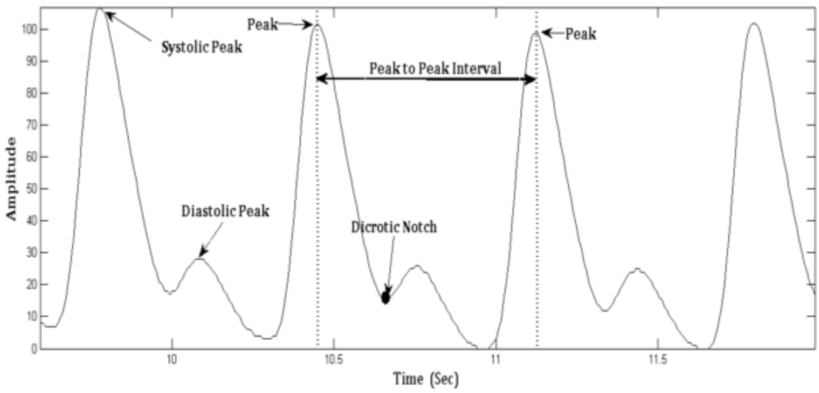


Figure 4 - An expected PPG signal [7]

With PPG, HRV is also possible to be calculated. The real time heart rate value in beats per minute (BPM) can be achieved using the following formula:

- heart rate (BPM) = 60 seconds/time of peak's occurrence. [7]

Electrodermal Activity

EDA is also known as skin conductance (SC) or galvanic skin response (GSR). EDA uses two bipolar electrodes, one sends a constant electrical charge to the other and these changes are the values measured by EDA. [8] The units used for EDA are microsiemens. This measurement has been linked to emotional arousal [9]. The more aroused a person is higher the EDA value.

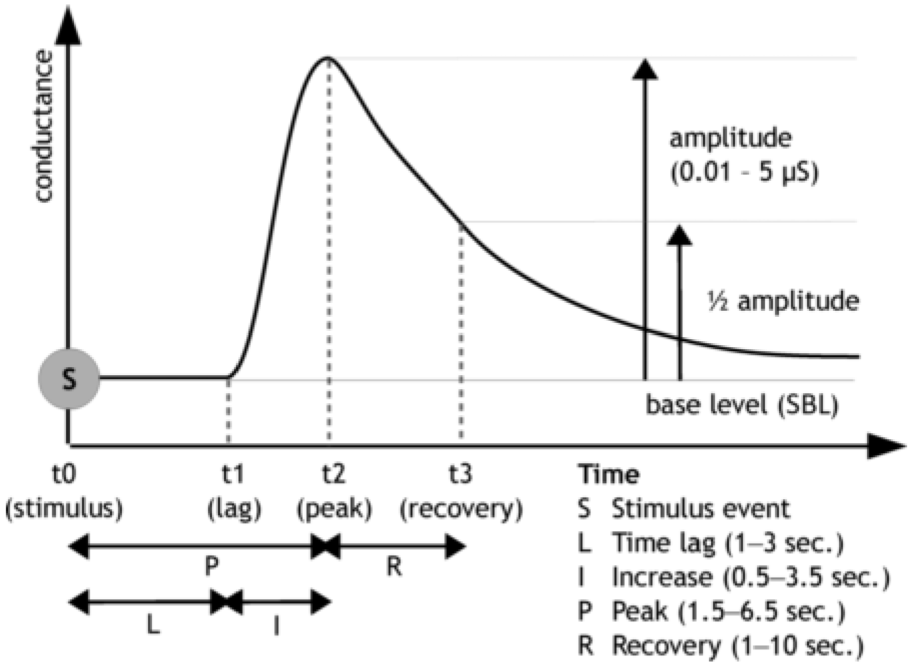


Figure 5 - Ideal EDA response [10]

EDA can be decomposed into two components. The tonic component or skin conductance baseline level (SBL) and the phasic component or skin conductance responses (SCR) that are the peaks. A peak is usually regarded as a response a certain stimulus. There is usually a delay in the response that can go up to 3 seconds. For real-time SCR detecting a threshold of 0.05 microsiemens is suggested. [11]

Electromyography

Electromyography or EMG is, usually, placed over a certain muscle and serves to record the level of that muscle's activation. EMG detects contractions or flexions in a muscle. When a muscle is activated an electrical signal is sent to the muscle and EMG record those changes. One common use of EMG is to identify emotions using the facial muscles. Regarding game experience, these emotions can translate to a positive or a negative reaction from the player.[2]

Summarizing, There are various physiological signals that can be used for multiple purposes. EEG can be used to detect arousal or players' attention. ECG or PPG are used to calculate heart rate values or to extract HRV. EDA signals can be used to detect the emotional arousal level of a player during game play. To access whether a muscle or group of muscles are activated EMG can be used. EMG also can detect positive and negative emotions, if placed on the user's face.

2.3. Physiology in game development

Earlier, the use of physiology or biosignals for Game User Research was described to be used to assess the emotional response to a stimulus in game. Although this is extremely informative to the game designer, the usage of these signals could be more effective. These signals can be part of the gameplay and act as an additional input to the game. Games which use the physiological signals as input and consequently adapt game are known as adaptive games.

As early as 1984 some companies like Atari, Inc. (New York, USA) tried to build games that would change based on the player's physiology. The Atari Mindlink used EMG placed on the forehead but it was never commercialized because it gave headaches to the players. Around the same year, a Canadian company developed a racing game using GSR. Later, Nintendo[1] built a version of Tetris, for the Nintendo 64 console, that adapted the velocity of the game based on the player's heart rate [12]. More recently, Nintendo had announced Wii Vitality [13], but it never reached the market. Ubisoft[2] has Ozen[3], an app for iPhone and iPad that teaches to relax by breathing. Even Sony has a patent for a sensor capable of recognizing emotions [14].

[1] Nintendo Company, Limited (Kyoto, Japan)

[2] Ubisoft Entertainment S.A (Paris, France)

[3] http://experience-ozen.com/en-GB

These are some examples of big companies in the gaming industry trying to push games that use biosignals as a mean to amplify the game experience. But not only big companies are working on these games. The indie game industry has also developed some adaptive games such as NeverMind[4] from Flying Mollusk (California, USA) or Unyte: Interactive Meditation[5] from Unyte Health Inc. (Toronto, Canada).

The Unyte game and Ozen are examples of games that were designed to train relaxation and stress relieve. Bersak et al. [15] also built a two-player racing relax-to-win game which made the player go faster the more relaxed he was. Space Connection was developed to promote collaboration between teenagers by controlling their physiological responses [16]. This genre of games provides an explicit feedback of the player's signals and the player is supposed to reach an optimal state. This way the player learns how to control his own physiology and relax, for instance, in a more stressful situation. [17] Others have not built games but applications using biofeedback as well [18]–[20].

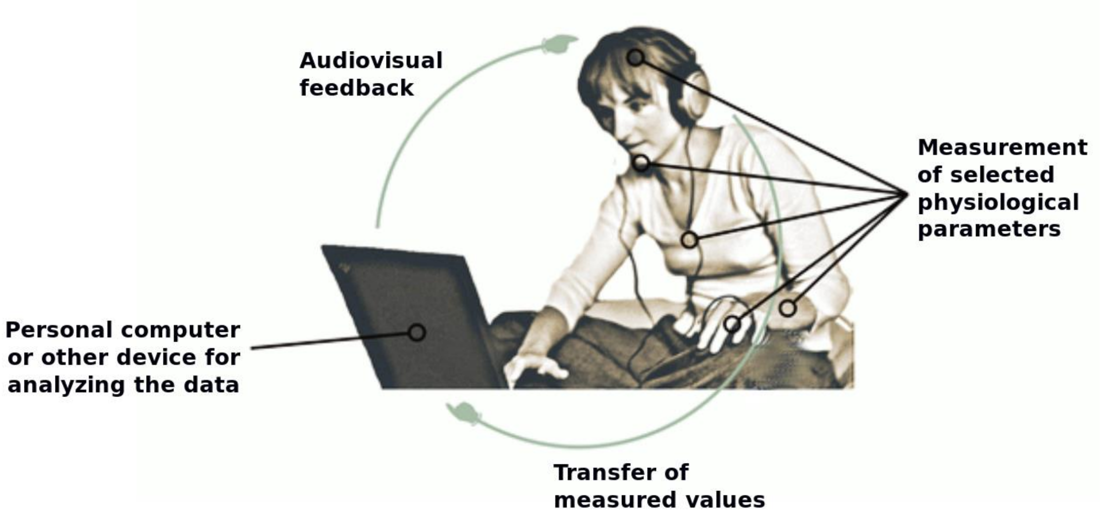

Audiovisual feedback
Measurement of selected physiological parameters
Personal computer or other device for analyzing the data
Transfer of measured values

Figure 6 - Biofeedback loop [21]

The biofeedback loop explains (Figure 6) how games and the applications mentioned before, use the physiological data to adapt their output. The signals are recorded using hardware built for the effect. This hardware then sends the physiological state to the software, the software applies changes to the visuals, to the audio and/or to the game mechanics and those changes are outputted to the user.

Rosalind Picard described affective computing as "computing that relates to, arises from, or influences emotions" [22]. The aim of affective computing is to create computers that have the capability to recognise emotions, through

[4] http://nevermindgame.com/
[5] http://unyte.com/

the physiological signals of its user and respond accordingly. Inspired by this new subject, Bersak et al. introduced the term affective feedback [15] opposing to simple biofeedback. The authors state that with biofeedback the player learns to control their emotions based on the information that the system (game or other software) provides, whereas with affective feedback the game also adjusts to the user based on his emotional state.

Moreover, there are two kinds of biofeedback: direct and indirect biofeedback [23]. The direct biofeedback is used as a mere input to the game, it acts the same way a click of a button (or sequence of buttons), after the input an action inside the game is expected. For instance, in a boat game using respiration to control the boat's velocity, the respiration is considered a direct input. Some examples of direct biosignals are: respiration, contracting a muscle, eye gaze or other signals which the player can directly control. On the other hand, indirect biofeedback is when the biosignals are not controlled directly by the user. These signals usually change the ambient of the game or add/remove powers. An example is [24] that used HRV and GSR to change the environment, adding and removing filters to the screen. Examples of indirect signals are heart rate, stress, attention. Nacke et al., further states in [23] that with the combination of direct and indirect biofeedback is possible to increase the levels of emersion and satisfaction. Direct and indirect biofeedback loosely translates to implicit and explicit feedback [25]. Explicit biofeedback is the biofeedback that is presented to the player to facilitate control over the signals, whereas implicit biofeedback are all the biosignals that are not presented to the user, consequently the player may not even be aware of the changes.

To differentiate games in which the user knows how their physiology manipulates the game from those where the user was not able to figure out which elements were changed, the concept of affective games was born [26]. Affective games may use affective feedback and change the gameplay amplifying or minimizing the player's emotions. In a sense, the player is not aware of the changes in the game and which physiological responses handle that change. To sum up, the authors describe that a game is affective if the player is not aware of the complete cycle of the biofeedback loop. Consequently, in biofeedback games, the player is fully aware of the biofeedback loop. There is a fine line separating both genres. For instance, when playing an affective game, if the player becomes familiar with the biofeedback loop, then that game becomes a simple biofeedback game.

To summarize, physiology has been used in game development for more than 30 years, manipulating the user’s state to create more immersive and compelling games. Research shows that players enjoy this kind of interaction and this is shifting, somehow, how we consume games and, in a way, how games respond (the physiological data) to the user. Affective games are games where the user has no perception of the changes in gameplay or cannot control his biosignals. However, if one becomes aware of how biosignals are affecting the game, it becomes a biofeedback game.

The next section is dedicated to how can one build games that are affective and the frameworks that are available.

2.4. Developing affective games

Even games that are not affective always have in mind the engagement of the player and how much the game is enjoyable to play. After all, all games are designed to be played. So, even non-affective games have some sort of adaptation. Usually in the form of game difficulty adjustment (easy, medium, hard, expert). In a limited way, this is an attempt from the designer to create an engaging game. The problem here is that the perception of level difficulty from the player can be different from the game designer [27]. Therefore, using adaptation decreases the gap of level perception and the game is, in theory, engaging for all kind of players, from novice to expert.

The adaptation can be made within two opposing patterns: positive or negative feedback. The former increases the gap between the desired emotional state and the actual state, while the latter reduces this gap [28]. In-game a combination of both loops can be used. The positive biofeedback is used as a challenge to the player and the negative biofeedback to maintain a desired state.

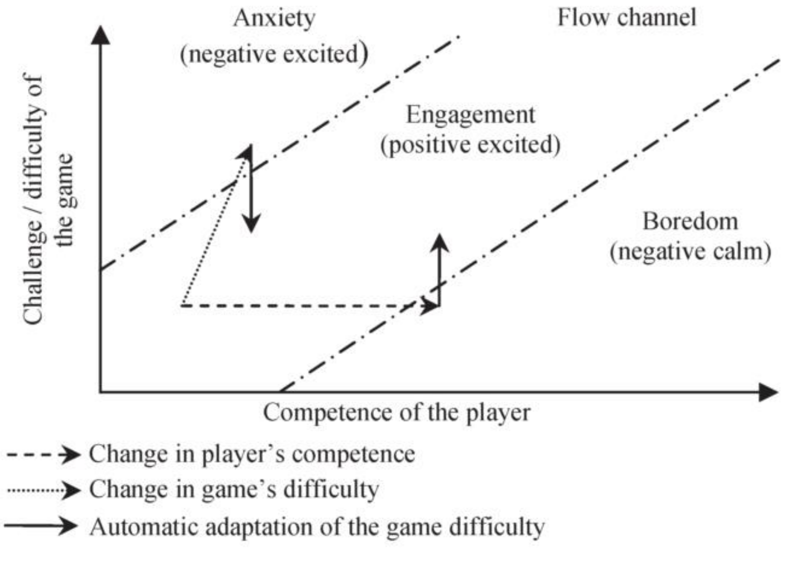

Anxiety
(negative excited)
Flow channel
Engagement
(positive excited)
Boredom
(negative calm)
Challenge / difficulty of the game
Competence of the player
Change in player's competence
Change in game's difficulty
Automatic adaptation of the game difficulty

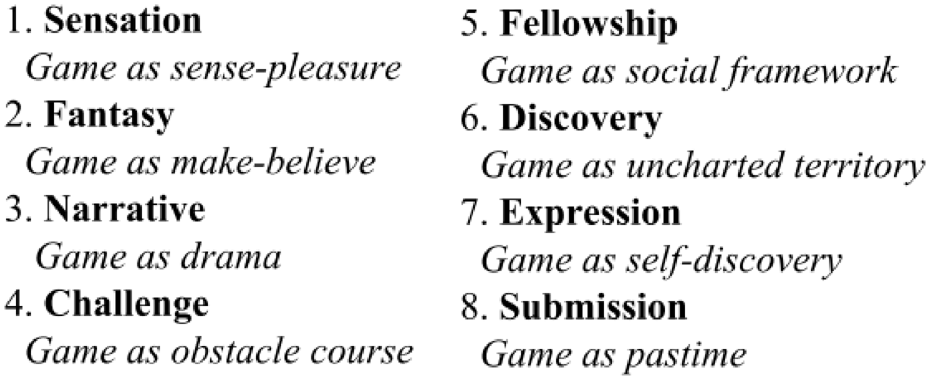
Figure 7 - Game flow and emotions associated to automate adaptation [29]

Figure 7 shows the flow channel which is the channel that the game designer wants the player to be through all game experience in both adaptive and nonadaptive games. The authors introduce a small change. Using three emotions (anxiety, engagement and boredom) it is possible to know if the player is inside the flow channel or not, thus changing the game whether the player is in the flow state or not. Using this approach, the user is always engaged with the game providing a better game experience. In a high flow state the low-frequency power of HRV decreases and there is a higher respiration depth [30].

Gilleade et al. in [26] present three models to design games: Challenge me, Assist Me and Emote me. Challenge me consists in creating strategies to increase the difficulty of the game based on the player's state. Using the player's physiology, one can place the player in a difficulty setting more appropriate. Also, the increase of difficulty can be adjusted based on both the performance and state of the player. On the other hand, assist me, has the main goal of assisting the player along the gameplay. Some actions that are trivial for some players may be difficult to others. Measuring the level of frustration of the player, the in-game location and the objective, the game designer can figure out why the player is feeling frustrated and give a clue making the objective simpler. For instance, if the player is looking for a special character in the game and can't find him, using the frustration of the player as input, the game could make the character reach the player, or place the character in a place where he would be more visible to the player. Two different kinds of frustration can arise [27]. At-game frustration which translates to the player not being able to use the input source as desired, such as when a sequence of fast commands is needed but the player is never able to complete the sequence. In-game frustration is related to the inability of completing a mission or not knowing how to proceed to the next game scene. Emote me, is thought to generate emotions during the gameplay. Every game designer when builds the game wants the player to feel a certain emotion, hence the soundtrack changes throughout the game, for example. However, a state that triggers a determined emotion for the game designer could trigger another in the user. Therefore, measuring the player's emotions the game designer can change the surroundings to trigger the desired emotion based on the current emotion. The two first modes of adaptation serve as support to the Dynamic Difficulty Adjustment (DDA) [31]. Traditional DDA is based on the performance of the player, meaning that the difficulty adjustment is made through positive feedback. This can be taxing on the player, though. A better way to implement the DDA is using the affective state of the player and decide whether to apply positive or negative feedback. Changchun Liu et al. demonstrated that DDA based on the player's physiology increased performance when compared to traditional DDA [32]. The authors suggest that a combination of both should be used though.

In [33] the authors describe three game task types that can be used to complement the physiology to be used in DDA. Explicit tasks are those defined by the game designer. They are mandatory for the player and are usually proposed as objectives, missions or goals. Examples are defeating a final boss or grab a key to unlock a door. Implicit tasks are the ones that the player is supposed to complete but is not obligated to continue the game. For instance, not dying or complete a mission without being found by the enemy. Lastly, player-driven tasks are tasks that are created by the user's imagination. These tasks are common in games that have an open world map and some examples of these tasks can be destroying all the blocks in Super Mário[6] or driving by the rules in Grand Theft Auto[7]. Another notable example is Minecraft[8] in which all its success is due to the player-driven tasks that each player creates during gameplay.

A game can be divided in three components: rules of the games, the system, which is how the rules apply to the game and how rules interact with the player, and the fun factor. The MDA approach [34] is a traditional framework that establishes three design components that correspond with the latter components. Mechanics are about the game rules and actions which the player can perform. Dynamics correspond to the system component and which mechanics are available at one point of the game and how inputs from the player manipulate the game are defined here. Aesthetics characterise the fun in a game and the emotional state of the player.



1. **Sensation**
   Game as sense-pleasure
2. **Fantasy**
   Game as make-believe
3. **Narrative**
   Game as drama
4. **Challenge**
   Game as obstacle course
5. **Fellowship**
   Game as social framework
6. **Discovery**
   Game as uncharted territory
7. **Expression**
   Game as self-discovery
8. **Submission**
   Game as pastime

Figure 8 - Suggestion to describe the fun factor and gameplay in MDA [34]

In conclusion, many approaches can be used to develop a game. The fundamental factor is to keep the level of engagement through all the gameplay. This is a priority in traditional and affective games. Keeping in mind the three modes of adaptation from Gilleade et al., Challenge me, Assist me and Emote

[6] Game owned by Nintendo Company, Limited (Kyoto, Japan).

[7] Game developed by Rockstars Games (New York, USA).

[8] Game owned by Microsoft Corporation (Washington, USA) created by Mojang (Stockholm, Sweden).

me it is possible to build more continuous game flows that adapt to every player. Although the games may be affective, former methods used in traditional game development should not be ignored but included when making affective games. Finally, games that record physiology usually require extra and dedicated hardware to record these signals. One ought to further study the hardware already built by researchers and those available commercially.

2.5. Recording physiological signals

All the affective games need, somehow, a piece of hardware that enables the recording of the signals. The hardware, sometimes, is custom-made and built by the researchers [6] and [23], other times some commercial available physiological system is used [12], [16], [19], [35]. Plus, some use DIY development kits such as the Arduino[9] (New York, USA) [36].

BIOPAC Systems Inc.[10] (California, USA) is a company that provides a variety of systems that can be used to record physiological signals from the user. The system configuration is very versatile and can be used to monitor static or mobile users, has data logging capabilities and integrated software to see all the data. The systems can record ECG, EMG, EEG, HRV, respiration and others that can be found on the website, both in animals or humans. The company provides from the electrodes to data analysis or software to stimulate the user. The prices are available upon consultation and depend on the setup required. Biopac states on its web page that is one of the most used systems in Universities [37]. Systems from this company have been used in [7], [32], [15].

[9] https://www.arduino.cc/

[10] https://www.biopac.com/research/

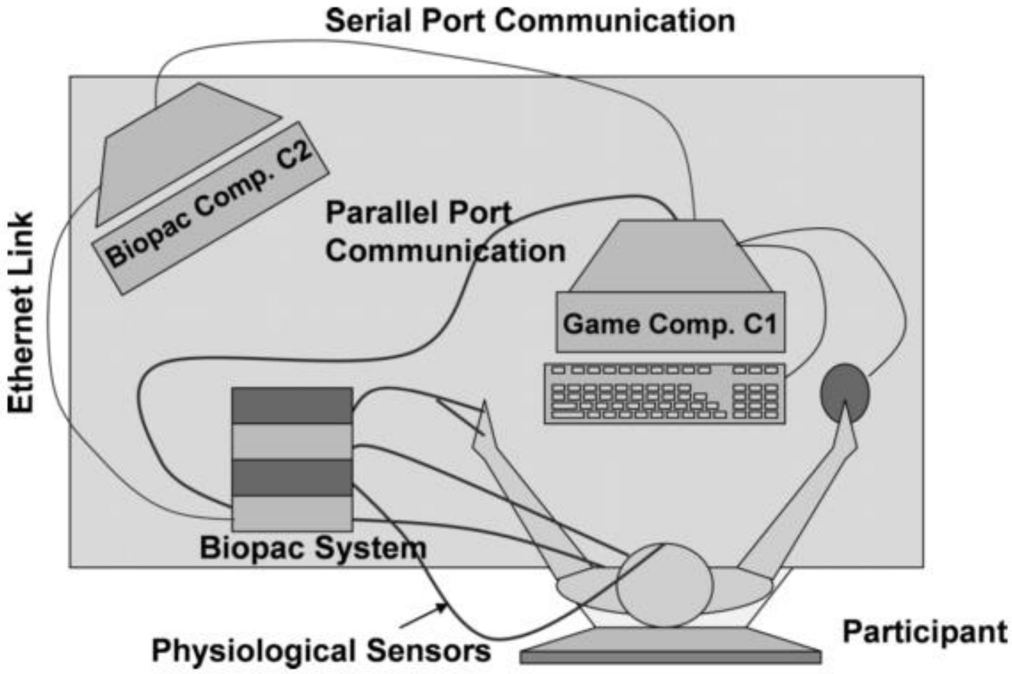


Figure 9 - Example of a system setup using Biopac [32]

A different hardware solution available is the biosignalsplux[11] [38] from PLUX, wireless biosignals, S.A. (Lisbon, Portugal) which has a big range of sensors also available such as ECG [39], EDA [40], EEG [41], EMG [42], respiration [43], temperature [44], blood pulse [45] and accelerometer [46]. It is a high-end acquisition system that works via Bluetooth and has an optional internal memory, making it portable not needing a computer at all times. It has up to four input analogue channels with a resolution of 16 bits and a sampling rate of 3 kHz. The biosignalsplux Solo is the cheapest kit available and costs 405.00 euros, however has only one input channel. The biosignalsplux Explorer kit is available with four input channels and four sensors included at 995.00 euros. The OpenSignals[12] [47] is an open-source software that is available to record and analyse the signals.

The portuguese company, Plux, has another hardware acquisition system. It is an Arduino based acquisition system that was developed thinking about researchers and enthusiasts with little background in signal processing called BITalino [48]. Similarly, to the biosignalsplux system, the BITalino also, connects via Bluetooth, has the same number of analogue inputs but in a lower bitrate (10 bits), and a sampling rate up to 1 kHz. Additionally, two digital inputs can be converted to analogue inputs up to 6 bits [49]. Concerning the sensors, EMG [50], ECG [51], EDA [52], accelerometer [53] and pulse sensors [54] are available for this board. Three distinct solutions are available. In the

[11] http://biosignalsplux.com

[12] http://biosignalsplux.com/en/software/opensignals

board version, the hardware is sold as one-piece ready to be tested, the plugged version the sensors and the main board are separated and can be easily attached as pleased and the freestyle version the sensors are also separated from the main board enabling people to use their own custom sensors [48].

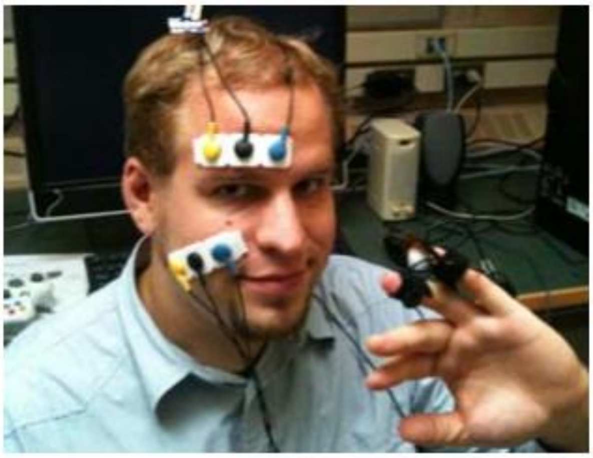


Figure 10 – Facial EMG and EDA setup [12]

However, these systems can be complex and cumbersome for the user. If these sensors are placed on the hand, they limit the use of said hand so physiology cannot be combined with traditional input devices like keyboard and mouse or even a game controller. Some companies have devoted their time to build less invasive hardware. MindWave is an example of a headset that uses a single electrode to record EEG signals [55]. On the EMG and muscle movement recognition ground, there is the Myo Armband. An armband that is capable to detect various arm and hand movements and send them to a computer or mobile device using Bluetooth [56]. Most of the smartwatches, nowadays, come equipped with PPG and are able to measure pretty accurate heart rate values [57]. Additionally, even the smartphone cameras with some image processing software that can measure the heart rate [58].

To enable easy recording of physiological signals and the use of game controllers at the same time, researchers have tried to come up with gamepads attached with physiological sensors. Previous work such as the Emopad tries to gather the physiological data on a controller in a way that the user only has to worry about grabbing the controller and play [59].

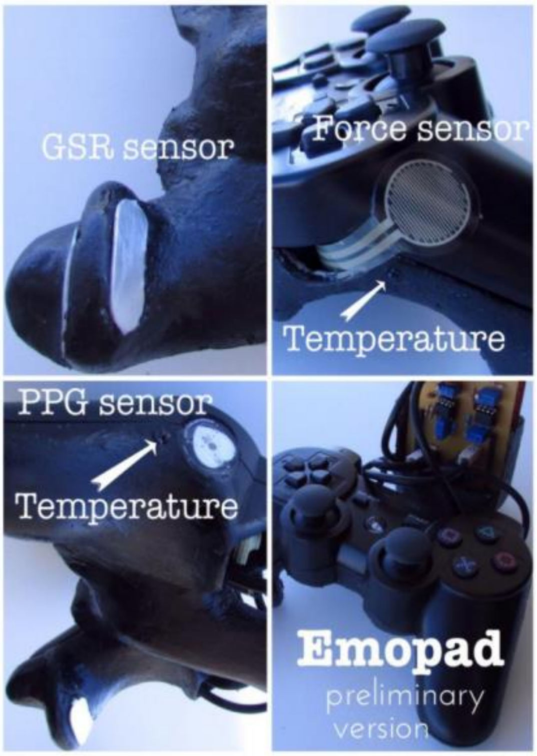


Figure 11 - Emopad prototype [59]

The controller chosen, a PlayStation 3[13] replica, has embedded GSR, PPG, TEMP and FORCE sensors and their placement can be seen in figure 11.

These sensors connect to the MSP430 TI [60] micro controller. The GSR and TEMP sensors were custom built and the circuitry is available in [59]. In Stanford a similar controller inspired on the Xbox 360[14] controller, has been implemented [61]. This controller can record the heart rate, respiration and temperature of the player during gameplay.

To conclude, there are a great number of hardware devices ready to record and process physiological signals, but most of them require a various number or electrodes placed on the correct site or are bulky and too expensive for the common user. Solutions such as Emopad are interesting because they facilitate the acquisition of signals and are not obstructive to the user and the researcher does not have to verify if the electrodes are in the correct position. The player just should grab the gamepad and play the game. Emopad and the controller from Stanford could be the first steps towards the adaptation of physiologically capable controllers by the casual player at home.

[13] Console owned by Sony Corporation (Tokyo, Japan).

[14] Console owned by Microsoft Corporation (Washington, USA).

3. Development

This thesis' results in the creation of two artefacts: a software one, and a hardware one. For both, the requirements were not well defined and changes to the existing ones could be necessary. For this reason, the development process chosen was prototyping. With prototyping, one can easily build a functional part of the system, evaluate and iterate based on the result. Even tough prototyping was used for the hardware and software development, different methods were applied. More information on the model processes can be found below (See section 3.1.1. for the hardware development process and section 3.2.1. for the software development). The development of the hardware and the software were done side by side but as independent systems, consequently, the description of their implementation will be separated to ease the description of both systems' implementation. The following section is dedicated to the hardware and the latter to the software implementation.

3.1. Hardware

In this section, one can find all the procedures and experiments elaborated while building the game controller. All the experiments are described chronologically from the earliest experiment to the latest. From the list of hardware solution visited on the literature review (section 2.5.), the hardware platform chosen to record physiology was the BITalino. This decision was based on (1) the affordability of the platform, when compared with others, (2) the portability of the system and (3) the ease of use and the support community built around the platform. BITalino has a forum[15] on its website with an active community which is a plus for people that have never used physiological devices before.

3.1.1. Hardware development process model

For the hardware development, throwaway prototyping was used [62]. Throwaway prototyping aims to build fast and cheap prototypes based on the requirements that are less well understood, giving the developer a better understanding of them. After, a final version is built using the knowledge acquired with the prototype. With a lack of knowledge in electronics and physiological signals, the throwaway approach was the most suited method. This way, the cost of the controllers' prototypes could be lowered. For instance,

[15] http://forum.bitalino.com/

using blue-tack and tape to place electrodes on the controller, instead of perforating the controller for each new position tested. After each discarded prototype, a part of the controller emerged resulting as the final prototype.

3.1.2. Requirements

This section is dedicated to the requirements definition for the controller. Below, a list of the functional and non-functional requirements that emerged during the development of the controller.

3.1.2.1. Functional Requirements

RF#1 - The gamepad must be able to record the heart rate.

RF#2 - The gamepad must be able to record the engagement of a player.

RF#3 - The gamepad must be ready to use in less than a minute.

RF#4 - The gamepad must be non-invasive.

RF#5 - The gamepad must work, at least, on pc.

3.1.2.2. Non-Functional Requirements

NFR#1 - The gamepad ought to be a commercial game controller.

NFR#2 - The gamepad ought to maintain the original structure.

NFR#3 - The gamepad ought to be replicable.

NFR#4 - The gamepad ought to be easily used by average gamers.

3.1.3. Gamepad map for hand placement

The main goal of this experiment was to understand how people hold and interact with the gamepad. With a map of where the hand touches on the game controller, we can determine the best spot to place the electrodes and sensor on a Gamepad. The experiment consists in people interacting with a tinted controller during some time. Finishing the interaction, the tint is transferred to the hand based on how the user holds the gamepad. The figure 13 (left) shows the palm of a tester after the experiment.

For the interaction, the *Grand theft Auto III*[16] was used because it has driving, shooting and character movement during its gameplay. The controller used was a wired version of a *PlayStation 3* controller. This controller is usually cheap and available in most online stores. Each session took 15 minutes and the tester ought to play through the missions in the game. There were 10

[16] Game developed by Rockstars Games (New York, USA).

testers, all male, ageing from 19 to 22, averaging 20 +- 1.2 years-old All the subjects were experienced gamers.

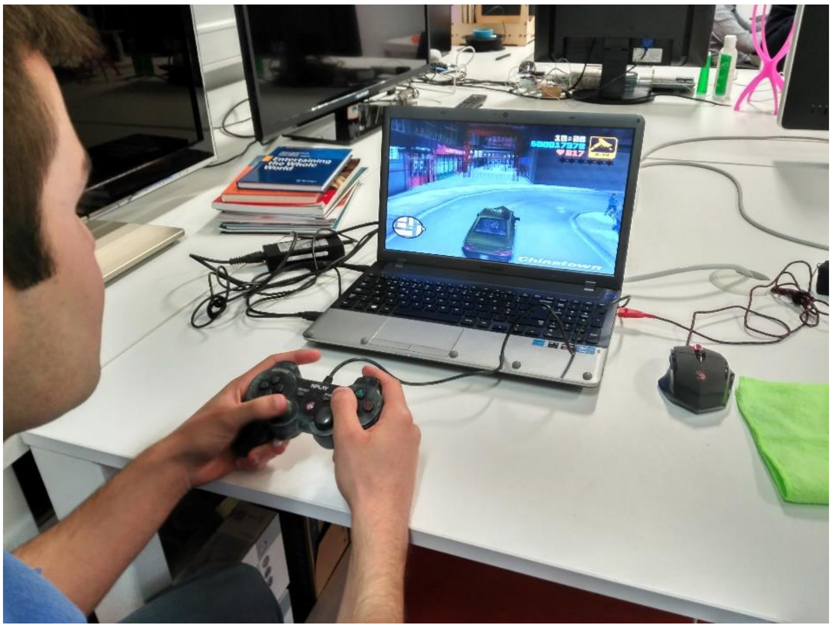


Figure 12 - Subject playing GTA game for the heat map experiment

After the test, the users would have their hand tinted where they were holding the controller. To enhance the tinted part all images were edited using the photos app available on *Windows 10*. All images got the same manipulation: (1) enhancement was enabled; (2) the brightness was brought down to -17; (3) the contrast was put on 100; and (3) highlights and shadows were set to -10. The rest of the editable options were left untouched. Figure 13 shows an example of a tinted hand, before and after the manipulation.

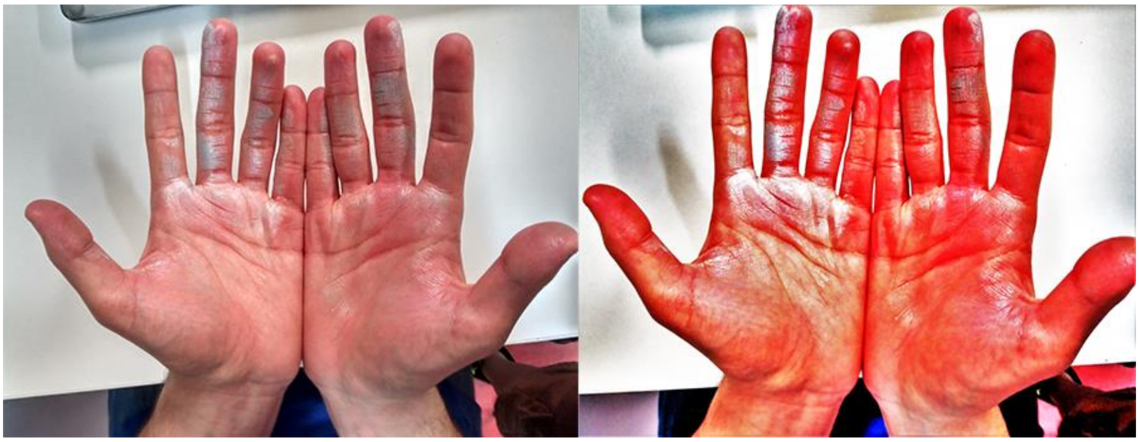


Figure 13 - Left image is a subject's hands after session and right picture after editing to enhance grey areas

To analyse the result all edited hands were overlapped using the free editing software GIMP[17]. The hands were cropped to only the parts that were in contact with the controller. To overlap all the images, opacity was scaled down to 70%. With this we can analyse the overlapping areas and see that the greyer areas are the ones which touched the controller the most. In figure 14 it is possible to see that the best positions to place electrodes are on the tip of the middle, ring and pinkie fingers and the top part of the palm.

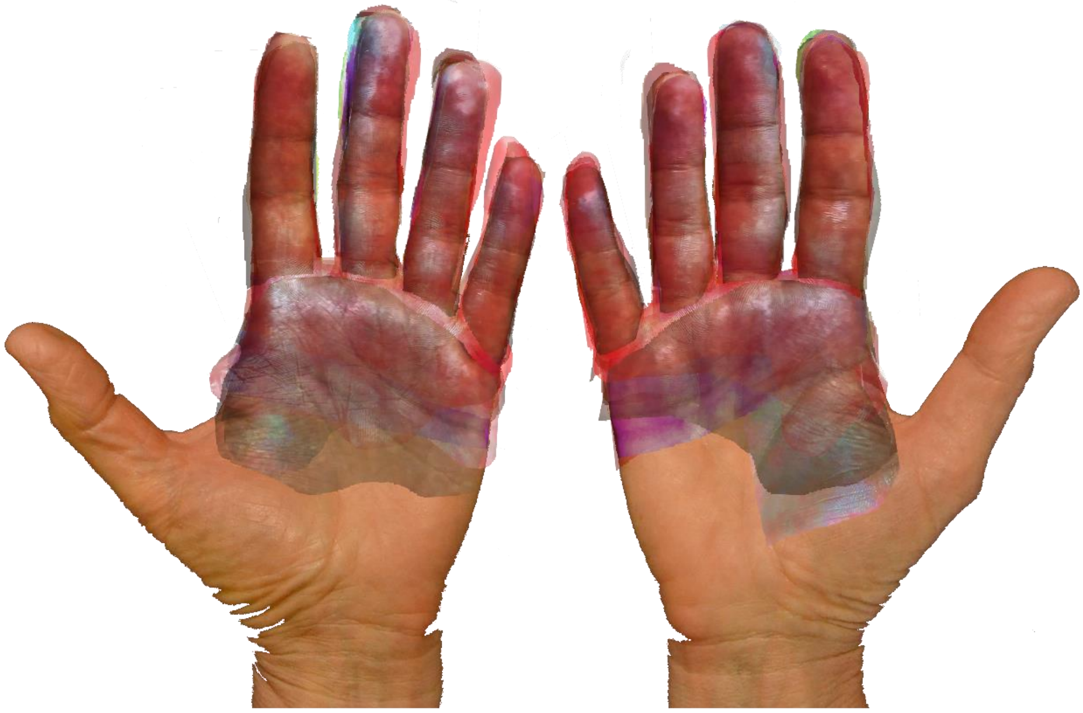


Figure 14 - Result of the experiment after all players' hands overlapped

3.1.4. Testing ECG positions on the hand

One of the goals, for this thesis, is to have the less invasive controller so the ECG should also be placed on the controller. Thus, this test had the objective to find which configuration of positions would be the best for ECG recording.

To record the ECG signal an older version of BITalino plugged board [63] was used, as well as its ECG sensor [51], which was the most recent version at the time and the BITalino software OpenSignals. A post-analysis was done using PhysioLab[18] [64] in order to calculate the heart rate (BPM) during the session and also the signal to noise ratio (S/N). Unable to figure out the noise of the ECG sensor and BITalino, the noise was computed using a gaussian noise

[17] https://www.gimp.org/

[18] https://neurorehabilitation.m-iti.org/tools/physiolab

function available on MATLAB. This will not give the accurate signal to noise ratio of the signal but will give a mean to compare the S/N ratio between positions.

The figure 15 shows the ECG sensor connector for BITalino. To represent each electrode and an easier visual understanding, the positive, reference and negative connectors were renamed to left (L), centre (C) and right (R), respectively.

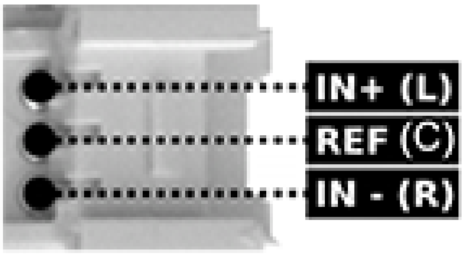


Figure 15 -BITalino's ECG connector [51]

For the positioning of the electrodes four configurations were defined. Figure 16 shows the positions of each electrode for each of the 4 distinct positions using the tags R, Land C tags described before. This position were based on the heat map experiment and were chosen based on some informal testing, looking for the cleanest signals.

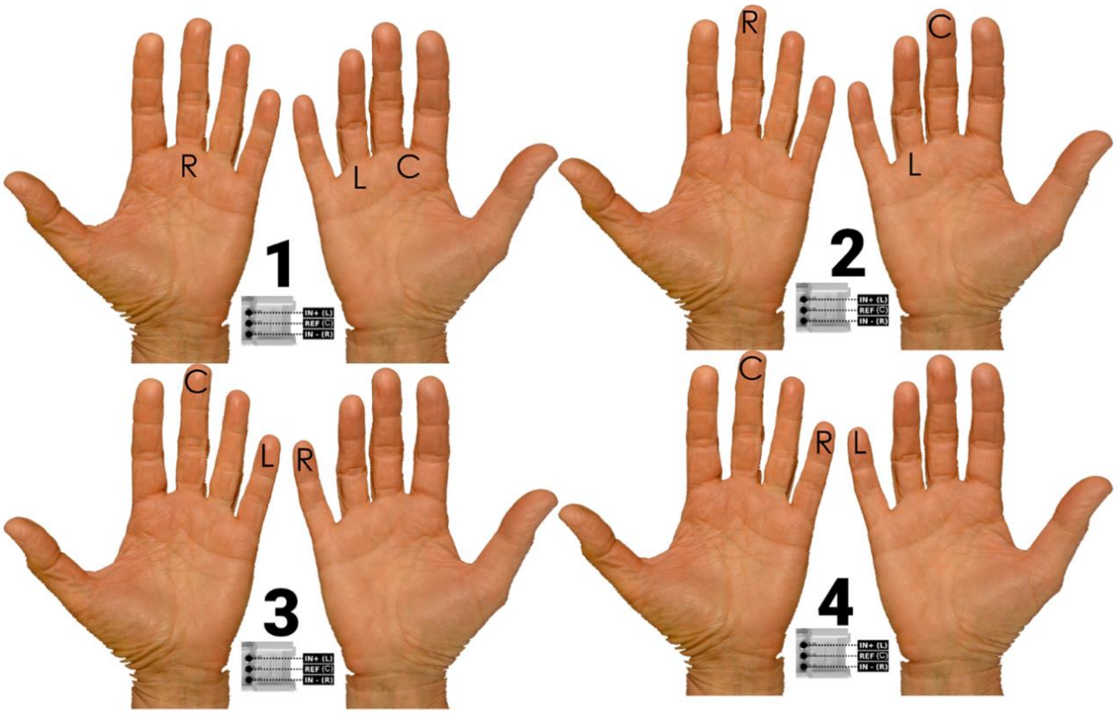


Figure 16 – Four configurations chosen to test ECG

Each session was composed of four one-minute ECG recordings, one recording for each configuration. This protocol was applied to 5 male users ageing an average of 20.2+-1.1 years old. All user were students from the computer engineering program from University of Madeira (UMa).

For the most part, one can observe that the peak detection was accurate as seen in Figure 17. The read triangles show the peaks being detected by Physiopad. A visual inspection show that all the R peaks were detected.

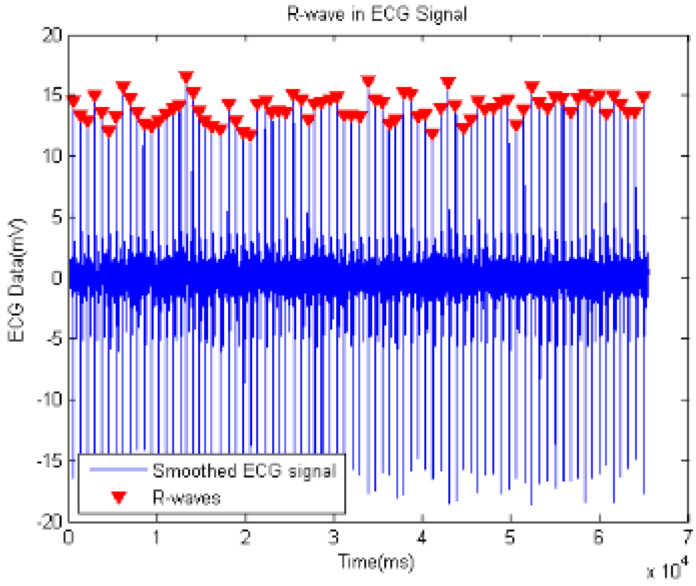


Figure 17 - ECG signal peak detection using PhysioLab

The HR values were also between the expected values when resting. So, the deciding factor would be the signal to noise ratio. As a result, the best configuration was the third one as observed on the plot below. The average HR result for this position was 76 BPM. Hence the configuration selected to be implemented in our gamepad was configuration 3.

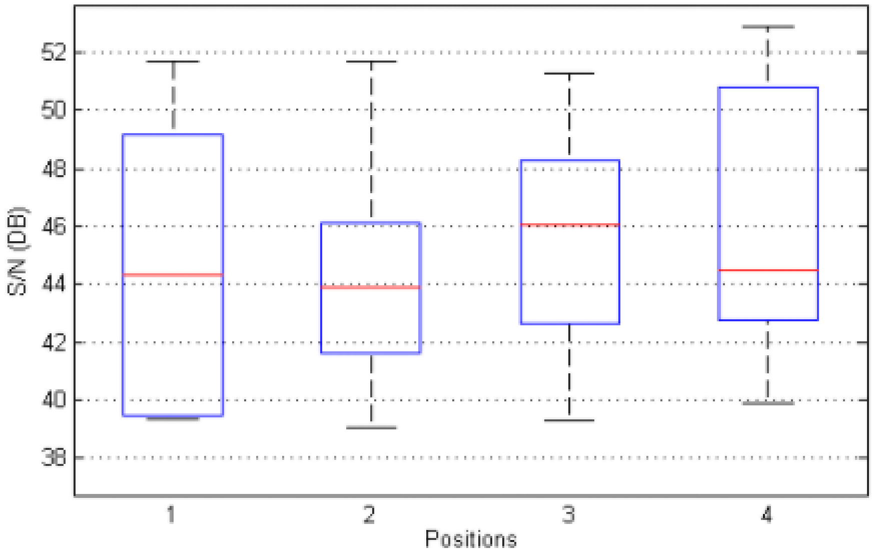


Figure 18 - Signal to noise ratio result from the 4 ECG positions

3.1.5. Testing PPG on the hand

With further research on the BITalino platform, a pulse sensor [54] was found. This sensor can record the PPG signal which, also, can be used to extract heart rate. The advantage of PPG over ECG is that PPG only uses one dry electrode where the ECG uses three wet electrodes. A disadvantage is that PPG is less accurate than ECG and is sensitive to misplacement of the sensor and the movement of the part of the body touching the sensor. Knowing the drawbacks, it was still a possibility to study because of the fewer electrodes, that translates to less space needed inside the controller to accommodate all the electrodes and sensors. So, as done for the ECG sensor, a similar test was done for the pulse sensor. Again, using the BITalino plugged board and the pulse sensor to acquire data. The recording was done using the OpenSignals Software. The HR was calculated after the sessions using the PhysioLab software. This time, five different configurations were chosen as seen in figure 19. Again, the positions were chosen with the heat map experiment in mind and with some informal tests to find the cleanest signal.

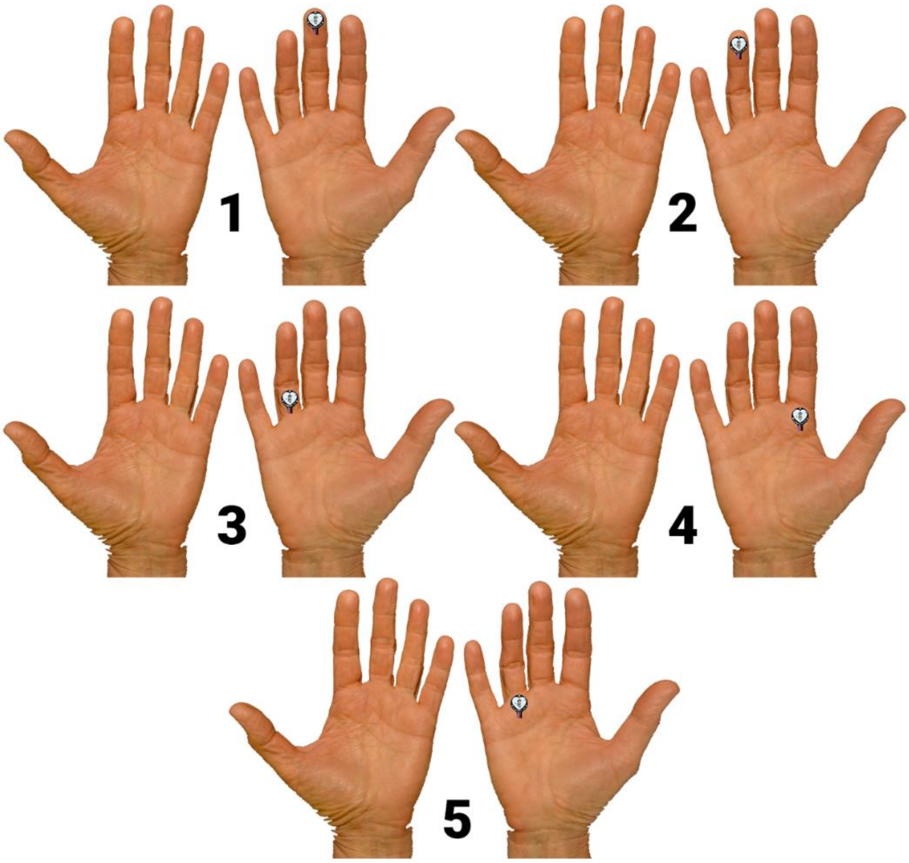


Figure 19 – Five positions defined to test PPG

The signals were recorded while resting and with the less movement possible from the user to have the most accurate signal. For each session, all the five configurations were recorded for one minute each. For this experiment, 5 users were selected from the computer engineering course at UMa. The ages ranged from 19 to 22, averaging 20.2+-1.1 years old. Each user did one session. Similarly, the ECG test, the HR values were inside the resting spectrum, and a signal to noise ratio was calculated. Again, a Gaussian function to compute the noise was used.

As can be seen in the results plot the best position was the second one, therefore the configuration chosen to be implemented on the controller, was configuration 2. Since the HR results were like ECG, it was decided to pursue a solution that uses the PGG for the HR extraction instead of ECG for the reasons and benefits already described.

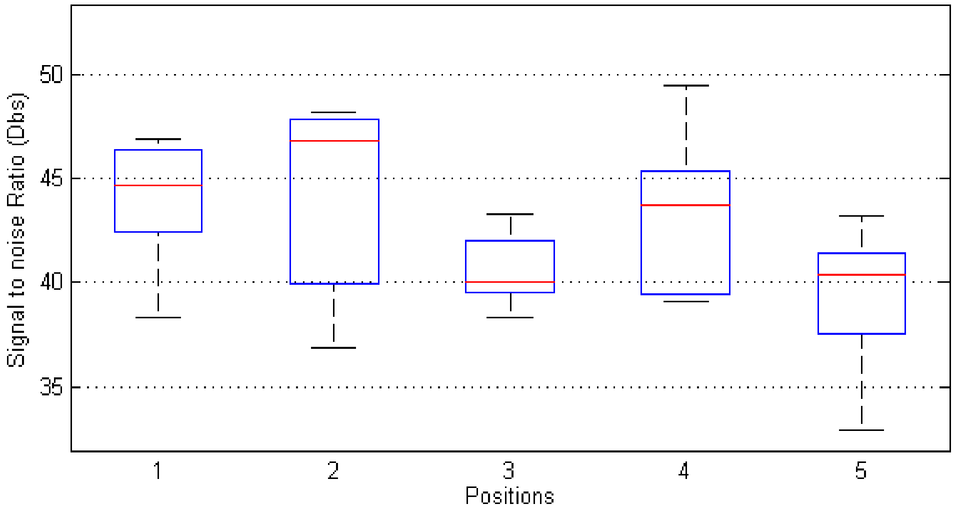


Figure 20 – Signal to noise ratio for each position of the experiment

3.1.6. Testing PPG position on the controller

With the earlier experience, it was possible to figure out which is the best position to place the electrodes on the hand. We are still missing the configuration to place on the controller, though. Hence, this experiment purpose is to figure out if the configuration defined for the PPG electrode is acceptable. The position, figure 21, was defined based on the most usual placement of the hand on the controller, which means that this is the position that the tip of the ring finger rests while grabbing the controller.

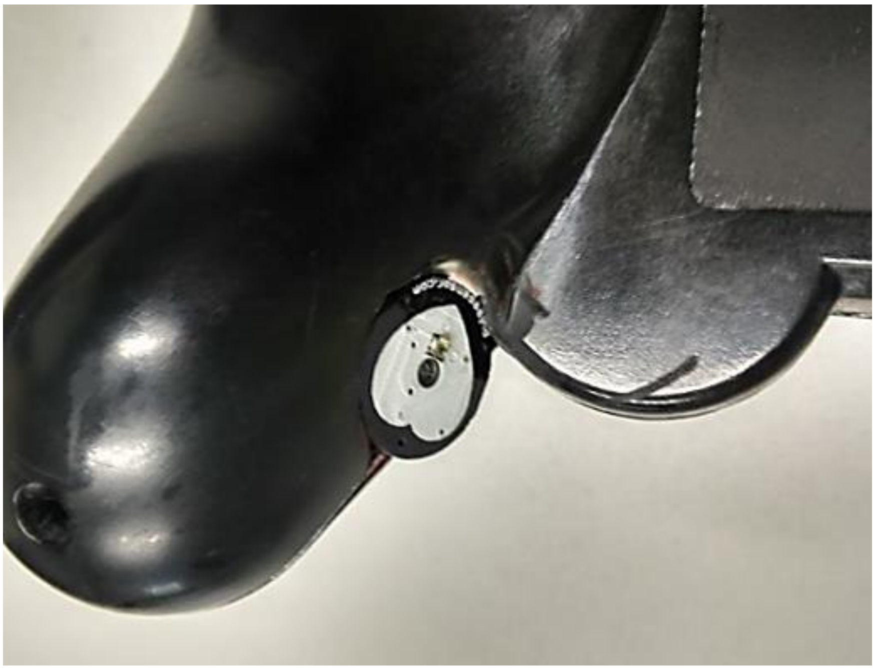


Figure 21 - PPG Position tested on the controller

This experiment consisted of playing a game during a period while extracting two PPG signals from dissimilar sources: from the gamepad (BITalino platform) and from the Smartwatch LG moto 360 [65]. The smartwatch acted as a mean to compare the signals recorded from the gamepad. The aim was not to compare the exact same heart rate value in any determined time, but to observe if the changes (increases and decreases) in the heart rate from smartwatch are also seen in the controller heart rate values. The assumption is that the PPG from the smartwatch is accurate enough to give reliable heart rate values even during exercise.

It was decided to use *WRC 4 FIA World Rally Championship*[19] game for this experiment. It is a rally game and the testers played the biggest track available averaging an eight-minute interaction with the controller. Six subjects were selected for this experiment. All subject were experienced gamers and ages averaged 20.2+-1.1 years old. The smartwatch was placed on the left wrist of all testers. To record the PPG from the controller the OpenSignals was used. Using the PhysioLab software it was possible to extract the heart rate per minute (BPM). To extract the heart rate from the smartwatch was used a software developed by the NeuroRehabLab research group[20] that saves, every second, the current heart rate to a file. For both, the controller and the smartwatch were given a 30 seconds period to stabilise the heart rate before the experiment.

Since the acquisition system for each PPG signals was different as its sampling rates, it was needed to resize some of the samples, making them comparable. Using the imresize [66] function available in MATLAB, the smaller samples were stretched to match the bigger one. The imresize function receives two arguments: the input to be resized and the factor of the resize. Two different comparisons were done with this experiment. The first, the raw heart rate values from the controller and the data from the smartwatch. The second, all the outliers (more than 170 bpm and less than 40 bpm) were removed the from the raw heart rate values of the controller using PhysioLab. This was done to remove all the artefacts introduced due to the movement of the finger from the sensor.

Limited by the way, each system functioned and the human capability to start recording both systems at the precise same time, some apparent delay may be added.

Since the objective was to understand if the reading from the smartphone and the gamepad would be similar and not testing que performance of the real-time heart rate detection algorithm, only a visual analysis was done.

[19] Developed by Milestone S.r.l. (Milan, Italy)

[20] https://neurorehabilitation.m-iti.org/lab/

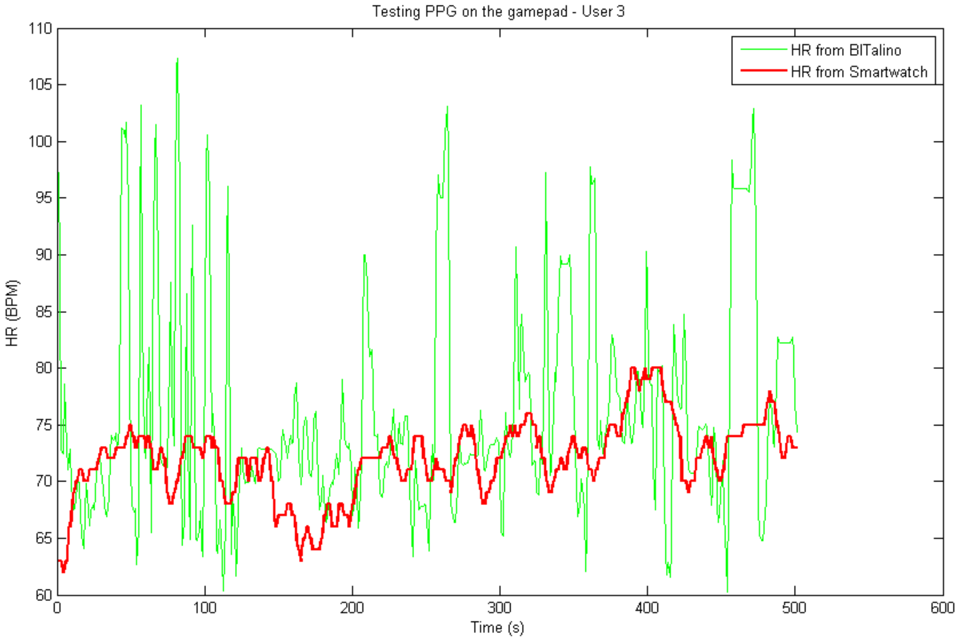


Figure 22 - Comparison of User's 3 hear rate from smartwatch (red) and Gamepad (green)

In figure 22 is possible to see that there are some discrepancies that could be from the natural movement of the finger. However, a trend is observed and it is believed that the real-time algorithm can reduce greatly the noise caused by the hand's movement.

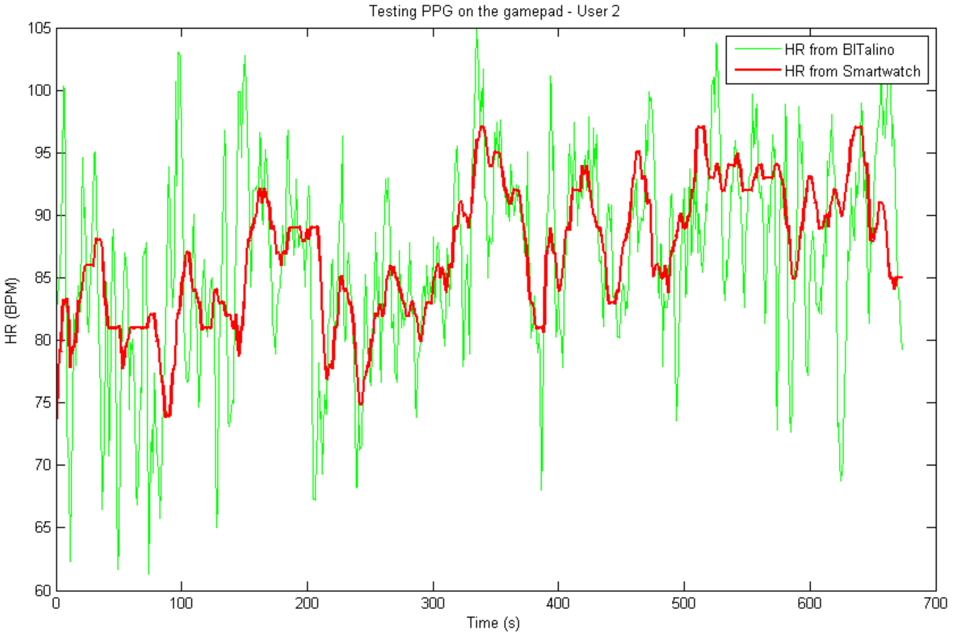


Figure 23 - Comparison of User's 2 hear rate from smartwatch (red) and Gamepad (green)

Figure 23 is another example that is possible to observe some overlapping of both signals.

Taking into consideration the nature of competitive games, some artefacts from hand movement are expected. All the subjects stated that the position was comfortable and it was placed right where they lay their finger. Listening to the users and knowing that the real-time algorithm for heart rate can reduce the abrupt changes in HR caused by movement, this position was accepted and chosen as the final position for PPG.

3.1.7. Placing EDA on the controller

Testing EDA signals' quality can be very difficult due to its ever-changing nature and there are no baselines that one can follow. Fortunately, one of the standard positions to measure EDA is on the fingers [67]. Contrary to ECG, that it is was needed to test the best position to record the signal, EDA was defined to be used with the index finger and middle finger or middle finger and ring finger. The player can choose the most comfortable configuration as long as the fingers are on the electrodes. For this prototype, copper coins were chosen. The coins have a nice texture and are easy to feel, so it is possible to know whether the fingers are on the electrodes or not.

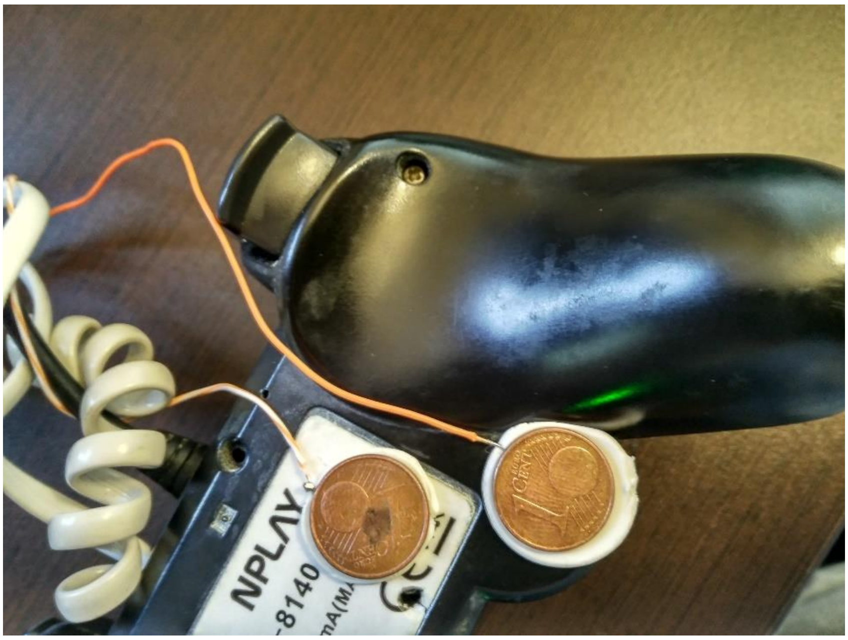


Figure 24 - EDA electrodes placed with blue tack

As a first approach, the electrodes were fixed with some blue tack. It eased the electrodes' replacement and position adjustment. Some informal tests were made with four players to adjust the electrodes. The players were just asked to grab the gamepad and try to reach the coins in a natural position. The electrodes were adjusted as needed and EDA's electrodes were fixed to the controller with hot glue.

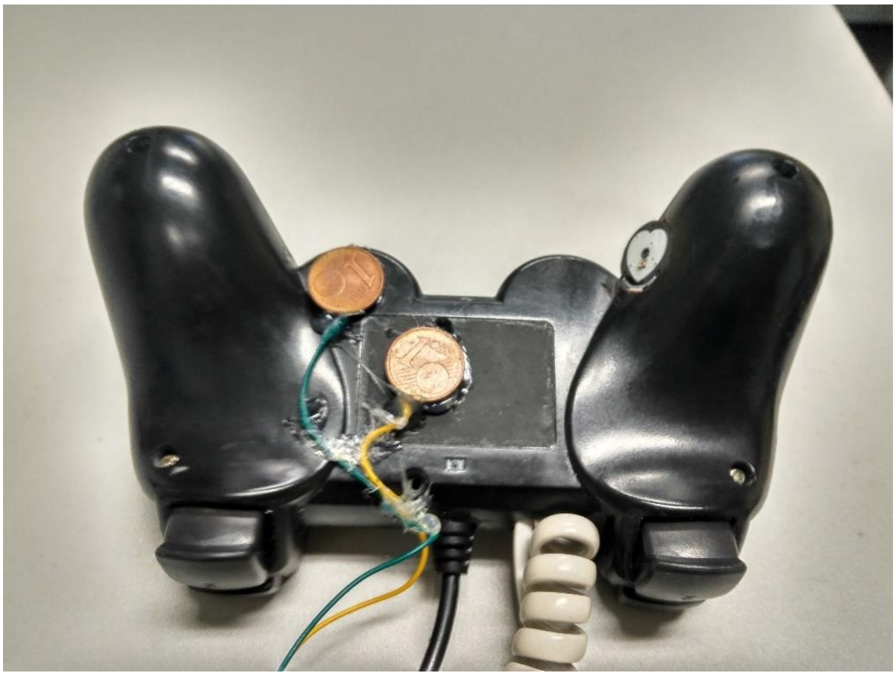


Figure 25 - Final game controller prototype

During the experiment, it was noticed that with the blue tack the EDA signal was affected greatly by the PPG sensor. The hot glue, isolated more the EDA signal reducing significantly the noise caused by the PPG. There was still some noise though.

3.2. Software

This is the software that is responsible to record, manipulate and send the physiological measures to the game and retrieve from the game, events that the game designer understands as meaningful for the interaction (e.g.: Character died, level completed, final boss appears). This section is dedicated to its implementation. Starting from the requirements that were defined for this software, the distinct phases of the implementation and the reasoning behind some changes that were made along the way as a mean to ease the user experience and reduce the set up time required for each experiment.

3.2.1. Software development method

For the software development, the approach chosen was evolutionary prototyping. Contrary to the throwaway method, the evolutionary method focus on the development of well understood requirements and each resulting prototype is part of the final product. Each prototype is built upon the previous prototype. With the experience gained on each cycle, new requirements may rise and the poorly understood ones become clearer [62]. A clear set of starting requirements was defined making this approach more suitable. Plus, the implementation of each part is built to take part in the final system. So, every cycle of the development a design phase is mandatory before the coding part. This way, the code will be cleaner and well-structured which helps the continuous implementation of the software.

3.2.2. Requirements

The first action taken for the development of the software was to look to other software implementations ([47], [64], [68] and [69]) that could record biosignals. With this approach, one can understand which features a software of this nature requires and which features are missing from these software with no big learning curve.

One feature that is a must in all similar software is real-time visualisation of the signals acquired. This allows the researcher to make sure the signals are being read from the device. Related to the signals visualization is, also, the real-time visualization of the features that are being extracted from the signals (e.g. HR, arousal). This ensures that the recordings are meaningful based on the expected result for each feature.

Even though a game controller that records physiological data was built, the software must work with different physiological devices or different configurations of the same device. The software must be open to the extension and implementation of new physiological devices.

All the features chosen by the researcher should be sent to the designated game, so the game can use those values to change its state or environment. The communication on the other way should also be possible. The software should receive game events from the game being tested. With game events tagging is possible to retrieve more meaningful conclusions to the results observed during the experiments as well as a correlation between physiology and game events.

Adding filters, through the software, to the signals is also a need to maximize the signal's quality and more precisely extract features from signals.

Finally, all the features selected by the researcher and all game events that happened during the session must be saved to be analysed later.

At the start of the implementation of the software, not all requirements had been defined. Many of the requirements rose at the end of each cycle of the development with suggestions from other developers. The complete list of the software requirements, both functional and non-functional, can be found below.

3.2.2.1. Functional Requirements

FR#1 - The software must record multiple physiological signals.

FR#2 - The software must support multiple hardware devices at the same time.

FR#3 - The software must enable more than one player.

FR#4 - The software must save signals configuration.

FR#5 - The software must load previously saved configurations.

FR#6 - The software must show the signals in real-time.

FR#7 - The software must have filters to be added to the signals.

FR#8 - The software must let to add multiple filters to one signal.

FR#9 - The software must show the effect of the filter in real-time.

FR#10 - The software must calculate features in real-time.

FR#11 - The software must have a time counter.

FR#12 - The software must have an event logger.

FR#13 - The software must have shortcuts to add repetitive events.

FR#14 - The software must send the physiological features to the games.

FR#15 - The software must log events coming from the game.

FR#16 - The software must save the raw data coming from the hardware device.

FR#17 - The software must save the physiological features calculation and events logged at 1 Hz.

FR#18 - The software must record heart rate.

FR#19 - The software must record engagement/stress.

3.2.2.2. Non-functional Requirements

NFR#1 - The software ought to be simple to use

NFR#2 - The software ought to be easy to learn

NFR#3 - The software ought to work in as many OS as possible

NFR#4 - The software ought to allow all devices to player configurations

NFR#5 - The software ought not to be CPU bound intensive

This software key features are:

- Support multiple physiological devices at the same time;
- Possibility to add as many filters as needed to each signal in real time;
- Two-way communication with games, sending the physiological data and receiving game events;

- Event logging. The research can attach a tag at any time during the session and;
- Open-source - open sourcing this software will make it easier to increase the number of different physiological devices available in the software as well as the different filters and feature extraction.

3.2.3. Technologies and software used

The BITalino website provides several API for different technologies. Android[21], MATLAB[22], raspberry pi[23], Arduino, Unity3D[24] or Visual C#[25]. However not every technology is suitable for this project, like the Internet of Things (IoT). Let us look at some of these technologies that are interesting. We will be focusing on Android, JAVA, Visual C#, MATLAB and Unity.

Android is a very interesting path to take. This would render possible a portable setup to follow the controller. However, the power of computing required to record and show real time physiological signals is not commonly available on affordable mobile platforms. Therefore, this kind of technology is not yet suitable, but in a couple of years, this might be one of the best solutions.

MATLAB is a very interesting option where its ecosystem already provides a lot of functions and options to process, filter and plot signals. From all these technologies MATLAB might be the most complete and prepared to process this type of signals and it is a software used by many people in the electrical engineering and signal processing domain. However, the aim of this thesis is to provide a system to be used inside the game development community thus MATLAB might not suit this use case since it is not broadly used by game designers and developers.

JAVA and C# are similar technologies that allow developing for various systems. Java runs on a Java virtual Machine which makes Java coded software available to Linux, MacOS, Windows, Android and web, which is a plus. The C# environment builds for all the above but Linux, plus iOS devices and windows store apps. So, using one of these technologies would be advisable because they handle almost every system. Another advantage of Java is that that has some frameworks designed to process biosignals [70].The deciding factor would practically be based on the preference on the language. However, there is also a plugin for Unity3d available.

[21] Mobile OS from Google, Inc. (California, USA)

[22] Software Developed by MathWorks, Inc. (Massachusetts, USA)

[23] Single board pc developed by Raspberry Pi Foundation (Cambridge, UK)

[24] Game engine owned by Unity Technologies (California, USA)

[25] Technology developed by Microsoft Corporation (Washington, USA)

Unity3D is a game engine where one can build 2D and 3D games. Even though the software being built is not a game, Unity is widely used for game development. This means that game designers, and game researchers are familiar with this kind software. Also, has the advantage of building for multiple platforms (e.g., windows, MacOS, Linux, Android, Web, iOS and game consoles). Unity supports 3 languages: JavaScript, C# and boolang. Another plus is that Unity and C# are widely used inside the NeuroRehabLab research group. Integration with other software developed by the group will be much easier and seamless. Therefore, for this project, it was decided to use Unity and C#

A code editor is needed to write code. Unity comes prepacked with MonoDEvelop[26] an Integrated Development Environment (IDE). Despite this, unity also supports Visual Studio[27]. Visual Studio has a great integration with Unity and eases the process of debugging, so it was chosen over MonoDevelop.

Lastly, to keep code up-to-date and to protect earlier versions of the working software, version control was used. Version control sits well with prototyping because it is simple to revert code changes and return to an earlier stable version of the software. The most commonly used source control technology nowadays is Git[28]. Subsequently, the code was stored on Bitbucket[29], which is one of the many Git solutions available on the market these days. To interface with bitbucket, Source Tree[30] was used.

Summing up, the technologies and software adopted for this project were: Unity 3D, Visual Studio 2017 and C# for the software implementation. Source Tree and Git were used for version control.

3.2.4. Conceptual Architecture

The architecture chosen for this software was based on components where each of them is an independent part of the software. This means that these components can be reused in other similar applications. This architecture has been updated along with the implementation of each requirement and. As a result, there are 8 independent components that are being described next.

[26] MonoDevelop is an open-source IDE maintained by Xamarin, owned by Microsoft, and the MonoDevelop community.

[27] IDE developed by Microsoft Corporation (Washington, USA).

[28] Technology developed by Linus Torvalds, creator of Linux.

[29] An online Git repository solution own by Atlassian (Sidney, Australia)

[30] Software interface for Git repositories developed by Atlassian (Sidney, Australia)

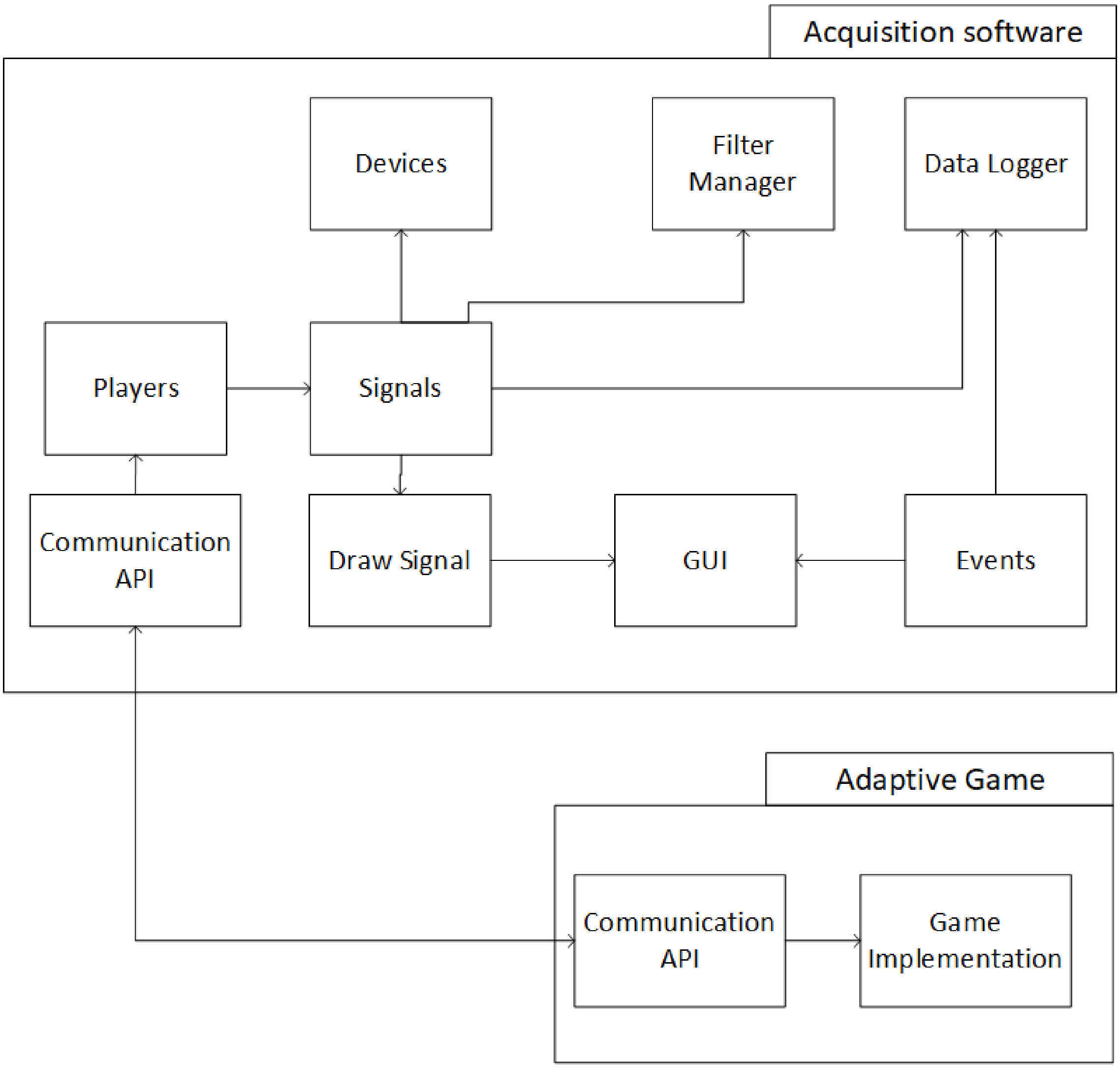


Figure 26 – Architecture of the signal acquisition software

3.2.4.1. *Devices component*

This component is responsible for managing all the psychophysiological hardware devices implementations. New devices Implementations can be added to this component as needed. A *DeviceManager* class exists to ease adding, updating and removing devices during run time. With this component, is possible to have more than one piece of hardware acquiring data at the same time.

3.2.4.2. *Players Component*

This component manages all the players during run time. Equal to the device component, a manager is available. Each player has a colour attribute to be easily distinguished, and a Signal manager to manage the signals attached to each player.

The player also has a name attribute limited to 3 characters. Each signal prepends to its name the corresponding player, so the character limit prevents long signal names.

Decoupling the hardware devices from the players eases the use of this software with a bigger range of setup configurations. For instance, using the same hardware for multiple users at the same time or one user using multiple hardware devices.

3.2.4.3. Signals Component

This component is responsible for managing the signals for each player. A signal has many attributes such as the device from where it should be reading data, the filters applied to the signal or its name. Taking a deeper look into the repository[31], it is possible the see the full list of properties and attributes. Here is also the implementation for each signal. Implementations for PPG, EDA, ECG and ACC are available. More signals or implementations to the same signal can be added if needed though. Each signal has a method Calculate() where it is implemented the feature that is derived from the signal (for instance PPG calculates heart beats per minute (BPM)).

3.2.4.4. Filters Component

Filters can be added during run time and the signal is updated in real time. Combining the Decorator and the Single Responsibility design patterns it was possible to do this. The decorator design pattern adds the functionality implemented by the filter to the signals and the Single Responsibility design pattern is responsible for activating or deactivating filters.

3.2.4.5. Events Component

Events can be generated by the game being tested or manually entered by the game researcher during the experiment. In this component, the events are sorted and organized chronologically. Each event has a brief description of the event and the event's time of occurrence. These events, simplify the work analysing the information after the session.

3.2.4.6. Data Logger Component

This component logs all the data to a comma separated value (CSV) file. The data is: (1) the players, (2) the features extracted from each player's signal, (3) the events for each player and (4) a time tag, in seconds.

3.2.4.7. DrawSignal Component

[31] https://bitbucket.org/drmoistbread/acqsys

Here is where all the signals are plotted on a real-time graph that then can be displayed on the GUI. Here, the plot limits inside the GUI and the basic manipulation of the plot (X or Y axis translation and Y axis scaling) are set.

3.2.4.8. GUI Component

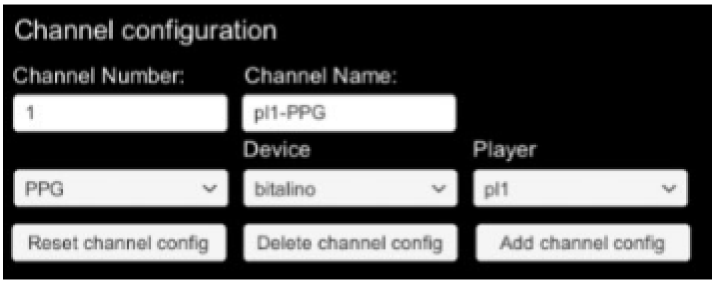
This is the component that is responsible for displaying everything. In the Unity environment, each different view of the page is called a Scene. Each scene has its GUI manager that displays the players, the devices, the signals, the timer, and everything else that is displayed on the screen.

3.2.5. Implementation

The acquisition software has 3 main purposes: (1) Signal Acquisition, (2) Signal Processing and (3) Signal Visualization. Each of the functionalities ended up divided in what, inside the Unity3D software, are called Scenes. Each Scene corresponds to a page if one is familiar with web development or screens if one is into mobile development. This section describes each Scene in detail and the operations that are available. Therefore, 3 Scenes emerged during the development of this software. The first, Signal Acquisition, is where all the signals, the players, and the connection, to hardware devices, is added. Signal Processing, as the name suggests is the Scene where one can add, remove or update filters to a specific signal. Signal visualization is the main Scene of this software. This scene responsible sends the physiological information to the game and receive from it all the game information, real time visualization of the signals and their features, logging notable events and record the signals to a file.

3.2.5.1. Signal Acquisition Scene.

As mentioned, this is the Scene where one configures the signals to be acquired. To add a new signal, 5 pieces of information are needed. The name of the signals, the type of the signal (e.g. EDA, PPG, EEG), the device, the channel from the hardware where the signal is coming from and to which player the signal corresponds to.



Channel configuration

Channel Number: 1

Channel Name: pl1-PPG

PPG

Device: bitalino

Player: pl1

Figure 27 – GUI of a new signal being added

As mentioned, the software enables physiological recording from multiple devices, as well as multiple users at the same time. The players are the users and from within this scene they can be added, removed or edited.

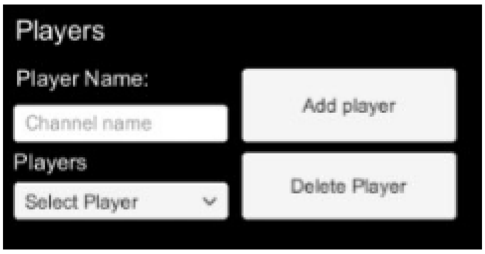


Figure 28 – Player configuration GUI

To add the physiological devices the game user researcher must indicate a name, the device that is using and the COM port or IP address which the device is connected to.

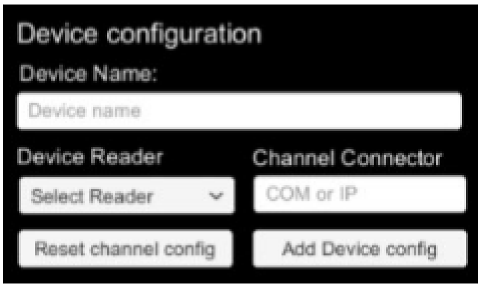


Figure 29 – GUI to add a new Device

After a successful new signal addition, it becomes available to check it's quality. All signals are listed and can be shown or hidden as necessary.

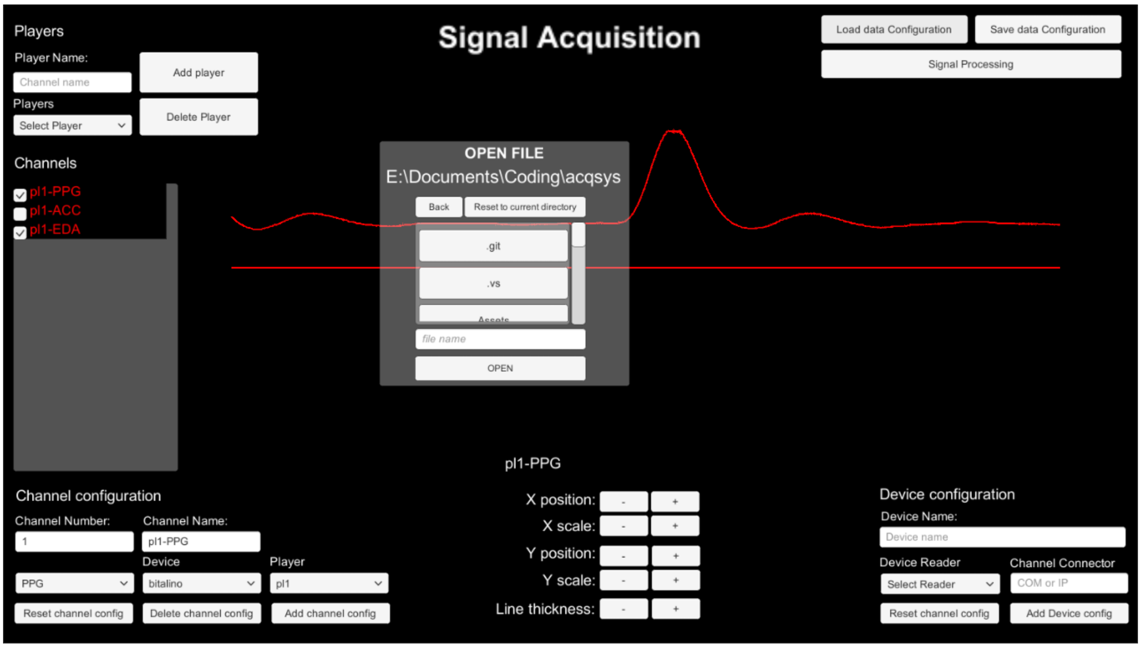


Figure 30 – Signal acquisition full scene

To allow such range of devices configuration, as described in section 3.2.2., the signals' configuration can become cumbersome if there are many devices, signals and users. Moreover, having to reconfigure everything each time a session occurs, is not optimal. Consequently, all the configurations can be saved to an XML file which is then used to load all the configuration every time they are needed. Additionally, configurations made on one machine can be transported to another using this configuration file. It is possible to save as many configurations as desired.

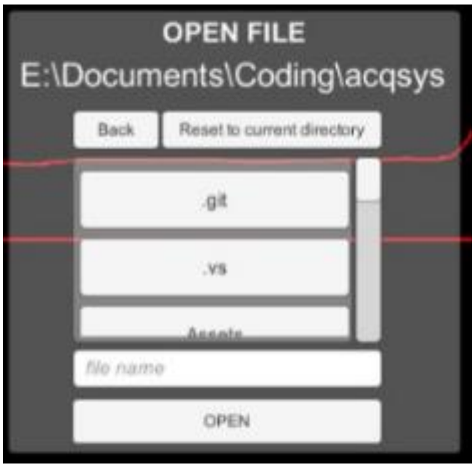


Figure 31 – Custom File explorer to load a saved configuration

3.2.5.2. Signal Processing

Signal Processing is the second scene of the software. In this scene is possible to add filtering to the signals. Filters can be added or removed and the changes are all monitored in real-time.

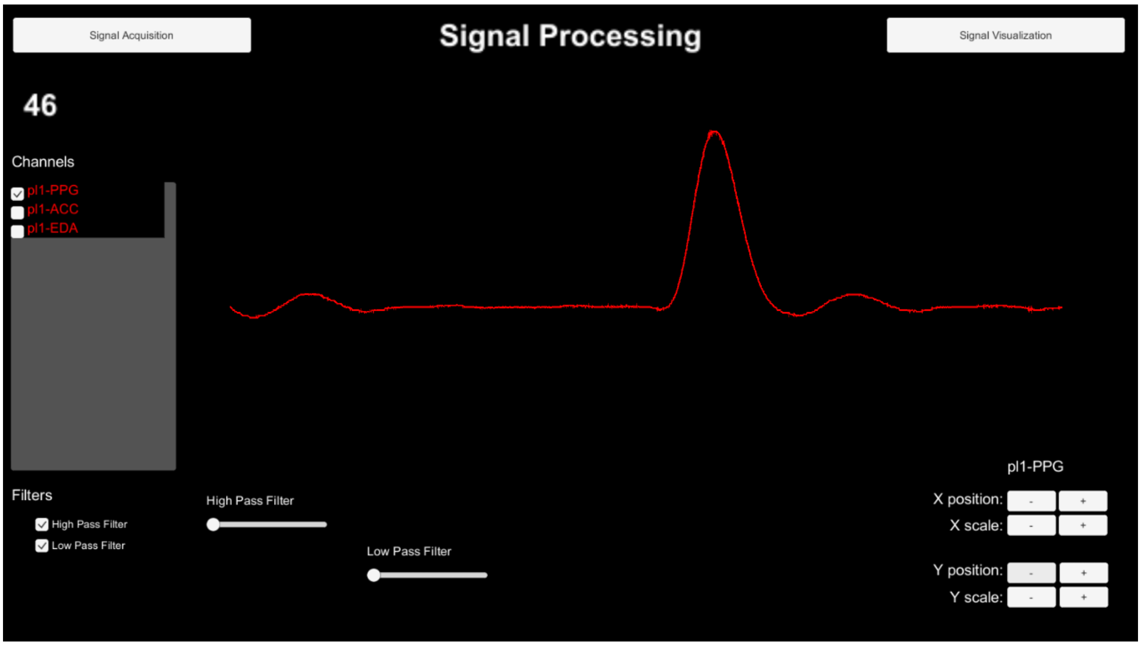
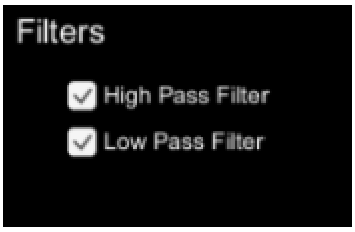


Figure 32 - Full view of the Signal Processing scene with two filters applied to PPG

This allows to maximize the quality of the signal for each user, resulting in cleaner outputs. New filters can be added by implementing the IFilter interface and adding the corresponding toggle on the scene.



Filters

☑ High Pass Filter

☑ Low Pass Filter

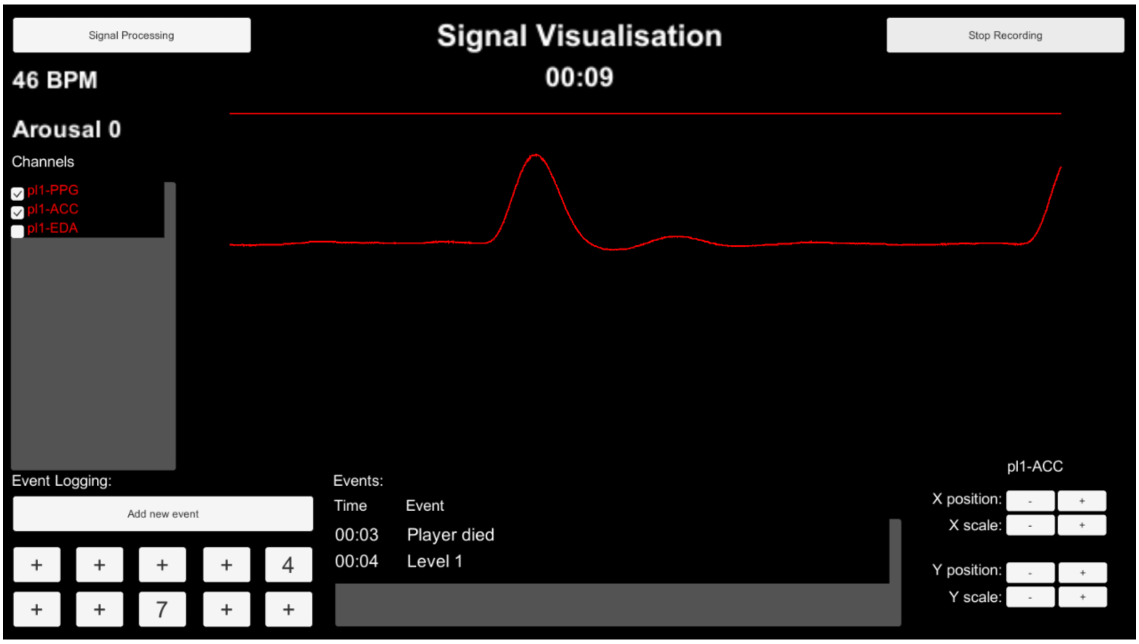
Figure 33 - Example 2 toggles for two filters. New filter's toggle is placed here

Each signal can have as many filters added as needed. At the same time, a real-time visualization of the extracted feature (a PPG signals extracts heart rate values) from the signal is displayed. With this information, the researcher can manipulate the signal, knowing how it will disrupt the feature.

It is always possible to move back to Signal Acquisition to change any of the signals, devices or player, without losing the filters already added. When finished here, one moves to the signals visualisation that is described next.

3.2.5.3. Signal Visualisation

This is the scene where the researchers will spend most of his time. In Signal visualization, one is similarly able to visualise the signal in real time as well as all the features that are being extracted from the signals.



Signal Visualisation

00:09

46 BPM

Arousal 0

Channels

☑ pl1-PPG

☑ pl1-ACC

□ pl1-EDA

Event Logging:

Events:

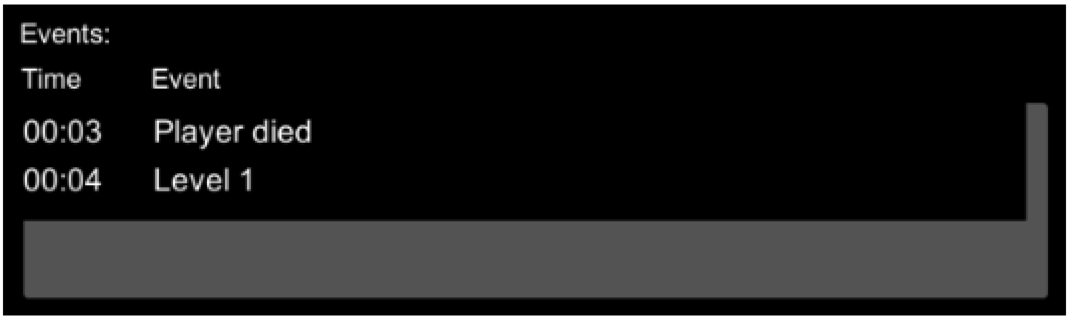
Time	Event
00:03	Player died
00:04	Level 1

pl1-ACC

Figure 34 – Full view of the Signal Visualization Scene

The novelty is the Event manager and the capability to add an event and tag the signal responses with events. There are 3 possible forms to add new events.

Firstly, the researcher can add events manually by clicking the button *Add new event*. An input box will appear and the event message is written and saved. It is important to note that each event saves the time of its occurrence. Considering that registering an event takes a few seconds, there would be some difference on the time of occurrence and the time tagged on the event. To tackle this problem the time of occurrence is saved right after the *Add new event* button is clicked. This way the delay in the actual happening of an event and the event log is the reaction time of the researcher. Another problem that could arise is some other event happening while another is being saved. Hence, the second possibility to add an event is using one of the ten shortcuts available to add more frequent events. This removes the time spent adding the message manually to every event and letting the researcher focus on the user and not in the software. In Figure 34, is possible to see the button with the shortcuts to events. The plus sign means that there is no event associated with that shortcut and one can be associated. When a shortcut has an event, a number appears. Clicking on the number on the keyboard will add it. Lastly, the game itself can send automatic and pre-determined game events to the software. Examples of these would be a player that died, a level completed, a rare item found. An event logger is also present in the scene where all the events added are shown and display the time of occurrence.



Events:

Time	Event
00:03	Player died
00:04	Level 1

Figure 35 - Event logger with two logs

To start this communication, a *Start Recording* button is available. This starts a timer and if the software is being used to create a biofeedback game or an affective game, the features' values are sent to the game for the game adaptation. The features are sent every second. Also, log files are created. One, that saves the features every second and events that happened that second. The other, the raw data sent by the physiological device to the software. These logs can be used for post session data analysis. To stop the experiment the researcher just needs to press Stop Recording and the game communication will be terminated and log files will be saved. This software is to be used only to record and visualise signals in real-time. For offline evaluation, other software such as OpenSignals or PhysioLab is required.

3.2.5.4. Arousal algorithm

From the EDA signal, it is possible to assess the arousal levels of a person. The implementation of this algorithm is based on [11], which does not need a baseline reading at rest and compare it to the data read. This eases the process to set up the controller and reduces the time in pre-game configurations. Another benefit is the simplicity of the algorithm which does not require almost any signal manipulation or separation of the signal in tonic and phasic. In this implementation, the arousal value lies between 0 and 10. 0 is considered relaxed and 10 is considered very aroused.

To implement this algorithm, it is needed to have the values in microsiemens, so if they are not in the correct units it is needed to convert the values. Two vectors are used with the same size: one that is used as a threshold and the other saves the last 100 values from the signal. The threshold value is the median value of the vector. Using median over EDA prevents ouliers or atefects due to movement influence the result. Then if the EDA value is greater than the (threshold + 0.05 microsiemens) then the arousal is increased and the threshold is updated. If the EDA value is lower than the (threshold - 0.05 microsiemens) then the arousal level is decreased. To prevent a drastic increase and decrease in arousal levels a timer of 3 seconds is set every time there is an update in arousal levels.

The implementation can be found in Attachment A in this thesis. For more detailed information visit the online repository[32].

3.2.5.5. *Heart rate algorithm*

This algorithm works for both ECG and PPG signals. The accuracy in ECG was not tested, though. This algorithm was adapted from the Unity 5 tutorial[33] project to detect the heart rate from ECG. The first step is to find the peak. The peaks are found using a threshold that is 70% of the maximum peak detected. After a peak is detected a timer is set just to make sure that it does not detect the same peak twice. Then, the instant HR value is calculated dividing 60 by peak's time. To remove hand movement artefacts, heart rates below 40 or above 130, are discarded. The HR value outputted by the algorithm, in BPM, is the median of the 100 previous instant HR. Using the median in place of mean reduces the influence of big outliers. The implementation, in c#, can be found in Attachment B.

[32] https://bitbucket.org/drmoistbread/acqsys

[33] http://bitalino.com/en/learn/tutorials

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4. Validation Experiment

This section is reserved for the discussion of the results of the final validation experiment and its description. One will start with the description of the materials used on the experiment and the protocol used. Later, an analysis to the data collected on each session and the results.

4.1. Experiment Description

This experiment serves three purposes. The first purpose is to validate the software and hardware built during this project. This validation is done through an affective game. The second purpose is to verify the quality of the signals recorded and algorithms implemented (heart rate and arousal). Lastly, a comparison between positive and negative biofeedback is done to further investigate the effects of each form of feedback.

4.1.1. Hardware

The hardware used for the experiment was: (1) the controller built during this thesis (Physiopad) as an input device for the game, (2) the BiosignalPlux device to record EDA and ECG, (3) a laptop to run the affective game and the signal acquisition software developed, (4) a mobile station used to record and save the data from the BiosignalsPlux and (5) a television that acted as monitor where the game was played. The mobile station is a normal desktop computer that was built on a rack with wheels and has a touchscreen display.

4.1.2. Software

The software used in this experiment was: (1) the signal acquisition software developed in this project, (2) an affective game and (3) OpenSignals which was used to interface with BiosignalPlux. The affective game chosen for the experiements was Exerpong [71]. This game has been developed inside the neurorehablab at University of Madeira and it suports physiology sent through a UDP connection. The main goal of this game is to destroy all colourful blocks (see Figure 36) using the ball and at the same time not letting the ball reach the bottom of the screen. This is accomplished with the paddle (green rectangle, Figure 36). Moving the paddle right and left and let the ball bounce on it will send the ball back to the top to destroy some more blocks. When all blocks are destroyed a new level appears. Each new level the block are displayed differently and the game has 4 levels that cicle endlessly. On the top right corner there is a display that shows the realtime heartrate of the player and a threshold where the player should meet with his physiology.

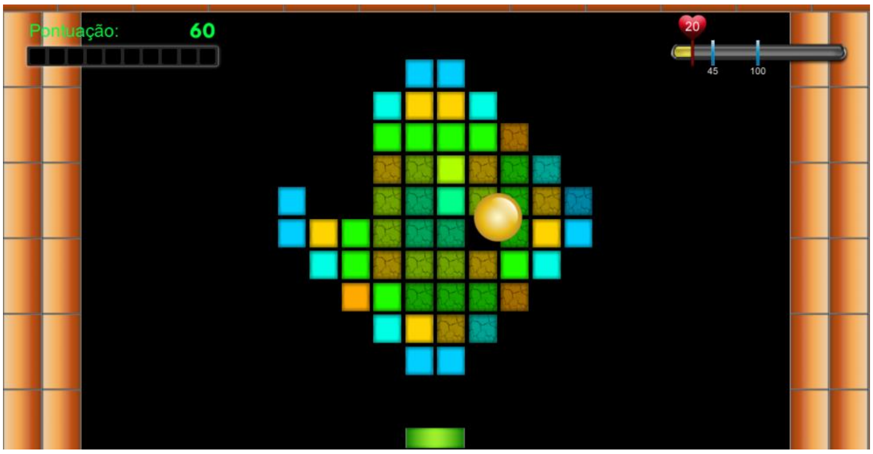


Figure 36 - Screenshot of ExerPong

OpenSignals is an open source acquisition software in real time developed by the Portuguese company Plux, manufacturers of the BITalino and biosignalsPlux devices. The software allows to record every channel available in the biosignalsPlux and as it was developed by the same company was chosen over other software. The software while recording displays the time elapsed and the signals. All signals being capture are shown together as shown on Figure 37, and some can be chosen to be display individually. As a bonus the software shows either the raw data from the device or the actual value for a certain sensor. For instance can show the raw data of the EDA signal or the EDA signal converted to microsiemens.

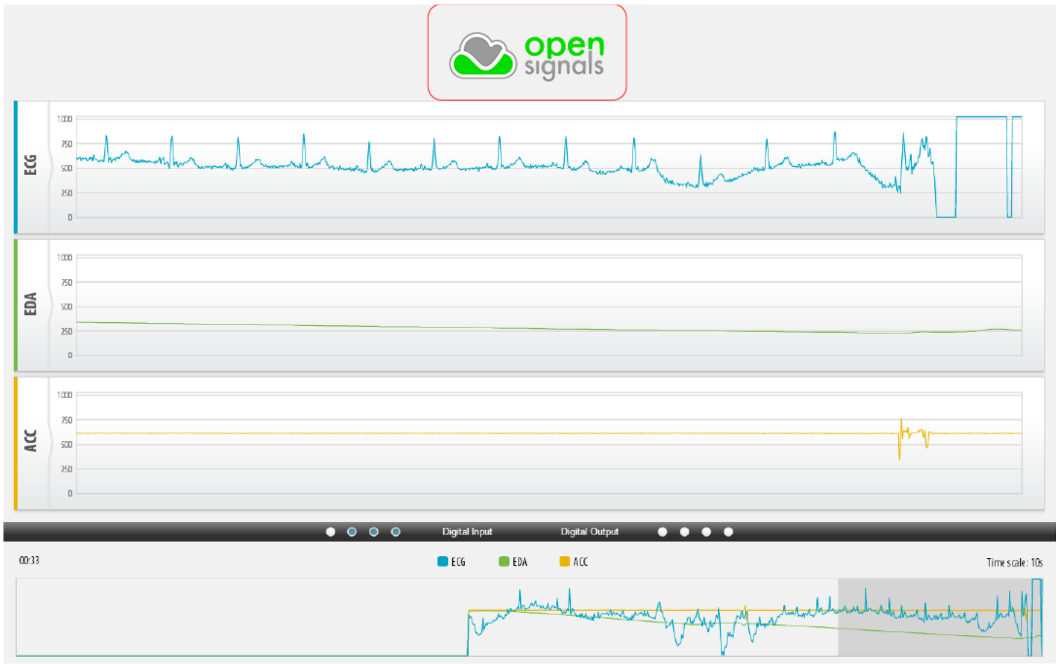


Figure 37 - Snapshot of the OpenSignals software

4.1.1. Setup

Figure 38 displays all the hardware and software used in the experiment. From the left, there is the mobile station with the OpenSignal, in the middle the laptop is running the software develop and the TV is running the game. The player sat on the chair and the controller was placed in front of the subject.

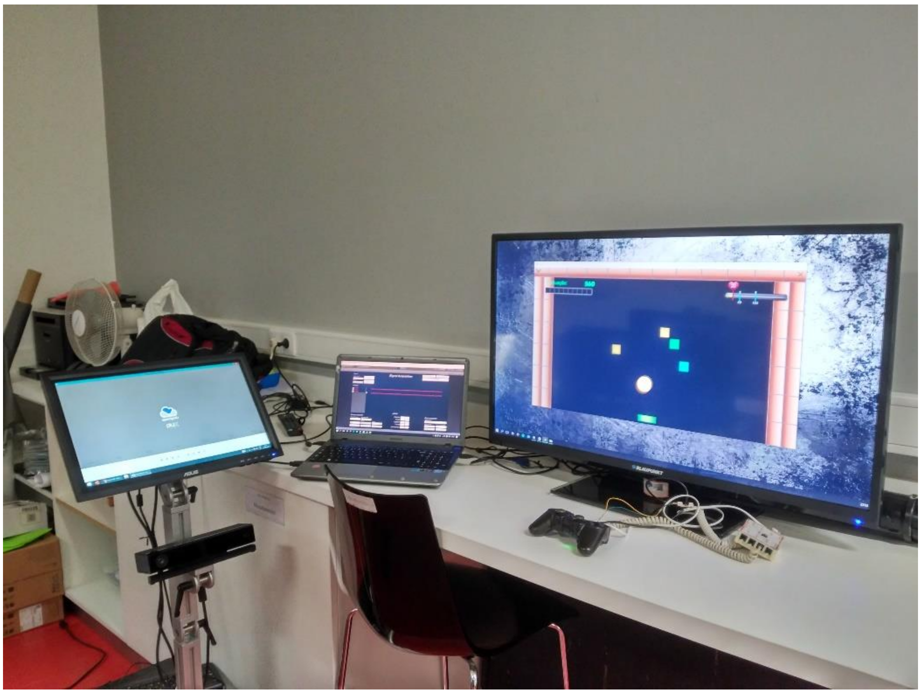


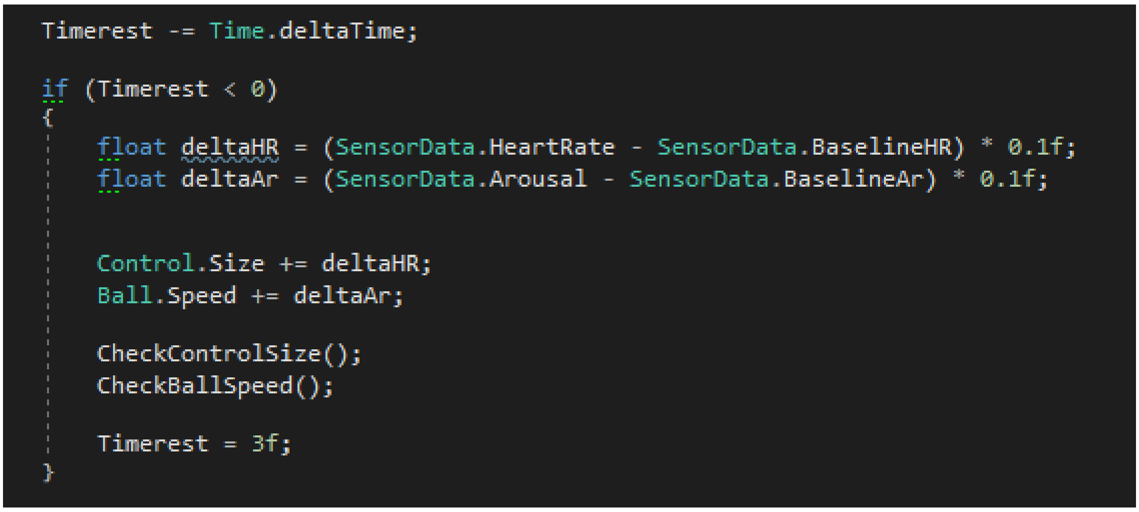
Figure 38 – setup used for the validation experiment

The BiosignalsPlux was connected to the mobile station, where OpenSignal was installed, through Bluetooth. The BiosignalsPlux was used to compare the controller's signal quality. The two electrodes of the EDA sensor were placed on the left wrist of all participant because it was the nearest arm to the mobile station. The ECG sensor had its electrodes placed on the chest of all players.

The television was connected to the laptop using an HDMI cable. The acquisition software was on the laptop screen and the affective game on the television. The controller was, also, connected to the laptop via USB.

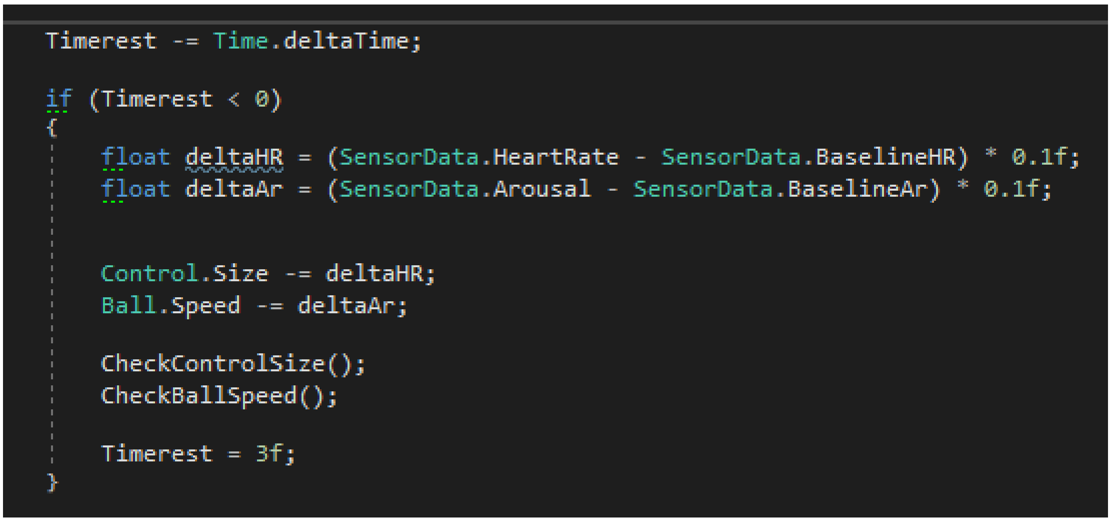
For this experiment, all the previous mechanics were removed and 3 conditions were implemented. This game had already some rules implemented to manipulate the ball and paddle, so this was removed. For the adaptation, only the velocity of the ball and size of the paddle were manipulated. Condition 1 was not affective and used a positive feedback to increase the ball velocity every 3 seconds. Every 5 balls lost the ball velocity was decremented in 3 units. Every time the ball touched the paddle the paddle's size was decreased and every ball lost the paddle's size was increased. Condition 2 and

3 used the physiology recorded with the controller to adapt the game and for both, the heart rate values changed the paddle's size and arousal the ball's velocity. Condition 2 was implemented using, again, positive feedback and the adaptation rules are shown in Figure 38. Condition 3 used negative feedback as Figure 39 shows.



```
Timerest -= Time.deltaTime;

if (Timerest < 0)
{
    float deltaHR = (SensorData.HeartRate - SensorData.BaselineHR) * 0.1f;
    float deltaAr = (SensorData.Arousal - SensorData.BaselineAr) * 0.1f;


    Control.Size += deltaHR;
    Ball.Speed += deltaAr;

    CheckControlSize();
    CheckBallSpeed();

    Timerest = 3f;
}
```

Figure 39 - Positive feedback algorithm to change the ball's speed and the paddle's size



```
Timerest -= Time.deltaTime;

if (Timerest < 0)
{
    float deltaHR = (SensorData.HeartRate - SensorData.BaselineHR) * 0.1f;
    float deltaAr = (SensorData.Arousal - SensorData.BaselineAr) * 0.1f;


    Control.Size -= deltaHR;
    Ball.Speed -= deltaAr;

    CheckControlSize();
    CheckBallSpeed();

    Timerest = 3f;
}
```

Figure 40 - Negative feedback algorithm to change the ball's speed and the paddle's size

4.1.2. Protocol

In this experiment, there were 9 subjects all students or former students at an engineering course at University of Madeira. The subjects' ages ranged from 20 to 32 averaging 23 years old. From the 9 subjects only one was a female, the remaining 8 were all men. All the subjects were experienced players with multiple years of experience in multiplayer games and competitive gaming. Some of the subjects were even game developers.

The very first thing done in each session with the subject was to explain the purpose of the experiment, explain the game being played and explained how the controller worked and what data was being collected from the Physiopad. Also, it was explained that the biosignalsplux was being used just to compare the quality of the signals and that this device was not part of the necessary equipment required to use play the affective game. Also, they were told that they would be playing 3 different conditions, however the subjects were never informed how the physiology was manipulating the game or even if the condition being played was using the biofeedback or not.

Every session included playing each condition for four minutes. Before each condition, the biosignals were recorded for 1 minute to act a baseline. To reduce bias the starting condition was changed in each session then following an incremental order. For this was used the Latin square approach. As explained before, condition 1 did not use biofeedback at all, condition 2 was using positive biofeedback and condition 3 negative biofeedback.

After the first session every player was asked to fill a questionnaire regarding the usability of the controller. The questionnaire chosen for this purpose was the system usability scale, SUS. To compare the game experience in each condition played and how the players perceived the game the game experience questionnaire was used. This last questionnaire was answered by the subject in the end of each condition. To ease the data processing and the filling of each questionnaire, these were presented to the user, using google forms, online. Both the SUS and the game experience questionnaire were anonymous and the only personal information asked was the age and gender for statistics.

4.1.3. Questionnaires

Two questionnaires were answered, the system usability scale questionnaire [72] was used to access how usable the gamepad was during gameplay. This questionnaire was presented after the first condition tested by each user. To access the game experience the game experience questionnaire [73] was used. This questionnaire was answered after each condition. The questionnaire is modular and has 3 core sections. The core questionnaire itself, a module for the social presence and a post-game analysis. There is also a short core questionnaire to be used during the session while the game is being played. Since the game did not have any social component, the social part of the questionnaire was discarded. Plus, the objective was to evaluate the gameplay so only the core part of the questionnaire was used, in this experiment. No questions were asked during the gameplay, so the player would not lose focus nor externally influence the physiological responses. The results of the game experience questionnaire are divided in six sections: competence, sensory and imaginative immersion, flow, tension / annoyance, Challenge and Negative and positive affect. Due to the length of the questionnaire and the number of times the questionnaire is answered the immersion section was, also removed, because it was not relevant for the comparison.

The two questionnaires used in the experiment are present in the attachments to a more detailed view of the questions asked.

4.2. Experiment Results

4.2.1. Usability

In regard to usability, as expected, the game controller scored well. To assess the usability was used the System Usability Scale (SUS). The SUS result ranges from 0 to 100, 0 not usable at all and 100 extremely usable. The Physiopad scored 88 out of 100. This means that the system built was highly usable and some users reported that would use the controller at home. One user reported that the BiosignalsPlux setup was much more intrusive and hard to use and would never use a similar system, but the controller was very easy to use.

This result shows that was possible to build a usable controller that does not require much expertise on the field of biosignals. Contrary, to the other controllers, presented in the literature review, which used custom electronics and hardware specially built to the effect, the Physiopad, uses a commercially available platform that can be used by anyone.

4.2.1. Game Experience

Regarding the comparison between positive and negative biofeedback it was used the game experience questionnaire [73]. This questionnaire has 6 components: competence, flow, tension/annoyance, challenge, negative affect and positive affect. In figure 41 is possible to see the results of the questionnaire between both conditions.

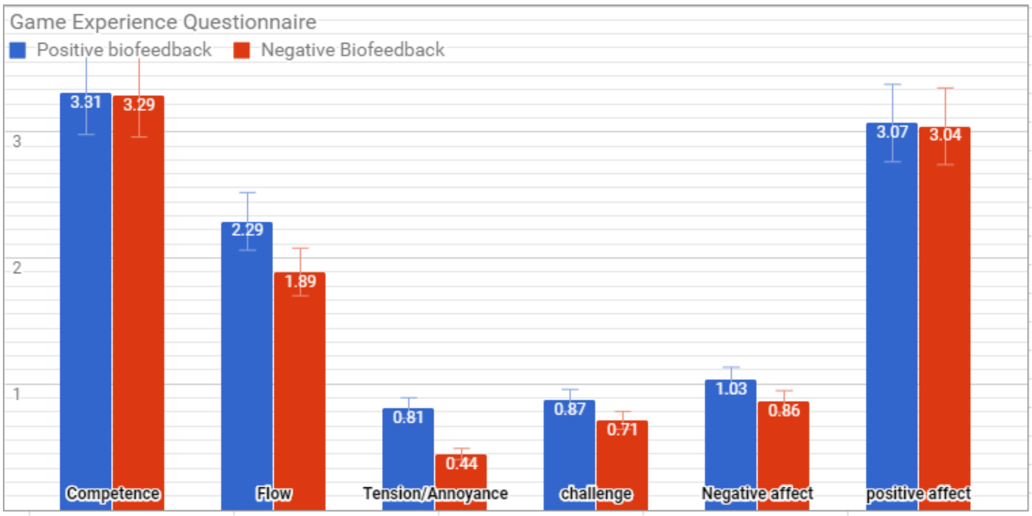


Figure 41 – Game Experience Questionnaire result comparison between condition 2 and 3

Statistical analysis was done to these results applying the Wilcoxon paired test. Competence and positive affect did not show significant differences between, but a trend can be observed. I had theorised that competence and positive affect in negative biofeedback should be higher. The gaming proficiency of the subjects could influence these results since the game difficulty increase is not necessarily a bad thing. However, a different result could be achieved if the users had no or little game experience. On the other side, the subjects felt that the flow, tension and challenge were higher. Thus, in general, results follow the literature which states positive feedback is used to increase the player's mastery in the game. Following the increase of tension, negative affect was also higher in condition 2. No significant changes between condition 2 and condition 3 components were found. More tests with a higher number of subjects should be done to confirm the identified trends.

Now onto the analysis of the game variables. Starting with the ball speed one can see in Figure 42 the average ball speed was 9.72 for the positive feedback and 5.15 for negative feedback. The signed paired test revealed that this difference is significative and that the ball moves faster with positive feedback making the game more engaging. Further, the standard deviation has a big difference between conditions. The standard deviation for positive biofeedback is 3.95 and 0.26 for negative biofeedback. This big difference is a result of some users being relaxed while playing the positive condition which led to an even more relaxed situation, resulting in a very low-ball velocity. In comparison to the non-biofeedback condition the positive feedback condition, the ball speed was very similar and one can think that there is no difference using biofeedback or not. However, a more detailed inspection show that the ball speed median in positive biofeedback condition reached higher speeds. So, in theory, the positive biofeedback was able to challenge more the players, making the game more compelling.

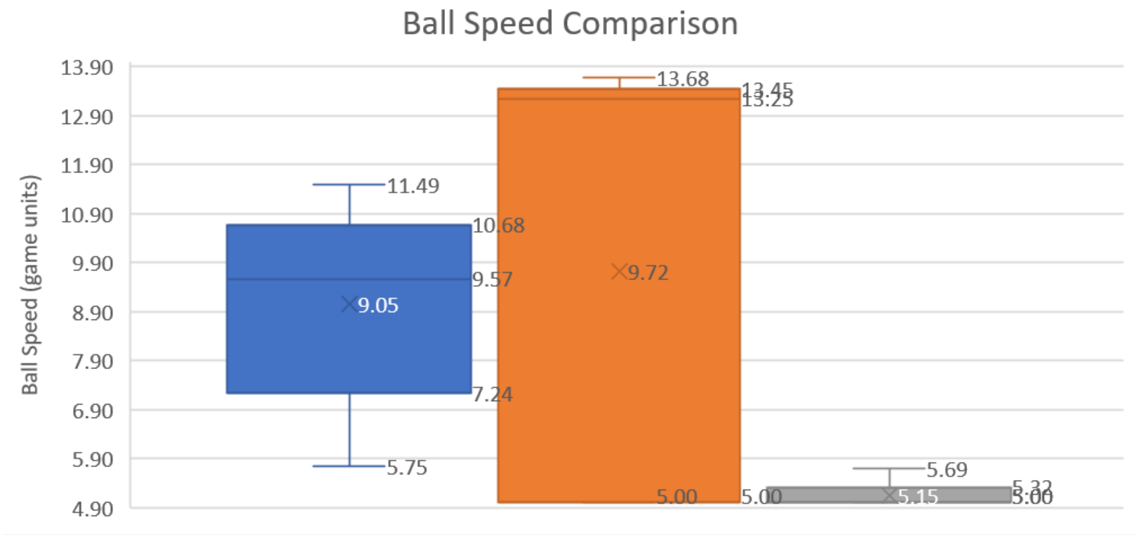


Figure 42 -ball speed comparison between no biofeedback, positive and negative feedback

Regarding the size of the paddle, in figure 43, the positive biofeedback averaged 5.72 while the negative one averaged 5.02. Although this difference is not significant it is possible to observe that the positive biofeedback condition engaged more the user which led to higher paddle sizes. The high-level value for the negative biofeedback can be explained by the fact that even though the negative feedback tends to relax the user, the players were engaged in this condition. However, some users were so relaxed during this condition that the paddle size was as small as 2.0. This could be due to the expertise of the user playing the game and the dexterity developed by being avid game players. Comparing the biofeedback conditions to the non-biofeedback, both have significant higher results. Using the Wilcoxon paired test to compare the non-biofeedback condition to the positive and negative feedback, individually, they returned p-values of 0.0078 and 0.0195, respectively,

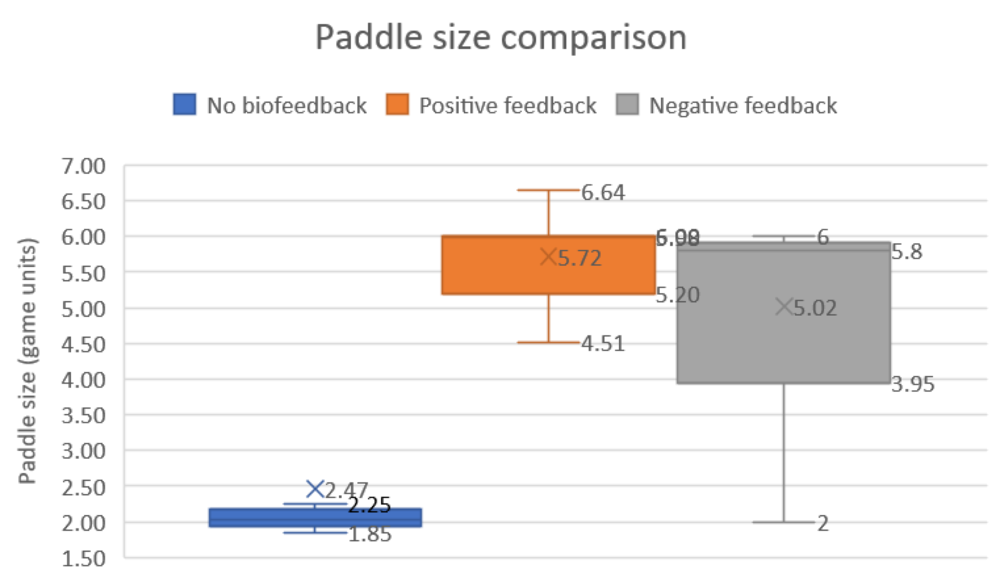


Figure 43-Paddle size comparison between no biofeedback, positive and negative feedback

Finally, taking lost balls into consideration one can see big differences. Again, using the Wilcoxon paired test to verify whether these differences were significative or not. The non-biofeedback condition compared to the positive biofeedback has a p-value of 0.0078 confirming that the difference is significant. A similar result was observed on the comparison of the non-biofeedback condition with the negative feedback condition. The p-value is 0.0039. On the other hand, there are no significant differences between the biofeedback condition, even though a noticeable trend is present. As expected the negative feedback resulted in very few balls lost, 2 balls on average. Now, going back to ball speeds between positive feedback and no biofeedback, where although the difference in averages were not to different, but the individual speeds, for some users, were higher on the positive biofeedback, the balls lost were lower on average. This difference in almost 17 balls between condition could indicate that the positive biofeedback was able to increase the difficulty, higher ball velocities, it was a difficulty that correspondent to the level of the player. Also, with less lost balls the flow of the game was less broken.

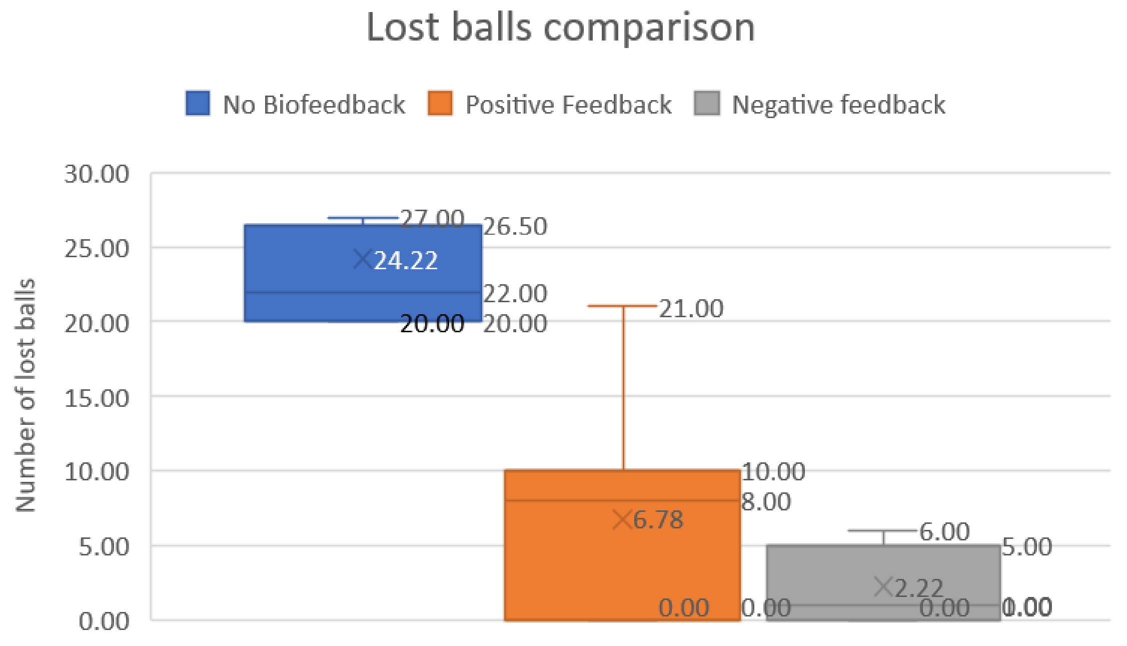


Figure 44 - number of lost balls in each condition

4.2.2. Electrodermal activity sensor

Another objective was to study the quality of the signals and how reliable the readings from the gamepad were in comparison to the BiosignalsPlux hardware. Starting with EDA the objective was to find a correlation between both signals. If there were a correlation that would mean that the Physiopad's EDA was somehow accurate, it behaved as expected and meaningful information could be extracted from the EDA. The MATLAB corr function [73] was used, it returns both the correlation coefficient (rho) and the probability value (p-value) of the two signals. The correlation coefficient indicates the correlation and values range from -1 to 1. One indicates that there is a correlation, Minus One indicates that there is an inverted correlation and 0 indicates that there is no correlation between two signals. The p-value is the probability of the null hypothesis that there is no correlation between two signals. If the p-value is below 0.05 then we can refuse the null hypothesis meaning that there is a correlation between signals.

Figure 45 shows the correlation between the EDA signal from the bioplux and the EDA from the physiopad. As one can observe there is no meaningful correlation. Some signals show an inverted correlation, however, others show no correlation at all. A detailed inspection of each reading one can see a lot noise in each signal. At this point, I was hypothesised that there was some sort of crosstalk between devices. The manufacturers of the biosignals acquisition devices were inquired about this possibility and they confirmed that if two electrodes from different devices are too close some interference may occur. Since all electrodes were placed on the left-hand palm, there is a high probability of interference. Therefore, the EDA analysis of the signals should be repeated using sensors in distant parts of the body (different hands, for instance).

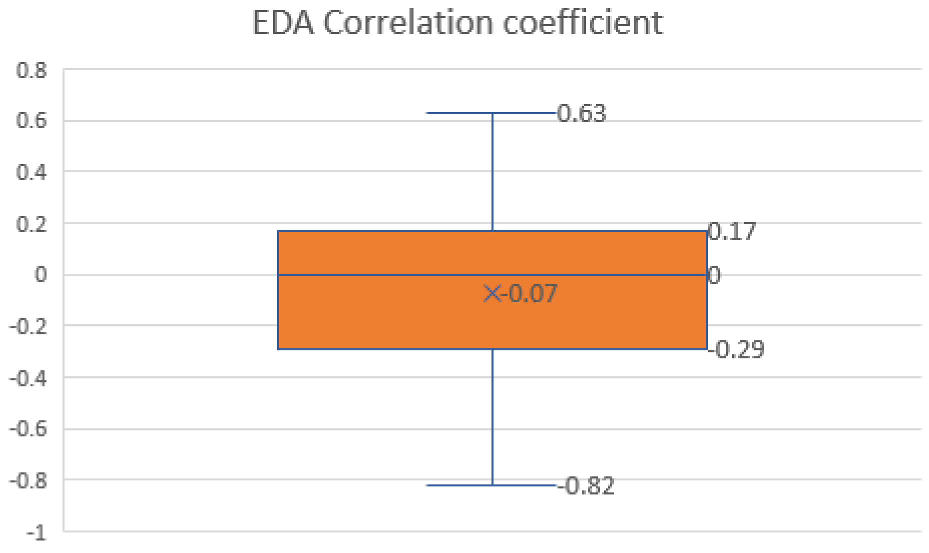


Figure 45 - biosignalsplux and physiopad's EDA correlation (p-values)

Comparing the results of the arousal levels during gameplay there were no significant difference across conditions. Again, due to the proximity of the EDA electrodes of both devices, a cross talk between devices is highly possible which justify these results.

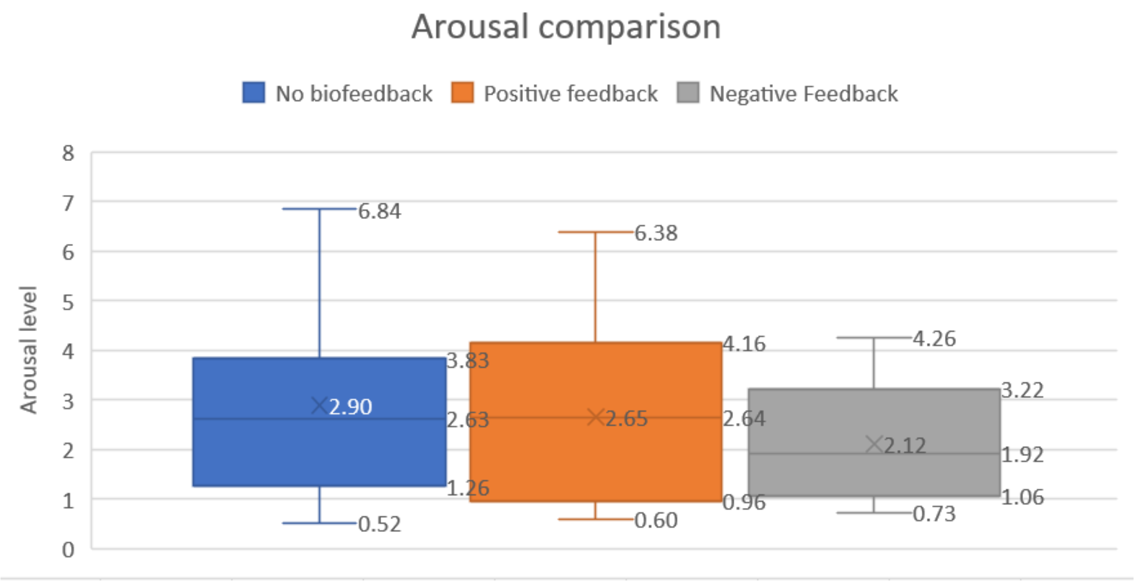


Figure 46 - Arousal values during each condition

4.2.3. Photoplethysmogram sensor

On the other hand, the results concerning the HR algorithm look promising. The heart rate values from the software developed were tested against the heart rate values extracted from the raw ECG using Physiolab. Both the mean absolute error (MAE) and the root mean sparred root (RMSE) were computed.

Observing the graph, in figure 47 and figure 48, comparison of the two heart rates it is possible to observe a slight delay on the controller's values. This is a trend that is observed in multiple subjects. This is an indication that the result, presented in this section, can be optimized with some tweaks on the algorithm making the controller even more reliable.

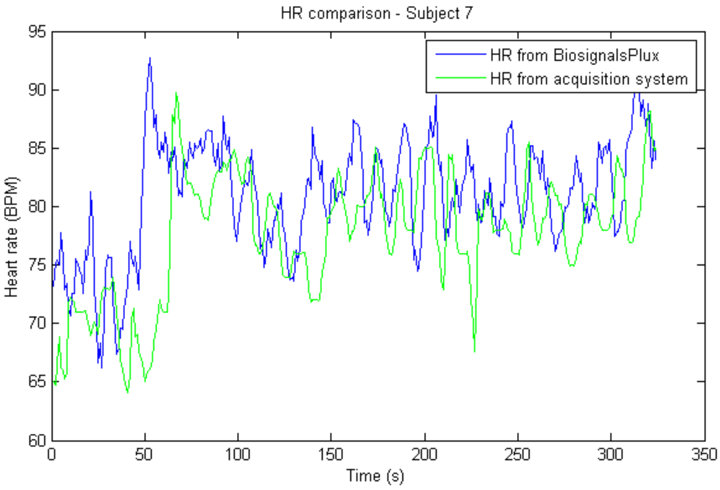


Figure 47 – HR comparison of one subject during a session

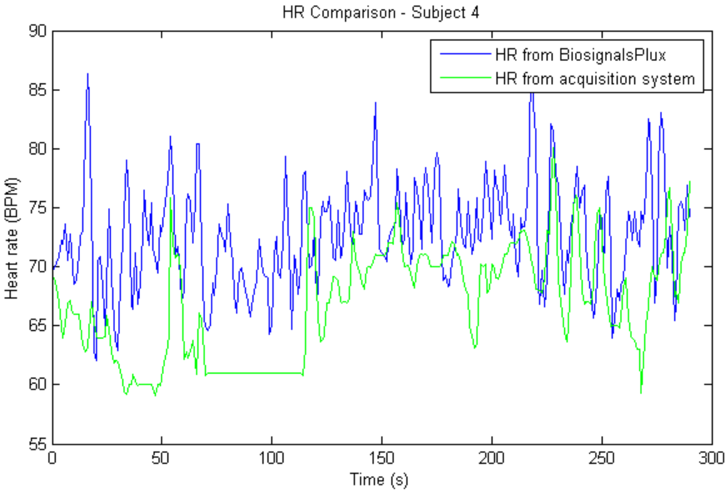


Figure 48 – HR comparison of one subject during a session

To quantify these difference between the heart rate values from the ECG and the Physiopad, three different calculation were made. The root mean square error (RMSE) is essentially the standard deviation of the differences between samples, so this represent how spread the physiopad results are from the ECG. The two last measures were the mean absolute error MAE and the mean error (ME). The mean absolute error is the mean of all the absolute differences of the two signals and is always positive. Finally, the mean error is similar to MAE but is only the difference between samples. The values can be positive or negative and indicate if the observed value is above or below the expected value.

Respectively, the results were 5.10 BPM, for MAE, and 9.47, for RMSE. These results were computed using all the 27 signals recorded (9 subjects, 3 conditions each) during the experiment.

The result shows that the heart rate from Physiopad is, on average, on average, off by 5 BPM. The mean error (ME) which averages -4.8 heartbeats, indicates that the heart rate value is usually below the real heart value by 5 BPM. As theorised in section 3.1.6, the heart rate algorithm was able to remove most of the noise added by hand movements.

As explained in section 4. both the heart rate and arousal were used to manipulate game variables, hear rate changed the paddle size increasing and decreasing it and the arousal was used to map the ball velocity. To understand fully the effect of the physiology a comparison between condition was done, regarding the game variables and, also, the physiological information. Once again, using the Wilcoxon paired test, a statistical analysis was done to find whether the differences were significant. Starting with the overall heart rates values in Figure 49, which is the mean of all heart rates values during each session, we have slightly higher values on condition two averaging 71.28 BPM while condition 3 averaged 68.99 BPM. Even though this difference is not significant, this is the expected outcome. Also comparing the standard deviation of the condition, one can see that the positive feedback has a greater while negative feedback that tends to balance the actual state of the player is lower. Condition 2 has a standard deviation of 8.36 while condition 3 value for standard deviation is 7.92.

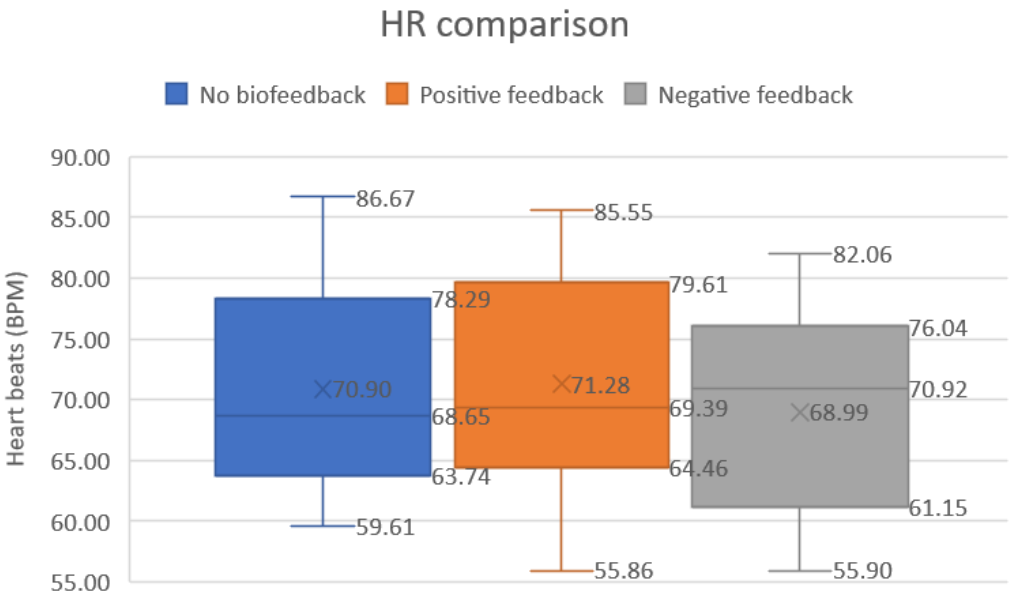


Figure 49 - Heart rates comparison between conditions

On a final note, the heart rate algorithm showed promising result and probably some optimization could lead to even better performance. On EDA and arousal, no correlation was found. More tests are needed to assert the signal's quality. Regarding positive and negative feedback, the results showed that even though negative affect and tension was superior on positive feedback, positive and competence were similar in both conditions. A different result might be seen if the subjects were not avid gamers.

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5. Final considerations

Closing this dissertation, in this final chapter, there are the main conclusions of the work, the limitations that this project suffered and some suggestions of future work that could diminish issues regarding limitations or some further investigations and studies to develop a better version of both hardware and software.

5.1. Conclusion

The goal of this project was to build a physiological acquisition gamepad that was non-invasive and easy-to-set-up. Along with the hardware, a software was developed to interface between hardware and games. This was motivated due to the complex and expensive systems, which require extensive knowledge on the physiological field.

Physiological adaptive games have been a subject of numerous studies over recent years. The physiological signals are divided into two types. Direct biofeedback signals, these are the signals that can be easily manipulated by the user, such as respiration, eye tracking or doing a certain movement. Games that only use this type of signals are known as Biofeedback games because the player is a direct participant in the biofeedback loop. Heart rate or arousal levels are examples of indirect biofeedback. In this category, one can find all the physiological signals that the user is not able to control willingly. Games that use this kind of biofeedback are considered affective games because the player is not a direct participant of the biofeedback loop. The user is unaware of the changes made inside the game. However, as soon as the user becomes aware of the biosignals and is able to influence them, even an affective game becomes a simple biofeedback game.

BITalino is a physiological device built thinking about researchers and enthusiasts that want to acquire physiological date but have little knowledge on the field. The BITalino team has worked to ease the use of physiological signals embedded in day-to-day items.

Following the literature, PPG and EDA signals were chosen to the part of the hardware to assess the heart rate and arousal during gameplay. A PlayStation 3 controller was chosen as input. BITalino was used to ease the replicability of the controller. Various tests were done to see how user holds the controller and the best positions to place the electrodes for each signal. Noticing that, usually, the synchronization of game events and physiological data is cumbersome this was one of the focus of this software. The software is also able to record multiple players at the same time with multiple devices connected to the same user if needed. Also, this software acts as a bridge between the gamepad physiology and games to enable the creation of affective games.

To evaluate the software and hardware a biofeedback game called ExerPong was used. Nine subjects played 3 different conditions of the game. One condition with no biofeedback and the others using either only positive biofeedback or only negative feedback. Also, a comparison between the Physiopad physiological data and BiosignalsPlux was done to test the signals' accurary. The heart rate showed promising results, being, on average only 5 heartbeats below the real heart rate. Derived from the proximity of the Physiopad EDA sensor and the control EDA, a lot of noise was added to the signals, therefore more tests should be done to analyse the signal responses. Overall, the positive feedback, as the literature suggested, showed increased results in tension, in negative affective and in flow in comparison to negative feedback.

To complement this work, more test should be done to assert the EDA signal quality and use a bigger sample that includes subjects lacking gaming experience. To facilitate the gathering of information by the researcher a second iteration of the software should allow the researcher to choose which feature is extracted from each signal.

5.2. Limitations

Every project is bound to some form of constrain, whether time related, number of subjects being evaluated, or even the materials that are available at that moment, be it software or hardware.

The lack of EDA results are the major limitation of this work. Although the number of subjects used in the experiments could be higher, the main objective was to validate the integration of the software with the hardware which was possible to do.

On the software side no usability test was performed. This should be done in the future, because one can have even the best physiological input device available but if its interface and configuration is not simple and easy to learn it is very hard to get people using it.

5.3. Future Work

As discussed in section 4.2.2., the lack of results concerning EDA data, request more tests. These tests should add another layer and assess positive or negative emotions. This will give better insight on why the arousal is changing as it is possible to infer what emotion the player is feeling. It is different to be aroused due to excitement or frustration. Frustration can lead to boredom meaning a decrease in arousal levels.

Further research should be done to make the controller wireless and the BITalino more compact. More sensors, for instance, skin temperature or force could be added to increase forms of adaptation during gameplay.

Tests with more interactive games which provide a richer game experience should be encouraged to study further the positive and negative feedback.

On the side of software, more filters should be added to accommodate the different needs each signal may require. The feature extraction could be abstracted from the type of the signal. This would make possible to more easily extract different features from each signal or even more than one feature (e.g. HR and HVR) simultaneously. Plus, a usability test to the software should be done to understand where one has to improve or what might still be missing.

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7. Attachments

7.1. Arousal algorithm

```
public float Calculate()
        {
            _threshold = GetThreshold();
            foreach (double signal in GetBuffer())
            {
                double resistance = 1 - (signal / 1024);
                double edaValue = 1 / resistance;

                UpdateArousalLevels(edaValue);
                updatePreviousBuffer(edaValue);
            }
            return Arousal;
        }
        private void UpdateArousalLevels(double edaValue)
        {
            if (!_updatedBuffer[bufferSize - 1].HasValue)
                return;

            if (edaValue > _threshold + 0.05 && _lastArousalUpdateInSeconds + 3 <
_timeInSeconds)
            {
                _lastArousalUpdateInSeconds = _timeInSeconds;
                Arousal++;
                if (Arousal > 10)
                    Arousal = 10;
                Array.Copy(_updatedBuffer, 0, _bufferToCompare, 0, _bufferToCom-
pare.Length - 1);
                _threshold = GetThreshold();

            }
            else if (edaValue < _threshold - 0.05 && _lastArousalUpdateInSeconds + 3
< _timeInSeconds)
            {
                _lastArousalUpdateInSeconds = _timeInSeconds;
                Arousal--;
                if (Arousal < 0)
                    Arousal = 0;
                Array.Copy(_updatedBuffer, 0, _bufferToCompare, 0, _bufferToCom-
pare.Length - 1);
                _threshold = GetThreshold();


            }
            else if (_updatedBuffer.Average() == 1f)
            {
                Arousal = 0;
            }
        }

        private void updatePreviousBuffer(double signal)
        {
            if (!_updatedBuffer[bufferSize - 1].HasValue)
            {
                for (int i = 0; i < bufferSize; i++)
                {
                    if (!_updatedBuffer[i].HasValue)
                    {
                        _updatedBuffer[i] = signal;
                        break; ;
                    }
                }
            }
            else
            {
                Array.Copy(_updatedBuffer, 1, _updatedBuffer, 0, bufferSize - 1);
                _updatedBuffer[bufferSize - 1] = signal;
            }
        }

        private double GetThreshold()
        {
            if (!_updatedBuffer[bufferSize - 1].HasValue)
                return 0;
            return Mean.Calculate(_bufferToCompare);
            //return _bufferToCompare.Average();
        }
```

7.2. Heart rate algorithm

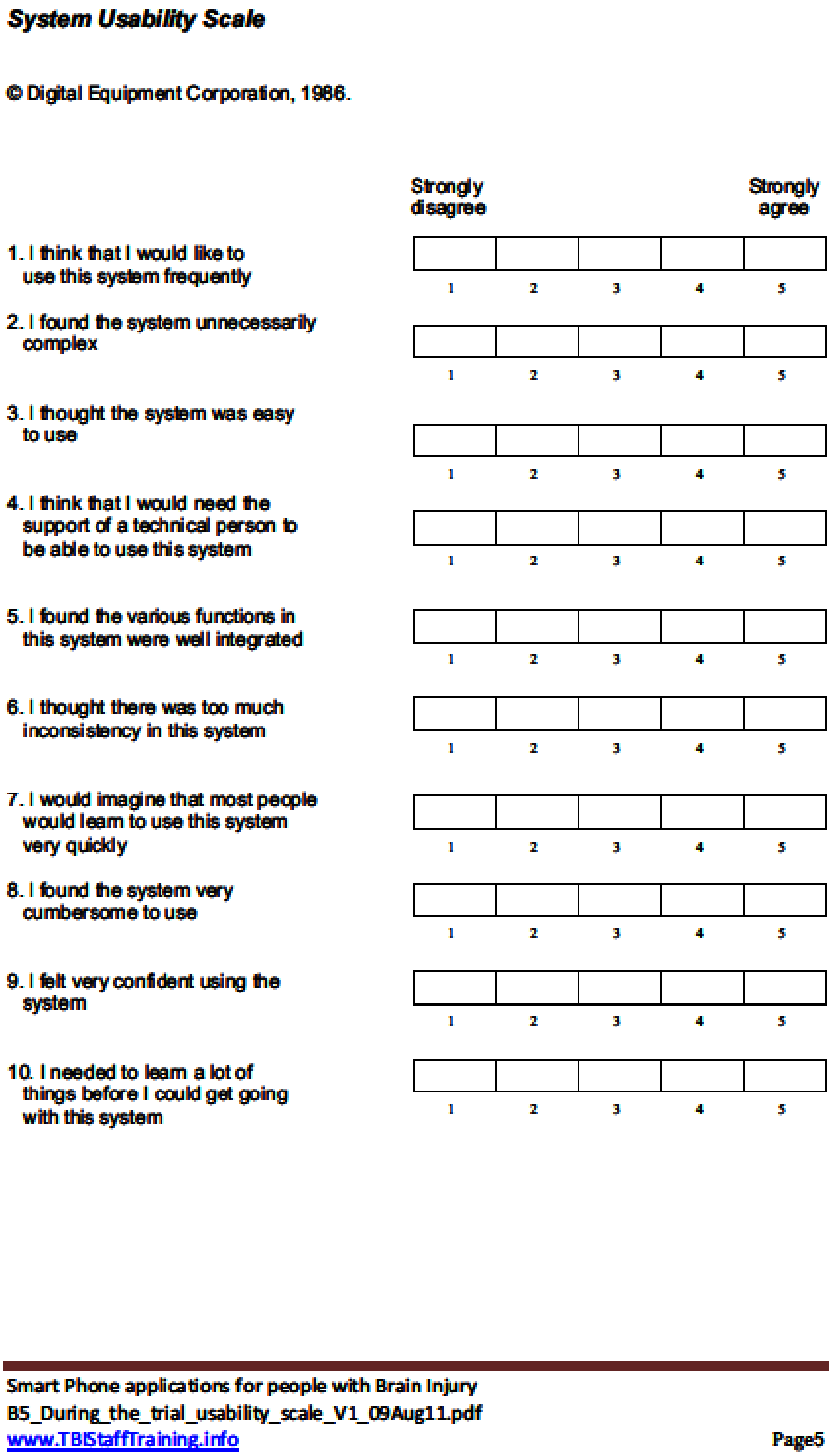
```
public float Calculate()
        {

            double m_maximum = 0;
            bool m_peakFlag = false;
            double m_peakThreshold = 0;
            double m_peakTimer = 0;
            int n = Reader.BufferSize;
            double m_fs = 1000;

            foreach (double b in GetBuffer())
            {
                double value = b * ScaleY;
                if (value > m_maximum)
                {
                    m_maximum = value;
                }
                m_peakThreshold = m_maximum * 0.7f;

                if (value < m_peakThreshold && m_peakTimer > 1.5f)
                {
                    m_maximum -= 0.01f;
                }

                if (value > m_peakThreshold * 1.1f && !m_peakFlag)
                {
                    double heartRate = 60 / m_peakTimer;

                    if (heartRate > 40 && heartRate < 130)
                    {
                        for (int w = _mHeartRates.Length - 1; w > 0; w--)
                        {

                            _mHeartRates[w] = _mHeartRates[w - 1];
                        }

                        _mHeartRates[0] = heartRate;
                    }
                    m_peakTimer = 0;
                    m_peakFlag = true;
                }

                if (value < m_peakThreshold * 0.9f && m_peakFlag)
                {
                    m_peakFlag = false;

                }
                m_peakTimer += 1 / m_fs;
            }


            return (float)Mean.Calculate(_mHeartRates);
            //return (float)_mHeartRates.Average();
        }
```

7.3. EDA correlation table

#	Correlation coefficient RHO	P-value
1	0.00	0.69
2	-0.08	0.00
3	0.01	0.00
4	0.01	-0.01
5	0.00	0.60
6	0.00	0.09
7	0.34	0.00
8	0.63	0.00
9	-0.62	0.00
10	0.00	0.99
11	0.00	0.61
12	0.00	0.27
13	0.21	0.00
14	0.17	0.00
15	0.00	0.27
16	-0.70	0.00
17	0.44	0.00
18	0.24	0.00
19	0.09	0.00
20	0.00	0.14
21	0.00	-0.02
22	-0.29	0.00
23	-0.65	0.00
24	-0.82	0.00
25	-0.66	0.00
26	-0.82	0.00
27	0.56	0.00

Table 1 - Correlation between EDA from biopluxsignals and Phyiopad's EDA

7.4. System usability scale Questionnaire

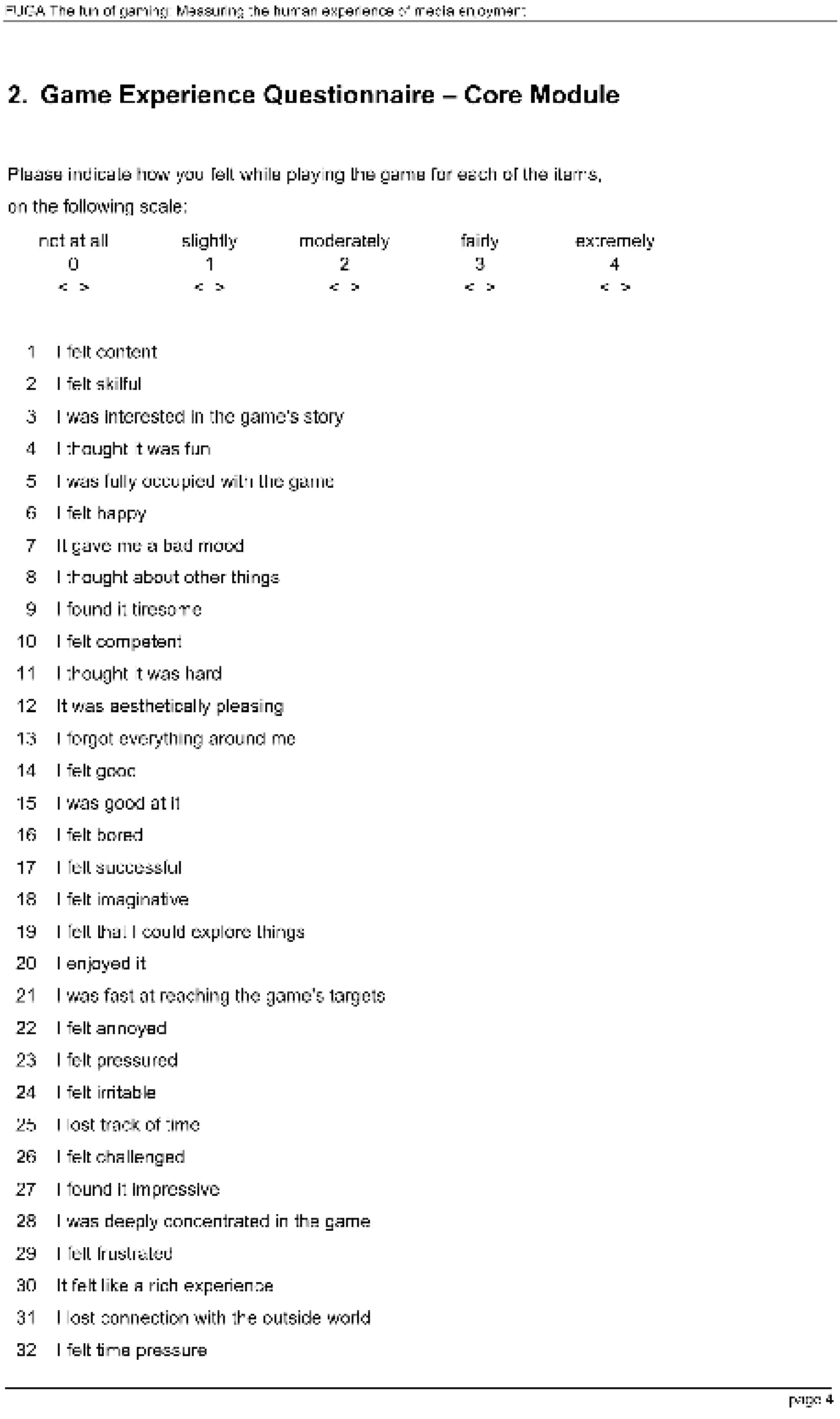


System Usability Scale

	Strongly disagree				Strongly agree
1. I think that I would like to use this system frequently	□ 1	□ 2	□ 3	□ 4	□ 5
2. I found the system unnecessarily complex	□ 1	□ 2	□ 3	□ 4	□ 5
3. I thought the system was easy to use	□ 1	□ 2	□ 3	□ 4	□ 5
4. I think that I would need the support of a technical person to be able to use this system	□ 1	□ 2	□ 3	□ 4	□ 5
5. I found the various functions in this system were well integrated	□ 1	□ 2	□ 3	□ 4	□ 5
6. I thought there was too much inconsistency in this system	□ 1	□ 2	□ 3	□ 4	□ 5
7. I would imagine that most people would learn to use this system very quickly	□ 1	□ 2	□ 3	□ 4	□ 5
8. I found the system very cumbersome to use	□ 1	□ 2	□ 3	□ 4	□ 5
9. I felt very confident using the system	□ 1	□ 2	□ 3	□ 4	□ 5
10. I needed to learn a lot of things before I could get going with this system	□ 1	□ 2	□ 3	□ 4	□ 5

Smart Phone applications for people with Brain Injury
B5_During_the_trial_usability_scale_V1_09Aug11.pdf
www.TBIStaffTraining.info Page5

7.5. Game experience questionnaire



2. Game Experience Questionnaire – Core Module

Please indicate how you felt while playing the game for each of the items,
on the following scale:

not at all	slightly	moderately	fairly	extremely
0	1	2	3	4
< >	< >	< >	< >	< >

1 I felt content
2 I felt skilful
3 I was interested in the game's story
4 I thought it was fun
5 I was fully occupied with the game
6 I felt happy
7 It gave me a bad mood
8 I thought about other things
9 I found it tiresome
10 I felt competent
11 I thought it was hard
12 It was aesthetically pleasing
13 I forgot everything around me
14 I felt good
15 I was good at it
16 I felt bored
17 I felt successful
18 I felt imaginative
19 I felt that I could explore things
20 I enjoyed it
21 I was fast at reaching the game's targets
22 I felt annoyed
23 I felt pressured
24 I felt irritable
25 I lost track of time
26 I felt challenged
27 I found it impressive
28 I was deeply concentrated in the game
29 I felt frustrated
30 It felt like a rich experience
31 I lost connection with the outside world
32 I felt time pressure