Design and Development of an Immersive Virtual Reality Serious Game With Biofeedback for Physiological Regulation: Alice, Beyond Reality

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Abstract: The adolescence period is characterized by significant changes in individuals' lives, which can lead to various emotional and behavioural problems. Therefore, it is important for young adults to have tools for self-regulation, understanding, and controlling their physiological symptoms. Integrating these tools as gamified elements into new technologies is a way to engage a younger audience. In recent years, the effectiveness of immersive Virtual Reality has been repeatedly demonstrated in fields such as Psychology and Education. The combination of this technology with biosensors enables individuals to be aware of their real-time physiological states. This physiological monitoring can lead to adaptations in applications based on the individual's emotional state, for example. This work describes the design and development of an immersive Virtual Reality game whose main interaction is through biofeedback. The game is called "*Alice, Beyond Reality*", and its objective is to help young adults learn to self-regulate their physiological responses. The game draws inspiration from the well-known story of "*Alice in Wonderland*". In this story, the Queen of Hearts has transformed all the characters into cards, and the players must help them escape before it's too late. To achieve this, the players are guided by the White Rabbit through different levels where interaction through physiology is key. For instance, the players must learn to increase and decrease their heart rate to solve puzzles that allow them to progress to the next level. Throughout the game, gamification elements such as points, progressive difficulty, and various challenges are included to motivate the players to continue advancing in the game. Through the biofeedback system, the players become aware of their physiological changes to control them voluntarily. In the final screen, the players are shown their progression throughout the game so they can recognize their evolution. In the near future, an initial validation with users will be conducted to assess the usability and functionality of the game.

Keywords: Biofeedback, Heart Rate, Immersive Virtual Reality, Serious Game, Physiology

1. Introduction

The adolescent period is characterized by significant changes in individuals' lives: physical and psychological maturation, changes in social relationships, brain transformations, etc. (Crone and Dahl, 2012). These changes can lead to difficulties in attention management, emotions, and behaviour. Such difficulties may escalate into more serious situations such as aggression or substance abuse, among others (Iannattone et al., 2024). Therefore, it is important for young adults to have psychological tools like self-regulation to use when needed.

The self-regulation of physiological state serves as a valuable mechanism within the organism, facilitating the management of situations characterized by high levels of anxiety or stress or negative emotions (Goessl, Curtiss and Hofmann, 2017). This process entails the attentive monitoring of physiological signals, the comprehension and management of emotions, and the adjustment of bodily responses to achieve an optimal state wherein negative emotions, such as anxiety, do not become incapacitating (Gratz and Roemer, 2004). Biofeedback systems help individuals train the voluntary capacity to control some physiological functions such as breathing (Aritzeta et al., 2022). Heart rate (HR) variability emerges as the most frequently utilized parameter in biofeedback applications aimed at self-regulation, given its intimate connection with respiratory processes (Lehrer and Gevirtz, 2014). Deep breathing technique, for instance, increases oxygen levels in the blood and stimulates the vagus nerve, resulting in longer intervals between heartbeats (Toussaint et al., 2021).

Gamification is a technique that involves incorporating game elements into non-game contexts (Deterding et al., 2011). This technique has gained popularity in the field of mental health in recent years. The inclusion of game elements such as rewards or challenges in therapeutic situations encourages individuals to become more engaged (Khaliq, Fowles and Moore, 2018). Games that combine some form of learning with gamification are referred to as Serious Games (SG) (Carrión et al., 2020). Gamification elements such as trophies or scores can create a sense of challenge and excitement that boosts attention and enhances cognitive engagement. The use of these elements fosters positive emotions that improve learning rates and cognitive skills (Christie et al., 2019).

In the field of Psychology, SG can be designed to achieve various objectives, including promoting techniques to mitigate and manage symptoms related to mental health issues. Among these techniques are breathing exercises and meditation (Alqahtani and Orji, 2020).

Immersive Virtual Reality (iVR) can be defined as a virtual experience in which the individual is completely immersed thanks to a Head-Mounted Display (HMD) (Suh and Prophet, 2018). This sensation is enhanced by the sounds played on the HMD and the feeling of control over the application though controllers or trackers (Murcia-López and Steed, 2016). In recent years, iVR has become increasingly popular across various fields, not just in entertainment. For instance, its significant potential has been observed in the field of education (e.g.,Checa, Miguel-Alonso and Bustillo, 2021). Similarly, numerous benefits have been discovered in the field of Psychology.

For example, iVR can assist individuals in confronting their fears in a controlled environment (e.g., Bzdúšková et al., 2022) or promote anxiety reduction (e.g., Bozdogan Yesilot, Ciftci and Ozcelik, 2021; Ziegelman et al., 2021).

iVR has been combined with biosensors to monitor user physiology in real-time. For example, one study found that individuals had better stress resilience when their heart rate data was displayed to them while they played and interacted with the game through biofeedback (Maarsingh et al., 2019). In another study, researchers found that biofeedback in iVR was effective for learning breathing techniques (Blum, Rockstroh and Göritz, 2020). Besides, the use of biosensors enables application customization as it adjusts to the needs of each user. This customization facilitates task focus, enjoyment of the experience, and enhances results. Individuals also prefer customization as it offers them a greater degree of control over the application (Alqahtani and Orji, 2020).

The present work is structured as follows: Section 2 explains the methodology followed for the creation of the serious game. Subsequently, Section 3 outlines the design and development process of the application. Finally, in Section 4, conclusions are drawn from the work, and future lines of research are proposed.

2. Methodology

For this work, a methodology proposed for the development of serious games in iVR has been followed (Checa and Bustillo, 2020). This methodology proposes different phases for creating a serious game in iVR. In the first phase, Pre-design, the target audience and the needs and objectives that the game aims to fulfil should be identified. It is also necessary to decide on the technology that best fits the research proposal. In the second phase, called Design, all the necessary materials for the game, such as assets or environments, are created. In this phase, the narrative and level structure, interaction mechanics, game objectives, etc., are also decided and developed. Finally, during the Evaluation phase, a validation must be designed to check if the educational objectives proposed in the Pre-design phase have been met. This last phase will be carried out in future research.

The project has been developed under the framework of established theories. Firstly, the Flow Theory has been employed, which posits that individuals seek to achieve final goals when they are engaged and motivated in an activity (Csikszentmihalyi, 2014). For this theory to be effective, there must be a balance between difficulty and challenge. The Reinforcement Theory has also been employed, which explains that extrinsic gamification mechanics such as rewards or rankings positively influence learning outcomes (Berkovsky, Freyne and Coombe, 2012).

Furthermore, other research has been taken into account for making more specific decisions within each of the sections. According to a research, the duration of gameplay should be short so that individuals can quickly appreciate their progress (Khaliq, Fowles and Moore, 2018). Likewise, increasing their motivation and helping them stay focused on tasks helps them achieve better outcomes. This is also positively influenced by the customization of applications and their adaptation to the needs of each individual (Cheng and Ebrahimi, 2023b). A biofeedback system aids in this customization of the application in real-time, adapting to the needs of each user.

On the other hand, navigating through a fantasy world generates a state of flow and concentration that allows players to feel immersed to the point of losing self-awareness and track of time. This state of flow enables players to set aside real-life concerns and focus on the intervention to address, for example, their physiological symptoms (Cheng and Ebrahimi, 2023a). To prevent players from being distracted by the use of new technologies, it is advisable to include a tutorial level where they can learn the game mechanics and avoid the novelty effect (Miguel-Alonso et al., 2023).

Regarding relaxation techniques, deep and conscious breathing has been shown to have a positive impact on factors such as stress and anxiety. Additionally, it is an easy-to-perform technique that can be used across various populations of individuals (Toussaint et al., 2021).

3. Alice, Beyond Reality

A serious game in immersive Virtual Reality named "*Alice, Beyond Reality*" has been developed, featuring its primary interaction through users' physiology with a real-time biofeedback system. In Figure 1, the design and development process of the application is illustrated according to the parameters outlined in the Methodology section.

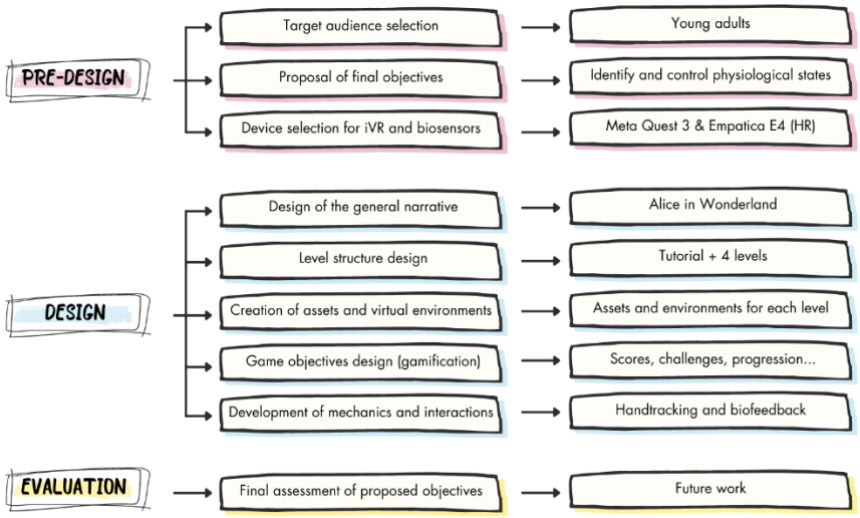

Figure 1: Summary of the game design and development process

The selected target demographic comprises young adults aged 15 to 20 years who lack understanding of how to manage their physiological state. On the other hand, the purpose of this study is to assist these young adults in becoming aware of their physiology and teaching them how to regulate it.

The game narrative draws inspiration from the story of *Alice in Wonderland*. As it is a well-known tale, the player is already familiar with the background from the beginning of the game. In this narrative, the Queen of Hearts has transformed all the characters into cards, and the player must assist them in escaping before it is too late. To achieve this, the player must overcome a series of levels with the guidance of the White Rabbit, where interaction through the player's physiology is the key.

3.1 Software and Device Selection

The game has been developed using the following software. Blender was employed for the creation of 3D assets. Photoshop was utilized for the creation of textures. Finally, Unreal Engine was used for the creation of environments and the programming of mechanics and interactions. These software tools were chosen due to their previous experience within the research group.

The game has been designed for use on the Meta Quest 3 device, although it could be utilized on any device that supports hand-tracking. Regarding the selected biosensor, the Empatica E4 wristband has been employed. The Empatica E4 wristband enables the collection of various raw physiological data, such as electrodermal activity or blood pressure volume, and can connect in real-time with the game engine. However, in this game, only the data related to heart rate is utilized.

3.2 Level Design

All the scenarios have been designed with a visual style that departs from realism. The textures evoke watercolour paintings, and the assets exhibit a slight fantastical character (for example, clocks that run backward). The scenarios have been designed so that the user can play within a real physical space of 2 square meters. This has been done to eliminate the need for players to move using controls, providing them with the sensation of actually moving within the virtual room. The interaction with virtual objects is accomplished

through a hand-tracking system integrated into the HMD instead of using controllers. Hand-tracking has been chosen as the main mode of interaction to make gestures such as grabbing and releasing objects feel more natural. Otherwise, the total duration of the game is approximately 25 minutes to ensure that the gameplay is sufficiently engaging, and that the player does not experience fatigue from the iVR device. In terms of audio, sounds have been incorporated to enhance the players' experience and immerse them further into the environment. Firstly, ambient sounds tailored to each level have been created to enhance the sense of immersion. These sounds align with the game's narrative, reflecting the tone and atmosphere of each level. Secondly, there are dynamic sounds related to the player's behaviour. For example, gratifying sounds play when actions are successful, and alert sounds signal if game objectives are not met. Additionally, these feedback sounds will be complemented with visual cues for individuals with hearing impairments.

The game is structured as follows: 1) a tutorial level for users to learn basic interactions and establish their individual baseline, 2) four levels with different environments and challenges where biofeedback plays a fundamental role, and 3) a final screen displaying the progress and results for each user.

3.2.1 Level Tutorial

The player emerges in a forest surrounded by trees, as can be seen in Figure 2.A. There is a picnic bench and various objects, including a key that opens a door located in one of the trees. The player has time to explore how the mechanism of picking up objects works and can practice with those placed on the bench. If the player is unable to do so independently after a few minutes, an off-screen voice will provide instructions on what needs to be done. When the player opens the tree door, the scenario changes as the player enters Wonderland.

As a transition between levels, a black environment will open up where cards fall around the player.

When the player enters Wonderland, a new level begins in a nearly empty room, as shown in Figure 2.B. In that room, there is a card with a printed white rabbit that can only move its eyes and mouth. The White Rabbit explains that "they are all trapped in Wonderland" and reveals the evil plan of the Queen of Hearts to turn everyone into cards. Subsequently, the White Rabbit seeks the player's aid in searching for and saving the characters throughout the different levels.

The White Rabbit warns the player that the rooms are aware of how people feel when they enter them: they use the player's heart rate information to alter the environment, making it more challenging to escape Wonderland. Additionally, the White Rabbit gives the player a gift: a watch that displays real-time heart rate. This watch makes it easier for the player to recognize a state of calmness or agitation. The purpose of using this watch is for the player to learn how to consciously regulate the physiological state. To achieve this the White Rabbit teaches the player what happens when body movement is increased (heart rate increases) and then demonstrate the effects of deep and conscious breathing technique (heart rate decreases). Following this brief introduction, the adventure through Wonderland starts.

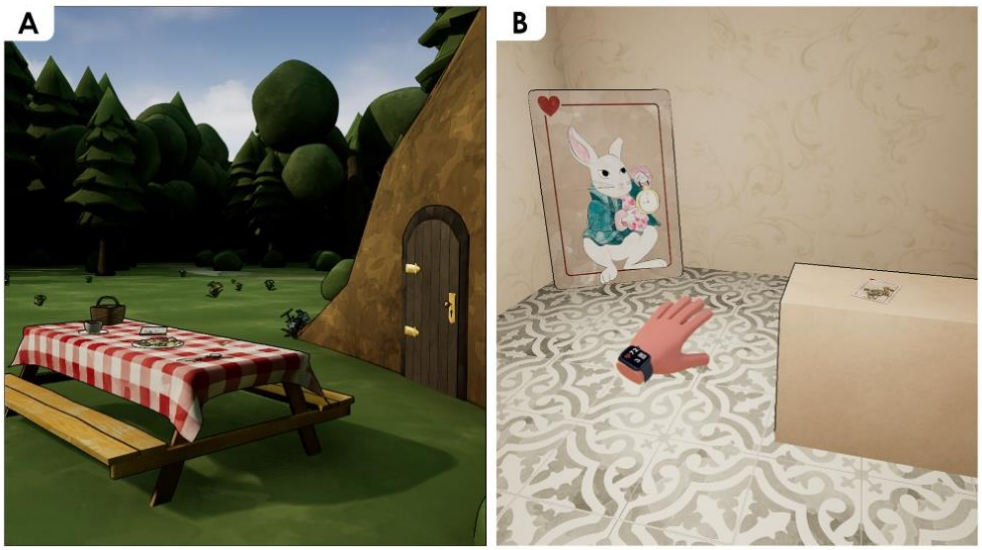

Figure 2: Overview of the tutorial level: the initial screen with the picnic bench (A); and the tutorial and first interaction with the White Rabbit (B).

3.2.2 Level 1

In the first level, the player appears in an exceedingly large room. Within this room, there is a tea table with various items on it: plates, cups, teapots, cookies, etc, as shown in Figure 3.A. The player needs to do exactly the same as in the tutorial level: increasing the heart rate to grow in size and be able to search for a key in the room; and breathing deeply to reduce the heart rate, become small again and exit through a small door.

Apart from searching for the key, the player is also able to find some character cards hidden in the room. Each time a character card is found, the number of cards collected throughout the game will appear on the watch. The White Rabbit's card is present in this and the other levels to assist the player in case they are unsure of what to do or need some form of help.

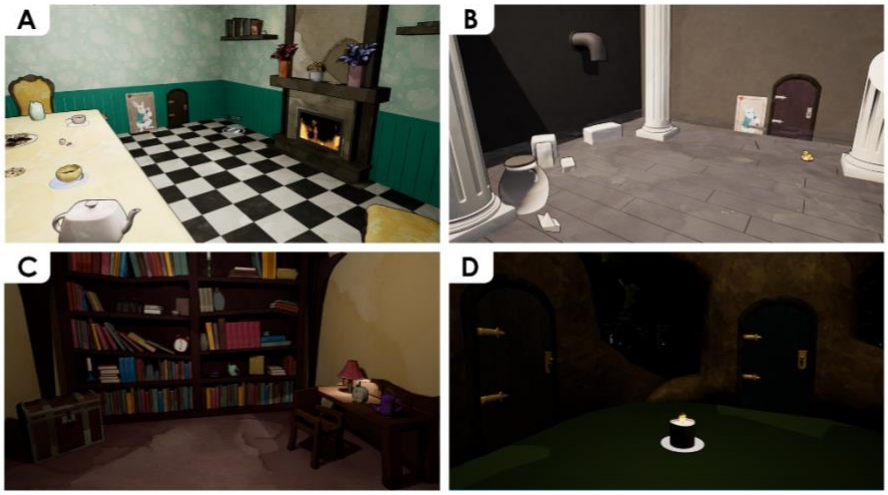

Figure 3: Overview of the game levels: initial level (A); level 2 (B); level 3 (C); and final level (D).

3.2.3 Level 2

At the beginning of this level, the player appears in a room with water on the floor, as can be seen in Figure 3.B. In the background, the sound of falling water is heard. The water level on the floor rises as time passes. The player must search the stage for some cards and a key to exit before the water reaches head level.

To successfully complete this level, the player must stay calm to slow down the rising water. If the heart rate increases, the water will rise rapidly, giving the player less time to play. If the water reaches the player's head, the level will restart, giving the player the opportunity to practice controlling their physiology despite the stress of the situation. The player can request assistance from the White Rabbit whenever necessary so they can successfully complete the level.

3.2.4 Level 3

In a room filled with objects and numerous keys, the player must search for the correct key to unlock the door and exit the room. The player won't have any clues; there will only be a timer clock with a countdown, and the sound increases with each passing second, as shown in Figure 3.C.

The player must maintain a state of calm despite the countdown timer to ensure that time does not run out. If time runs out, the level will restart, providing the player with the opportunity to learn how to control their physiology in order to progress to the next level. As in the other levels, the player can also search the environment for character cards and ask the White Rabbit for help at any time.

3.2.5 Level 4

The player appears in a clearing in the middle of the forest at night, surrounded by trees with doors, as can be seen in Figure 3.D. In the middle of the clearing, there is only a candle that slightly illuminates the surroundings. The candle's appearance is influenced by the player's HR: if it remains steady, the candle will shine brightly. In case the HR fluctuates, the candle will lose intensity, and the player won't be able to see the surroundings clearly.

The player must maintain balance while searching for the exit. Only one of the doors contains the clue on how to exit the adventure to the final screen.

3.2.6 Final Screen

The player reappears in the initial forest with the picnic bench, as if the adventure never existed. On this screen, the player's progress in the game, the saved character cards, and the number of times help has been requested are visible. Additionally, the White Rabbit running through the forest and disappearing among the trees can be observed. When the player wishes, the game and the adventure will be concluded.

3.3 Gamification Elements

Throughout the game, various gamification elements have been incorporated. Below is a list of these elements.

3.3.1 Points and Badges

Players must search for character cards throughout the levels. These cards are badge-shaped and collectible. The more cards they manage to obtain, the higher their score will be.

3.3.2 Levels and Difficulty

Levels increase in difficulty as the player progresses through the game. The first level replicates the same interaction as in the tutorial level, while the last one requires the player to figure out what to do on their own.

3.3.3 Narrative and Challenges

There is a narrative that drives the progression of the game. Additionally, various challenges are included to prevent the game from becoming monotonous.

3.3.4 Progression

In the final screen, the players are shown their progression throughout the game so they can recognize their evolution. Specifically, the relationship between the stressors in the game and the player's physiological control required to overcome them will be displayed.

The difficulty of the levels and the various challenges can induce stress in players. Although these situations might seem counterproductive, it is essential to include challenges where players can apply what they have learned throughout the game. For instance, in Level 2, the rising water will likely make players anxious, leading to an increase in their heart rate. However, the challenge in this level is to try to reduce their heart rate despite the stressful situation. These types of scenarios mirror real-life situations, where the true effectiveness of this application in teaching users how to regulate their physiology will be tested.

3.4 Biofeedback System

For the creation of the biofeedback system in this game, the Empatica E4 wristband has been utilized. The wristband transmits real-time data and connects to the computer via Bluetooth. An application programmed in C# has been developed, serving as an intermediary between Unreal Engine and the Empatica data acquisition service in real-time. The code of this application implements a TCP/IP socket client connecting to a remote server (E4 Streaming Server) and also acts as a server to receive data from Unreal Engine. This code utilizes the official documentation of the wristband (https://developer.empatica.com/windows-streaming-server.html).

Within the Unreal Engine project, a blueprint has been created that requests information from the wristband. Specifically, it instructs the wristband to acquire only heart rate data. The heart rate data is obtained from the Blood Volume Pressure measurement (BVP) provided by the wristband at a frequency of 64 Hz and is acquired using a photoplethysmogram. To calculate the HR value, the application uses the interval between peaks of the BVP signal, also known as the Inter-Beat Interval (IBI). The formula for calculating HR is as follows: 60/IBI (in seconds). The result is the number displayed to the player on the virtual smartwatch and used by the application. The tutorial level's duration will be utilized to establish each player's physiological baseline, serving as a reference throughout the game because it is assumed that during the tutorial level, players are in a neutral state between relaxation and arousal.

Throughout the levels, an average of the most recent HR values is calculated, to create a *dynamic baseline* for each player. The biofeedback system compares the current HR with the dynamic baseline value to determine if the goals set for each interaction are achieved. These goals have been programmed as percentages to adapt to each player's baseline. For example, if the HR is more than 110% of the dynamic baseline, the goal is considered achieved. This system for obtaining HR from BVP data using the Empatica E4, and its classification of emotional states through various percentile thresholds, is similar to that used in a study aimed at detecting real-time stress by exposing individuals to both stressful and non-stressful situations (Campanella *et al.*, 2023).

4. Conclusions and Future Lines

A serious game in immersive Virtual Reality, functioning through biofeedback, has been designed and developed. This serious game called "*Alice, Beyond Reality*" aims to teach players to regulate their physiology through gamified educational content. In this way, by incorporating a familiar narrative and engaging gameplay mechanics, the players can learn to understand and control their own physiology, specifically, their heart rate through breathing.

In the game, various gamification elements have been included, such as scoring, diverse objectives, progressive difficulty, and a summary of progress during gameplay. Additionally, a tutorial level has been created to mitigate the novelty effect of the Virtual Reality device.

In the near future, an initial validation with users will be conducted to assess the usability and functionality of the game. Following this validation, any identified areas for improvement will be addressed, leading to a subsequent large-scale validation to gather data on the learning outcomes related to self-physiology management. The validation will be conducted with a large group of young adults, specifically university freshmen, divided into three groups. One group will use the VR application with real biofeedback, another group will use the VR application with a fake or placebo biofeedback system, and the third group will receive lessons on the relationship between the use of breathing techniques and their physiological state. All three groups will undergo several tests to determine which group has learned the most about physiological control, with the expectation that the group using VR with real biofeedback will show the most improvement.

In the future, the possibility of incorporating additional physiological data into the biofeedback system will be considered to enhance the complexity of the game. With this data, complex algorithms can be trained to learn from users' physiological responses, enabling the prediction of user behaviours.

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