Exploring the Effect of Personalized Virtual Reality Serious Game for Stroke Rehabilitation

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Abstract

This report details the design and development of a functional prototype of a Serious Game for stroke rehabilitation. The project focuses on personalized Virtual Reality (VR) environments approach to enhance survivor motivation and satisfy their individual needs and goals.

Contents

1 Acknowledgments

I acknowledge the use of Gemini for text translation and grammatical correction, for generating images for the game's UI and the report, and NotebookLM for verifying the consistency of the written content against the references.

Part of this game was developed for the practical component of the **Virtual and Augmented Reality** course with my colleague, student **Ana Rita Guimarães (Student Number: 124362)**, who was responsible for designing the environment, developing the mechanics of the archery game, and creating the 3D models for the balloons, bow, and arrow, as well as animating the Ferris wheel.

Some of the 3D models were imported from the Poly Pizza website. Here are the authors of those models:

- **Google:** Sheep Model, Ferris Wheel Model, Tent Model;
- **Quaternius:** Fence Model;
- **J-Toastie:** Persons Models and Animations;
- **sirkitree:** Carnival Booth Model, Merry-Go-Round Model;
- **Adam Tomkins:** Grass Floor Model;
- **Ian MacGillivray:** Big Tent Model;
- **Don Carson:** Popcorn Cart Model;
- **Sammy** Bench Model.

2 Context of the Serious Game and its Problematic

Stroke is a medical condition that affects severely the global population. It occurs when a blood flow to the brain disrupted, due to a blocked artery (**ischemic stroke**) or a ruptured blood vessel (**hemorrhagic stroke**).This disruption deprives brain cells of oxygen causing their deaths and possibly leading to a range of neurological impairments[5]. Accordingly to the **World Stroke Organizition**, over **100 million** people have already experienced stroke and over **12 million** people will have their first stroke this year of whom **6.5 million** will die[6].

Despite, **54 %** of people survive to stokes their life after the event is often followed by a new set of challenges. The majority of strokes result in permanent disabilities, that can affect physical mobility, swallowing, speech, vision and cognition. These impairments impact the survivor's ability to perform daily activities and diminish their quality of life, which can make them feel useless and lead to serious psychological problems, such as depression and social isolation[4][1][3][2].

While survivors may not fully return to their pre-stroke state, it is recommended that rehabilitation begin as soon as possible to maximize the recovery of lost capacities and improve performance in daily activities[4]. Although it might seem good in theory, traditional rehabilitation methods have significant constraints. To understand these limitations, the rehabilitation process can be conceptualized through an analogy of building a brick house, where the structure represents the recovery of the survivor's capacities. Just as a house cannot be built without bricks and mortar, successful rehabilitation requires fundamental components. In this analogy, the survivor's spirit, motivation, determination and engagement are the bricks the essential, foundational elements without them no progress can be made. The exercises constitute the mortar, binding the components together and translating motivation into visible progress. However, traditional rehabilitation often relies on the repetitive practice of the same exercises. This can make them feeling tedious, monotonous over time, detouring the patient's motivation and engagement the essential ***'bricks'*** thereby compromising the entire recovery process[1][3][2].

Another major constraint of conventional rehabilitation programs is often establish identical exercises to everyone. As a result, survivors who struggle with the tasks while seeing their peers succeed may become demotivated, which again breaks the essential ***'bricks'*** of this process. This brings to mind a famous quote by **Albert Einstein**, ***"Everyone is a genius. But if you judge a fish by its ability to climb a tree, it will live its whole life believing that it is stupid."*** In this context, the quote suggests that the issue is not with the survivors, but with the programs that simply don't adapt to the specific needs and pace of each patient[1][3][2].

This leads to an important question, **How can we create rehabilitation programs that adapt to the individually needs for each survivor?** The solution relies in introducing a certain degree of personalization into these programs focusing on adapting to the survivor's specific needs and progress.

However, monitoring a survivor's progress with the accurate precision and adapting the exercises in real-time based on their performance is overly complicated for healthcare professionals. Manually recording times, comparing results across sessions, and analyzing various performance parameters is time-consuming and inclined to error. Therefore, there is a clear need for a tool that can automatically make these adjustments and assist professionals in monitoring progress.

When considering automation, digital solutions such as computers are what comes to mind. A bright approach is to consider the use of **Virtual Reality VR** combined with **Serious Games**. Virtual Reality environments are well know for creating immersive experience that increases user engagement engagement. In addition, **VR** Headsets can track users hand/arms, allowing users to control **VR** applications in a natural way. This feature cab be useful for stoke survivors practicing specific movements required to recover their lost motor skills. Serious Games are digital games which are designed for purposes beyond entertainment, bu they incorporate gamification elements similarly or equal to those found on traditional digital games, which are responsible for keeping player motivated and engaged. Other similarity between this type of games and the traditional one they also have the benefit of improving cognitive functions. Serious Games are particularity known to be use to adapt to user's performance through automatic algorithms such as **Dynamic Difficulty Adjustment DDA** ensuring that the challenge still remains in the new level of difficulty and still maintaining the fun of playing the game. When combined these technologies have the potential to boost user motivation and engagement[1].

3 Game Synopsis

The game is set in a **Country Fair** environment, chosen for its cultural resonance and emotional value. Upon entering the fair, the player receives a brief introduction given by the owner of the fair (**Zeca Bigodes**) (Figure 1). He explains the purpose of the game to the player, lists the mini-games that the fair offers, and introduces another character, **Carny Wise** (Figure 2), who will explain the mini-game rules and guarantee that the game matches the player's level.

The current mini-games avaible are: an Archery game, where the targets are balloons, and a Frisbee game, where the player must throw a frisbee to certain areas for a dog to catch in order to score points.

After the player finishes playing one of these games, he is transported back to the fair, and the owner congratulates him on his performance.

Figure 1: Country Fair's owner explaning the purpose of the game to the player

Figure 2: Carny Wise explaning to the player what he must do in the archery mini game

4 Gameplay Description

Following the game's introduction, the mini-game tents appear in front of the player. To select a mini-game, the player must press the button located in front of the respective tent.

Upon entering a mini-game for the first time, **Carny Wise** explains the rules and objectives. After this explanation, he presents a short challenge to allow the player to practice the required gestures before the game begins. The character also displays a demo video of the challenge, allowing the player to visualize and mimic the correct hand movements. Once the practice component is finished, the player proceeds to the game, playing until a specific target score is reached.

Upon achieving the score, the player is transported back to the fair, and the owner congratulates him on his performance. At this stage, the player can choose to replay the same mini-game or select a different one.

Additionally, the player can return to the fair at any time during a mini-game by pressing a specific exit button within the interface.

5 Rules, Victory, and Defeat Conditions

5.1 Rules

To complete either mini-game, the player must achieve a specific target score, which simulates the goal of a rehabilitation session. Although the objective is similar, the scoring mechanics differ between the two games.

5.1.1 Archery Mini Game

To score points, the player must target balloons that match the specific color displayed on the mini-game's UI, rather than shooting randomly. The points awarded do not depend on the balloon's color but on its behavior parameters, as shown in Table 1.

Table 1: Archery Mini Game Score System

Balloons Parameters	Score Points
Static	1
Moves	2
Transparency Can Change	3
Moves And Transparency Can Change	6

5.1.2 Frisbee Mini Game

In this mini-game, the player scores by throwing the frisbee into specific target zones: the area surrounding the dog or other designated orange areas. The dog's zone has a fixed score, whereas the other zones award points based on their dynamic parameters (Table 2).

Table 2: Frisbee Mini Game Score System

Dog Area	Score Points
	8

Other Score Areas Parameters	Score Points
Static	1
Moves	2
Can blink/Disappear	3
Moves And Can blink/Disappear e	6

5.2 Victory and Defeat Conditions

Both mini-games operate on a "flow-based" system rather than the traditional bwin/loss system to maintain optimal player engagement. While reaching the target score serves as the completion condition (Victory), there is no traditional "Game Over" state (Defeat), the session continues until the rehabilitation goal is met

6 Mechanics

6.1 Fair Navigation

After the game's introduction, the environment is populated with tents representing the mini-games. The mini-games are selected via a gaze-based interaction system (eye tracking), which consists of the following elements:

- **Focus Detection**: If the player's camera is directed towards a tent's collider, that object becomes highlighted.
- **Spatial UI**: A World Space Canvas UI is enabled above the tent, displaying the mini-game's title, a representative 3D object, and an interaction button.
- **Transition**: When the player presses the button, they are transported directly to the selected mini-game

6.2 Archery MiniGame Mechanics

The game's interaction uses a two-handed system, where the bow is locked onto the player's left hand, with the arrow automatically being attached. The player, with their other hand, grabs the bow string and pulls it back. After releasing it, the arrow is shot forward. When the arrow hits a surface, it is then returned to the bow.

To assist with aiming, a trajectory line renderer visualizes the predicted path of the arrow based on the current string tension.

To help the player with aiming, a black trajectory line renderer is used to show where the arrow is expected to go based on the current string tension force. The arrow's flight has a parabolic trajectory which results from three main forces, as shown in Figure 3:

1. **Launch Force (Flaunch):** An initial force is given to the arrow at the exact time of release. The force magnitude is calculated through linear interpolation between minimum and maximum force thresholds, directly proportional to the current distance the string was pulled.
2. **Gravity (Fgravity):** A constant force poiting down acting during flight (Unity Physics Engine Force).
3. **Drag (Fdrag):** A force (Unity Physics Engine air friction force) with the opposite direction of the arrow's velocity.

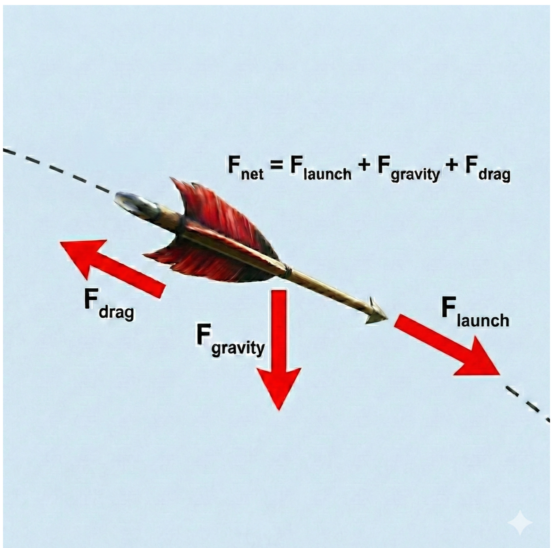

Figure 3: Forces applied in the arrow's launch

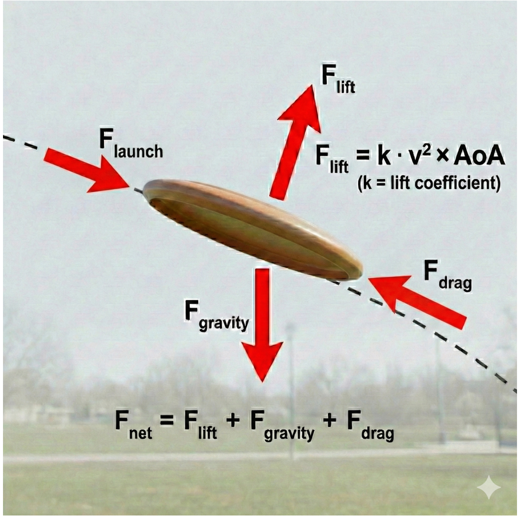

Figure 4: Vector diagram of the forces applied to the frisbeeic.

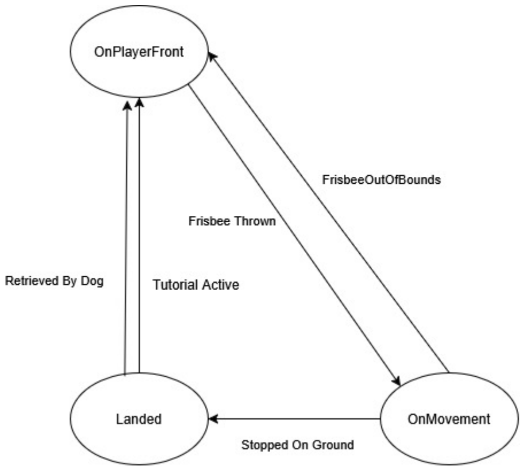

Figure 5: Frisbee Finite State Machine (FSM) Diagram describing the interaction flow.

6.3 Frisbee Minigame Mechanics

6.3.1 Frisbee Behaviour and Physics

The interaction logic of the Frisbee mini-game was implemented through a Finite State Machine (FSM) represented in Figure 5.

The interaction mechanic is based on three main states:

1. **OnPlayerFront (Interaction & Spawning):** Before being grabbed, the frisbee is positioned in front of the player using a rule to follow the user's headset (Center Eye Anchor position). To prevent cybersickness, a smal delay is applied to the movement, ensuring the object does not jitter with minor head movements.

   The object interacts with the Grab Hand system, allowing the player to grab it with either one of their hands. The transition to the *OnMovement* state occurs when the player opens its grabbing hand.

2. **OnMovement (Physics Simulation):** Upon release, the frisbee enters a physics-driven state. The **Launch Force** (F_{launch}) is calculated based on the velocity vector of the player's hand at the exact moment of release.

Unlike standard projectiles, the frisbee's flight path is determined by an aerodynamic equation using a lif force, as shown in Figure 4. Where the Lift Force (F_{lift}) is proportional to the square of the velocity (v^2) and the Angle of Attack (AoA) (which is calculated throgh the dot product between its normal force and the firsbee velocity) , represented by the equation:

$$F_{lift} = k \cdot v^2 \times AoA$$

(Where k represents the lift coefficient). This ensures the frisbee glides a bit rather than falling instantly like a stone.

3. **Landed (Resolution):** The interaction cycle ends here. From here, the cycle resets via two triggers: either the dog retrieves the disc to the player, or when the tutorial is active, which forces the frisbee returning to the player's front.

Additionally, the transition ("FrisbeeOutOfBounds") ensures that if the frisbee leaves the playable area during its flight, it is immediately resets to the player's front.

6.3.2 Dog Behaviour

The dog is a **NavMesh Agent**, controlled by the Finite State Machine (FSM) shown in Figure 6. The logic dictates the agent's navigation and interaction with the player through five distinct states:

Idle: When enter this state the dog barks to alert the user where it is using **3D spatial audio** and only exits from this state after the frisbee lands.

Jump: Plays a jump animation to alert that player that it saw the frisbee landing.

Catch Frisbee: Goes to the frisbee landed position to catch it.

Give Frisbee to Player: After catching the frisbee the dog moves in direction to the player to deliver it.

Go To Target: The dog moves to a waiting position for the next throw. The destination is determined by the player's performance:

- **Point Scored:** The dog moves to a **new position**, generated at the same distance from the player as the previous wating position.
- **No Point:** The dog returns to its **old position**.

After reaching the waiting position the dog's cycle is reseted.

6.4 Score Feedback

Both minigames track the player's **Score**, **Streak**, and **Target Goal**. These metrics are shown via the game's (UI) to enforce the core feedback loop:

- **Objective Clarity:** The UI provides immediate confirmation of the game state and win conditions.
- **Player Retention:** The visibility of these metrics, particularly the *streak* counter, acts as an extrinsic motivator to maintain engagement.

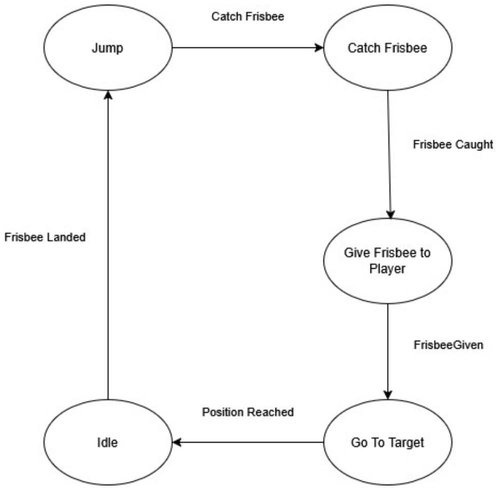

Figure 6: Dog Finite State Machine Diagram

To complement the UI, the system incorporates distinct audio-visual feedback mechanisms to signal success through environmental cues rather than just text:

- **Frisbee Game:** After the player socres, the target zone is instantly deactivated. This event triggers to spawn ballons that after explode in middle and plays a cheering sound effect to reinforce the positive outcome.
- **Archery Game:** Feedback is delivered through NPC behavior. When the player scores, a crowd next to the player execute a reaction animation, by jumping and rotate 360°.

6.5 DDA System

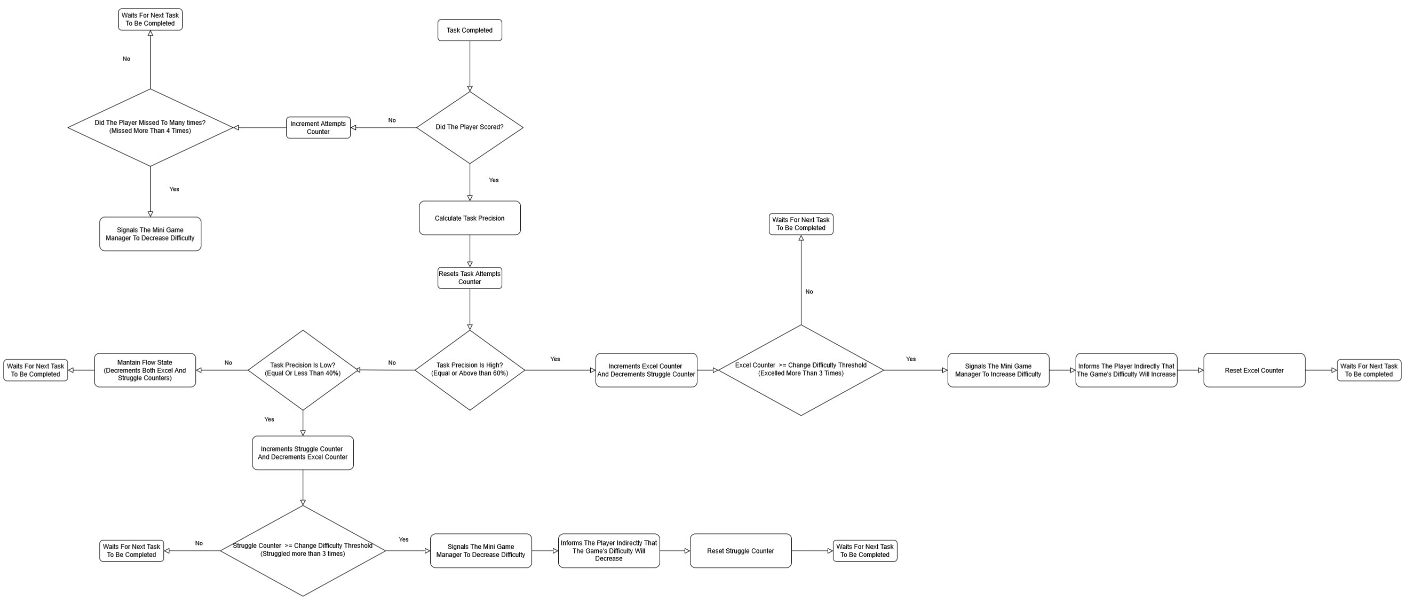

Figure 7: CarnyWise (DDA Algorithm) Flowchart

The Dynamic Difficulty Adjustment system, designated as **CarnyWise**, manages the minigames' difficulty level. The term is derived from the colloquial North American word "Carny," referring to carnival workers, and "Wise," indicating an intelligent agent, depicted in the game as the narrator character.

Figure 8: Carny Wise Informing the player in frisbee minigame that the difficulty will change(increase in this situation)

As can be seen in Figure 7, the system assesses player performance after each task cycle. The logic is divided into failure handling and precision analysis:

1. **Failure Handling:** If the player fails to score, the system increments an internal *Attempts Counter*. To prevent frustration, if the player misses more than 4 consecutive times, the system immediately signals the minigame manager to decrease difficulty.

2. **Performance Analysis:** After the player scores, the system calculates the **Task Precision**. Based on this percentage, the algorithm updates two opposing counters: the *Excel Counter* and the *Struggle Counter*.

   - **High Precision ($\geq$ 60%):** Increments the *Excel Counter* and decrements the *Struggle Counter*. If the player excels regularly (reaching the difficulty threshold of 3 times), the difficulty increases.
   - **Low Precision ($\leq$ 40%):** Increments the *Struggle Counter* and decrements the *Excel Counter*. If the difficulty threshold (3) is met, the difficulty decreases.
   - **Flow State (41% - 59%):** If performance is average, both counters are decremented. This indicates the player is in a flow state, where skill matches the difficulty, so no drastic changes are required. This ensures the player does not feel anxious or bored.

3. **Feedback Loop:** Whenever a difficulty threshold is crossed, the system signals the specific Minigame Manager to adjust its procedural generation parameters and provides indirect feedback to the player(Figure 8).

6.5.1 Adaptation Mechanism

CarnyWise manages the adaptation timing, and the specific form of the difficulty is managed by the manager of each mini game using a hybrid framework. This framework divides the parameters into two groups to provide infinite progress, which is essential for rehabilitation:

- **Physical/Quantitative Parameters:** Parameters such as the distance and quantity scale using a code-based algorithmic progression model, which follows the formula ($y = mx + b$). This model provides the player with limitess difficulty, as the player's physical capabilities are constantly challenged according to the defined increments.

- **Cognitive/Complexity Parameters:** Parameters such as the probability of the target's movement and visual distractions are managed using Unity's Animation Curve model. Unlike the previous model, which depends on mathematical formulas, the Animation Curve model depends on visual curve creation within the Unity Inspector. This model provides the developers or clinicians with the opportunity to create non-linear progress curves without the need for mathematical or coding knowledge.

Table 3 details the specific adaptation parameters manipulated in each minigame.

Table 3: Adaptation Parameters per Minigame

Parameter Type	**Frisbee Game**	**Archery Game**
Target Quantity	*Infinite Scaling:* Increases by roughly 1 target every 5 levels.	*Infinite Scaling:* Increases by roughly 1 balloon every 2 levels.
Spatial Challenge	**Distance:** Linearly increases the dog's distance (capped at 14m).	**Density:** Increases the number of balloons that the ballon spawner can spawn.
Cognitive Load	**Movement:** Percentage of targets moving laterally. **Visibility:** Percentage of targets blinking/disappearing.	**Movement:** Percentage of balloons moving. **Transparency:** Percentage of balloons becoming translucent (ghosts). **Color Rule:** The specific balloon color required to score changes dynamically.

6.6 Dynamic Text Feedback

To keep players engaged and provide feedback when the mini games difficulty is changed, the system makes use of a context-aware dialogue system. Instead of using hard coded messages, feedback after completing a mini game or difficulty adjustment occurs in data-driven fashion.

This framework can import external JSON files that hold categorized arrays of dialogues. This structure allows random selections of different motivational quotes or reaction dialogues that can occur during events, thus preventing monotony in long game sessions

7 Visual Environment

The game has a virtual 3D envirnonment of a "Country Fair". The environment is designed to be vibrant and stimulating, incorporating three main categories of assets:

- **Dynamic Structures:** Includes animated background elements such as a rotating Ferris wheel.
- **Animals:** The scene contains ambient animals (sheep) and the dog used in the Frisbee minigame.
- **Crowd System:** To mitigate feelings of isolation often associated with rehabilitation therapy, the fair is populated with ambient NPCs. These agents can be idle with proper animations or move around in the fair, creating a sense of "Social Presence" and a living, active scenario.[3]

8 Gameplay Tests and Results

Table 4: Users's Time for Each Task

Tasks	User1	User2
Select a mini-game to play	12 seconds	3 seconds
Return to the fair	5 seconds	8 seconds
Pop 3 balloons in the archery mini-game	11 seconds	11 seconds
Score 1 point in the frisbee mini-game	53 seconds	37 seconds

As mentioned before, part of this game was developed for the practical component of the **Virtual and Augmented Reality** course. An informal user test with 2 participants(Figure 9) was conducted before the final presentation of this course. Table 4 shows the tasks they performed and their completion times.

Figure 9: User's playing the game

Overall, the users did not struggle significantly with the tasks. However, User 1 had difficulty with Task 1 due to initial bad headset calibration, and with Task 4 because they did not initially understand the scoring mechanic.

The users also provided some feedback about their experience:

Overall Experience

- The mini-games were fun to play;
- The users felt immersed in a country fair;
- They liked the sound feedback;
- They felt the mini-games needed a tutorial.

Frisbee Mini-Game

- The frisbee curved too much in the direction of the throwing hand;
- Instead of going to the user's exact position, the dog delivered the frisbee directly to the nearest outstretched hand.

Archery Mini-Game

- Balloon Scoring: Suggested considering texture (e.g., metallic) or legend plates for scoring, not just color;

- The arrow sometimes launched while the string was still being pulled.

This feedback was useful for the current version of the game. Since both users felt they needed a tutorial, and one of them felt lost while playing, implementing this feature became essential. Regarding the archery mini-game scoring system, which initially depended only on balloon color, the feedback led me to reconsider the approach. While the suggestions to use textures or legend plates seemed complex to implement, I implemented a new rule for this version: to score, the player must shoot a balloon of a specific color. This is more engaging and can help train cognitive functions in stroke survivors.

Some observations made during this test: users were visibly amused while playing, and there were no signs of any negative after-effects.

9 Tests with Target Audience

The were no user tests maded with the target audience.However since this project is part of the pratical component of my master's thesis and one of its the goals is to test a functional VR game prototype at **Rovisco Pais Rehabilitation Center** with stroke survivors. If it is not possible to go to **Rovisco Pais**, the testing will be conducted at the **Var Lab (IEETA's Virtual and Augmented Laboratory**) with stroke survivors, by contacting other organizations such as **Portugal AVC** or **GAM Aveiro**(which meet annually at **ESSUA)**.

A Appendix

A.1 Planning Documents

Theoretical Framework

A.2 Project Links

- Repository;
- Demo;
- Build

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