BACHELOR‘S THESIS ASSIGNMENT

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II. Bachelor’s thesis details

Bachelor’s thesis title in English:

Therapy of individuals with hemiplegic partial cerebral palsy using interactive games

Bachelor’s thesis title in Czech:

Terapie osob s jednostrannou částečnou mozkovou obrnou pomocí interaktivních her

Guidelines:

Individuals with hemiplegic partial cerebral palsy can benefit from rehabilitation. The goal of rehabilitation is to maximally regain the functions of the affected limb(s). Serious games are used to support rehabilitation, typically in home settings. Most of the available solutions are based on VR, which may introduce issues with high costs, complicated setups, and problematic use by young children. Serious games engaging users to use bi-manual interaction for off-the-shelf devices like tablets may increase the availability of rehabilitation, especially for young children.
Analyze the current state of the art in the domain of hemiplegic partial cerebral palsy rehabilitation by means of serious games [1-4]. Perform analysis of specific needs, abilities, and preferences of individuals with hemiplegic partial cerebral palsy, focusing on rehabilitation and interaction with modern ICT. Define requirements for an application that will utilize serious games to help with rehabilitation. Analyze technical platforms suitable to address the requirements. Consider young children as the primary target user audience. Using the User-Centered Design methodology [5], design, implement, and evaluate a set of prototypes. Consider implementing the final prototype for tablets (portable devices with larger multi-touch displays). Evaluate the UI of the final prototype by usability test method with at least three participants. If necessary (e.g., ethical issues), a suitable substitutive user group can be used for the evaluation.

Bibliography / sources:

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[2] Ferre, C. L., Brandão, M., Surana, B., Dew, A. P., Moreau, N. G., & Gordon, A. M. (2017). Caregiver directed home based intensive bimanual training in young children with unilateral spastic cerebral palsy: a randomized trial. Developmental Medicine & Child Neurology, 59(5), 497-504.
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Assignment valid until: **21.09.2025**

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III. Assignment receipt

The student acknowledges that the bachelor’s thesis is an individual work. The student must produce his thesis without the assistance of others, with the exception of provided consultations. Within the bachelor’s thesis, the author must state the names of consultants and include a list of references.

Date of assignment receipt	Student’s signature

Bachelor Project

Czech
Technical
University
in Prague

F3

Faculty of Electrical Engineering
Department of Computer Graphics and Interaction

Therapy of individuals with hemiplegic partial cerebral palsy using interactive games

Nazar Ponomarev

Supervisor: Ing. Miroslav Macík, Ph.D.
Field of study: Open Informatics
Subfield: Computer Games and Graphics
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With sincere gratitude, I acknowledge my supervisor, Ing. Miroslav Macík, Ph.D., for his invaluable guidance and support throughout my Bachelor's Project development.

Declaration

I declare that I have prepared the submitted work independently and that I have listed all the literature used.

In Prague, 24. May 2024

Abstract

This thesis explores the development of an interactive application with games for the rehabilitation of individuals with hemiplegic partial cerebral palsy, focusing on children aged 5 to 10 years. Rehabilitation aims to maximize the functionality of the affected limbs, and serious games present an innovative approach to achieving this goal. Traditional solutions often pose challenges such as high costs, complex setups, and usability issues for young children. This study proposes the use of bi-manual interaction games on off-the-shelf tablets to enhance the accessibility and effectiveness of rehabilitation.

A comprehensive analysis of the current literature and existing rehabilitation technologies was conducted, revealing the gaps that this project seeks to address. The study involved defining the specific needs and preferences of the target user group, followed by the development and implementation of prototypes. The usability of the final prototype was evaluated with children, ensuring that the application is engaging, intuitive, and beneficial to improve motor skills.

Keywords: hemiplegia, cerebral palsy, serious game, game for tablet

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Abstrakt

Tato diplomová práce zkoumá vývoj interaktivní aplikace s hrami pro rehabilitaci jedinců s hemiplegickou částečnou mozkovou obrnou, zaměřenou na děti ve věku 5 až 10 let. Cílem rehabilitace je maximalizovat funkčnost postižených končetin a vážné hry představují inovativní přístup k dosažení tohoto cíle. Tradiční řešení často přinášejí problémy jako vysoké náklady, složité nastavení a problémy s použitelností pro malé děti. Tato studie navrhuje využití bimanuálních interakčních her na běžně dostupných tabletech pro zvýšení dostupnosti a efektivity rehabilitace.

Byla provedena komplexní analýza současné literatury a existujících rehabilitačních technologií, která odhalila mezery, které tento projekt chce vyplnit. Studie zahrnovala definování specifických potřeb a preferencí cílové skupiny uživatelů, následovaný vývojem a implementací prototypů. Použitelnost finálního prototypu byla hodnocena s dětmi, aby bylo zajištěno, že aplikace je poutavá, intuitivní a prospěšná pro zlepšení motorických dovedností.

Klíčová slova: hemiplegie, mozková obrna, vážná hra, hra pro tablet

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List of Abbreviations

AI	Artificial Intelligence
API	Application Programming Interface
CFCS	Communication Function Classification System
CIMT	Constraint-Induced Movement Therapy
CP	Cerebral Palsy
GDT	Goal-Directed Training
GMFCS – E & R	Gross Motor Function Classification System Expanded and Revised
MACS	Manual Ability Classification System
MAUI	Multi-platform App UI
VR	Virtual Reality

Chapter 1
Introduction

Healthcare and quality of life issues are becoming increasingly relevant in modern society. One of the important areas that requires special attention and innovative approaches is the rehabilitation of people with hemiplegic partial cerebral palsy (CP). This category of patients, who face limitations in the mobility and functionality of their limbs, requires effective rehabilitation methods to achieve maximum recovery and improve quality of life.

This work aims to develop and implement an application with interactive games designed for the therapy of people with hemiplegic partial cerebral palsy. The main goal of these games will be to maximize user involvement in two-handed interaction using modern devices such as tablets. This approach provides a unique opportunity to improve the results of rehabilitation and make it more accessible and attractive to children. The goals of the thesis are outlined as follows:

1. **Define Specific Needs and Preferences of Target Users:** Identify the specific requirements and preferences of children with hemiplegic CP to ensure that the developed games are engaging, intuitive, and beneficial for motor skills improvement.

2. **Conduct Comprehensive Analysis of Current Technologies:** Perform a detailed review of existing rehabilitation technologies to identify gaps and opportunities for improvement in current methods.

3. **Prototype Development and Implementation:** Develop and implement game prototypes that are specifically tailored to the rehabilitation needs of children with hemiplegic CP.

4. **Usability Evaluation:** Conduct usability testing with children to ensure the final prototype is effective and user-friendly.

The goal of this work is to create an innovative solution that can improve the rehabilitation process for hemiplegic partial cerebral palsy, making it more affordable and motivating primarily for children.

Chapter 2

Cerebral Palsy

In this chapter, cerebral palsy will be discussed in more detail. The key classification systems used to assess different aspects of cerebral palsy, including topography, gross motor function, manual ability, communication function, and the ability to eat and drink, will be explored. In addition, various physical therapies aimed at maximizing hand function and overall functionality in people with cerebral palsy, such as constraint-induced movement therapy (CIMT), bimanual training, context-focused therapy, and goal-directed training, will be examined.

2.1 Overview

Cerebral palsy is a term that encompasses a group of neurological disorders [7]. These disorders, which manifest in infancy or early childhood, permanently affect body movement and muscle coordination. The root cause of CP is damage or abnormalities within the developing brain, which disrupt the brain's ability to control movement and maintain posture and balance.

CP is not a rare condition; it occurs in approximately two to three out of every 1,000 live births [8, 9, 10]. The causes of CP can vary. In some cases, the brain areas responsible for muscle movement do not develop as they should during fetal growth. In other cases, the damage is due to an injury to the brain that occurs before, during, or after birth. According to [8], approximately 92% of cases of cerebral palsy are traced to the perinatal period.

Although, indeed, there is currently no cure for cerebral palsy, a wide range of supportive treatments, medications, and surgical interventions can significantly improve the quality of life of those affected. These therapies can help many individuals improve their motor skills and the ability to interact with the world around them.

2.2 Classifications of Cerebral Palsy

In the following paragraphs, key classification systems used to assess different aspects of cerebral palsy will be explored, including topography, gross motor function, manual ability, and communication function.

2.2.1 Topographic Classification

The topographic classifications of CP are hemiplegia, diplegia, and quadriplegia. These terms describe spasticity, depending on the affected limbs [10, 11].

1. **Hemiplegia** is a condition caused by brain damage or spinal cord injury that leads to paralysis on one side of the body (either the left or the right). In spastic hemiplegia, the arm is typically affected more than the leg. Children with spastic hemiplegia may have associated sensory deficits. These sensory deficits are reflected as poor muscle mass on the affected side and do not correlate with motor deficits. In addition, they may have associated intellectual impairment and behavioral problems, such as anxiety, oppositional defiance, and specific phobias. However, most children with spastic hemiplegia have normal cognitive abilities, can maintain independent ambulation, and have a high level of functional abilities.

2. **Diplegia** is a symmetrical paralysis that usually affects either the arms or the legs. Thirty-five percent of children with CP have spastic diplegia, which is the most common clinical phenotype of CP. Most children with spastic diplegia have normal cognitive function and a good prognosis for independent ambulation.

3. **Quadriplegia** is the most severe form involving all four limbs, and the upper trunk limbs are more severely involved than the lower limbs. Spastic quadriplegia is associated with significant functional limitations, cognitive deficit, epilepsy, visual impairment, and other associated conditions. Children with spastic quadriplegia have a poor prognosis for independent ambulation.

2.2.2 Gross Motor Function Classification System

GMFCS – E & R (Gross Motor Function Classification System Expanded and Revised), the most widely used evidence-based tool, focuses on gross motor function, specifically self-initiated movements and, in particular, sitting and walking. It classifies these functions according to five levels, from Level 1 = independent movement to Level 5 = complete assistance. Each level of the GMFCS – E & R provides functional descriptions for five age groups: 1 to 2, 2 to 4, 4 to 6, 6 to 12, and 12 to 18 years [12, 13, 14]. However, there is also a generalized description that does not depend on age, which can be seen in Table 2.1.

Level I	Level II	Level III	Level IV	Level V
Walks without Limitations	Walks with Limitations	Walks Using a Hand-Held Mobility Device	Self-Mobility with Limitations; May Use Powered Mobility	Transported in a Manual Wheelchair

Table 2.1: General headings for each level of GMFCS – E & R, from [4]

2.2.3 Manual Ability Classification System

MACS (Manual Ability Classification System): evaluates how children with CP can use their hands when handling objects in daily activities by pointing out the child's typical manual performance, not the child's maximal capacity, and the use of both hands together [12, 13, 15]. It consists of five levels, which can be seen in Table 2.2.

Level I	Level II	Level III	Level IV	Level V
Handles objects easily and successfully	Handles most objects but with somewhat reduced quality and/or speed of achievement	Handles objects with difficulty; needs help to prepare and/or modify activities	Handles a limited selection of easily managed objects in adapted situations	Does not handle objects and has severely limited ability to perform even simple actions

Table 2.2: Functional levels of MACS, from [5]

2.2.4 Communication Function Classification System

CFCS (Communication Function Classification System): classification was designed to assess the ability of people with CP to communicate with familiar and unfamiliar communication partners in different environments to establish shared understandings [12, 13, 16]. Its levels can be seen in Table 2.3.

Level I	Level II	Level III	Level IV	Level V
Effective sender and receiver with unfamiliar and familiar partners	Effective but slower paced sender and/or receiver with unfamiliar and/or familiar partners	Effective sender and receiver with familiar partners	Inconsistent sender and/or receiver with familiar partners	Seldom effective sender and receiver even with familiar partners

Table 2.3: Functional levels of CFCS, from [6]

2.3 Physical Therapy

As mentioned above, there exists a broad spectrum of supportive treatments, medications, and surgical interventions that can significantly improve the quality of life of those affected. Since the primary goal is to create a tablet game that supports bimanual interaction, this chapter will exclusively focus on physical therapies, as they are particularly beneficial in maximizing available hand function [9].

2.3.1 Constraint Induced Movement Therapy

Constraint-induced movement therapy (CIMT) involves restraining one limb of the body to promote increased movement and the use of the opposite limb. In the context of cerebral palsy, CIMT is commonly used to increase the use of an individual's affected arm by restricting the unaffected arm [17].

Many individuals with cerebral palsy may benefit from CIMT, as it was designed to treat upper limb deficits in individuals with neurological conditions. It is ideal for those with hemiplegia or monoplegia when only one arm has motor impairments. It can be used for individuals of any age [17].

How does CIMT work?

According to [17], CIMT involves two key components:

1. The unaffected arm must be restrained using a splint, glove, mitt, cast, or sling. This promotes the use of the affected arm, as it is more readily available for use.

2. The affected arm must undergo intensive therapy to learn to move and function accurately. By encouraging the use of the affected arm, you are stimulating the brain to strengthen associated movement pathways.

2.3.2 Bimanual Training

Bimanual training, often known as intensive bimanual training, is a therapeutic approach used for children with cerebral palsy, especially those diagnosed with hemiplegia. It involves repetitive task training that requires the use of both hands. The goal of this therapy is to improve the use and coordination of both hands [18, 19, 20].

How does bimanual training work?

Bimanual movements are defined as both hands working together to achieve a goal. They are more complex than unimanual movements, as they involve coordination of both upper extremities, coupling the amplitude of movement and the direction of both hands [20].

In bimanual training, children perform one to five bimanual tasks in laboratory settings, mainly activities of daily living or game scenarios. Examples of these tasks include crossing the midline. Training is often home-based, with parents providing support during training [18, 20].

2.3.3 Context Focused Therapy

Context-focused therapy in terms of Cerebral Palsy is about adapting the environment and tasks to improve the functional performance of the individual, rather than only focusing on changing the individual's movement abilities. It is part of a larger shift in therapeutic interventions towards improving participation, activity, and environment [21].

How does Context-focused therapy work?

As suggested in [21], the objective is to modify the task or the environment to enhance functional effectiveness. A potential method could be outlined as follows:

1. Identification of motor-based tasks a child was initiating, trying to modify, or showing an interest in.
2. Identification and analysis of constraints in the task through analysis of task performance together with parents, child, and therapist.
3. Treatment is focused on changing the environment or the task, ideally in a natural environment (school, home, etc.).

2.3.4 Directed Functional Training

Directed functional training, also known as goal-directed training (GDT), focuses on activities based on the goals set by the child, using a motor learning approach.

Research [22] shows that GDT works very well if the child wants to learn a new gross motor skill, use their hands, learn a new self-care skill, or achieve a functional goal. It can also be used to support thinking, learning, and communication.

How does GDT work?

Here's a detailed explanation of GDT, according to [22]:

1. **Goal Selection:** The child and their caregivers choose a goal that is important to them. This could be everyday skills such as pressing buttons, walking upstairs, or eating with a knife and fork.

2. **Active Participation:** The child is active in performing the movements associated with the goal.

3. **Real Task Practice:** The child practices their goal by doing real tasks and activities. For example, they will learn to use a knife and a fork when they are having a meal.

4. **High-Intensity Practice:** Practice needs to be high intensity, which means a lot of repeated practice in a set period1.

5. **Feedback:** Feedback from a therapist helps the child to know what they are doing well and what else they can try.

6. **Home Practice:** Home practice is an important part of GDT. It will help the child do the amount of practice needed to change the way their brain works.

Chapter 3

Target User Group Analysis

The specific needs and characteristics of the target user group must be understood to develop effective therapeutic applications. This chapter explores the concept of neuroplasticity, examining how the brain's ability to adapt and change can influence the timing and efficacy of therapeutic interventions. Critical periods of brain development and their implications for therapy are analyzed to identify the optimal age range to initiate interventions. In addition, topographic classification and classification system levels are discussed to tailor the application to the unique needs of children with hemiplegia.

3.1 Neuroplasticity of the Brain and Age. When Might Therapy Be Most Effective?

Neuroplasticity is the ability of the brain to change its structure and function in response to experience and learning. It exists throughout a person's life, but its character changes with age. Neuroplasticity plays a critical role in the effectiveness of rehabilitation therapies, especially in individuals with hemiplegic partial cerebral palsy. The characteristics of these changes in neuroplasticity at different ages make the timing of therapy initiation strategically important.

3.1.1 Critical Periods of Brain Development

According to the study [23] by Chugani and Harry T., which refers to the critical period of brain development, glucose utilization in the human brain varies significantly with age:

1. **Birth up to the age of 4 years:** The study found a rapid increase in glucose utilization from birth until about the age of 4 years. At this stage, a child's cerebral cortex uses over twice as much glucose as that of an adult. This high rate of glucose consumption is likely due to the intense growth and development occurring in the brain during these early years.

2. **Age 4 to 10:** The very high rates of glucose consumption are maintained

during this period. This aligns with significant cognitive and physical development in children.

3. **Age 10 to 16-18:** After the age of 10, there is a gradual decline in the rate of glucose consumption. By the age of 16 to 18, glucose metabolic rates reach adult values.

The study [23] also discusses the correlation between glucose utilization rates and synaptogenesis, the formation of synapses. Synapses are crucial for learning and memory, as they are the junctions where neurons communicate with each other.

The high rates of glucose consumption and synaptogenesis during early childhood suggest that this is a period of high brain plasticity, or the brain's ability to change and adapt as a result of experience. This has implications for recovery from brain injury, as well as for understanding when the brain is most capable of learning, referred to as 'critical periods'.

3.1.2 Strategic Therapy Approaches for Children with Cerebral Palsy

Based on the research [24] by Wittenberg and George F., early interventions (from birth) for children with CP should focus on improving the survival of crossed corticospinal tract axons. The corticospinal tract, a part of the nervous system that transmits signals from the brain to the spinal cord to control movement, crosses over from one side of the brain to the opposite side of the body. In CP, these axons can be damaged, so therapies aim to improve their survival and function.

As for later therapies, they should address the imbalance between intact and damaged motor representations. Motor representations, which refer to how movement is mapped in the brain, can exhibit imbalances in children with CP because some brain regions operate effectively while others are impaired. The goal of these therapies is to correct this imbalance to improve movement. Since bimanual therapy will help to solve problems with uneven functioning of healthy and damaged parts of the motor system, these data help to more accurately determine in which period the application being developed will be most useful. In addition, according to [10], physiotherapy and occupational therapy at 4 to 5 years of age are relatively more effective than if started at a later age.

3.1.3 Conclusion: Age Restrictions

Based on the above facts, the most suitable age group for a tablet game designed to provide bimanual interaction is children aged 4 to 10 years. This is due to their high brain plasticity, significant cognitive and physical development, and the effectiveness of early interventions and therapies during this period. However, it was decided to limit the minimum age to 5 years, as younger children will have great difficulty using tablets. Thus, the application being developed is mainly focused on children aged 5 to 10 years but is not limited to this group and can be used by people of any age.

3.2 Selecting Appropriate Topographic Classification and Classification Systems Levels

The target audience of an application developed for the treatment of cerebral palsy can be effectively classified using the systems mentioned in Section 2.2, namely topographic classifications - hemiplegia, diplegia, quadriplegia, as well as GMFCS - E & R, MACS, CFCS. These classifications allow therapeutic approaches to be more precisely tailored to the individual characteristics and needs of users.

3.2.1 Topography

In the development of this therapeutic application for cerebral palsy, the topographic classification of hemiplegia was specifically chosen as the primary target. Hemiplegia, a condition that affects one side of the body, aligns with the main focus of the application on bimanual interaction. This means that the application is designed to involve both hands in coordinated activity, which is particularly beneficial for individuals with hemiplegia. Having a focus on this group, the application can provide a tailored and effective therapeutic approach that addresses the unique challenges faced by individuals with hemiplegia, improving their motor skills and overall quality of life. The use of such a precise topographic classification allows for a more personalized and effective treatment approach, catering to the specific needs and characteristics of the users.

3.2.2 Classification systems

The listed classification systems for children with cerebral palsy (GMFCS - E&R, MACS, CFCS) were analyzed and, as a result, only some of their levels were selected as suitable for describing the target audience of application.

- From GMFCS - E&R, it was decided to select levels I to IV. Although this classification is based on independent movement with an emphasis on sitting, transferring, and mobility, the ability of young people belonging to GMFCS - E&R group five to maintain an anti-gravity head position and torso and control the movements of arms and legs is limited. This makes tablets difficult to use and imposes significant restrictions on application development.
- From MACS, it was decided to select levels II to IV. The first level was excluded since people belonging to the first level require more complex and intensive approaches, which are almost impossible to implement using just a tablet. As for the last level of classification, it was excluded because people who do not handle objects and have a severely limited

ability to perform even simple actions will not be able to use devices such as tablets.

- From CFCS, it was decided to select levels I to IV. The fifth level was excluded since people belonging to this level are described as seldom effective senders and receivers even with familiar partners, which significantly complicates the application since they will not be able to use it effectively.

3.3 Conclusion: Target User Group Insights

In conclusion, the target user group for the application includes children aged 5 to 10 years with hemiplegia, falling within GMFCS-E&R and CFCS levels I to IV, and MACS levels II to IV. The application aims to provide a personalized and effective therapeutic approach through bimanual interaction, catering to the developmental and therapeutic needs of children with hemiplegia within this age range.

Chapter 4
Reference Solutions

The analysis of reference solutions proved to be quite challenging because most serious games designed for cerebral palsy therapy use rather complex technologies. The use of VR devices or narrowly focused gadgets significantly complicates therapy, making it inaccessible to a large number of individuals. This inaccessibility may arise from the difficulty of using such devices or their cost. The use of devices such as tablets aims to alleviate these shortcomings. After an extensive analysis of articles, solutions that employ touchscreen devices for the rehabilitation of children with cerebral palsy were eventually found. This chapter will analyze such games, identifying their shortcomings and advantages, which ultimately contributed to the development of the concept of the game proposed in this work.

4.1 Accessible Entertainment Tools for People with Special Needs

This section is based on a study [25] by M. I. J. Ferreira, L. Alves et al., the main idea of which is to explore how digital games can facilitate communication among nonspeaking children with severe oral communication disabilities due to cerebral palsy. Although the games in this study were developed for other purposes, the main advantage is that they were specifically designed for children with cerebral palsy.

4.1.1 Sustainable City Game

The Sustainable City Game is designed to teach children the importance of selective trash collection and environmental conservation. Here is a breakdown of how the game works:

- **Objective:** The player's primary goal is to maintain a clean and unpolluted environment by correctly sorting and disposing of various types of garbage that appear in the river.
- **Gameplay:** The game presents three scenes representing different environmental conditions: polluted, moderately polluted, and unpolluted.

Initially, the player is presented with an unpolluted environment. Trash items (metal, paper, glass, and plastic) start appearing in the river.

- **Trash Collection:** The player must actively collect the garbage items as they float down the river. Each type of garbage needs to be placed in the appropriate container for its material (e.g., paper goes in the paper bin, glass in the glass bin, etc.).
- **Environment State:** A scroll bar at the top of the screen indicates the state of the environment. It reflects the player's performance in trash collection. If the player successfully sorts all items, the environment remains unpolluted, and the bar stays completely green.
- **Winning Condition:** If the player manages to keep the environment unpolluted by correctly sorting and disposing of all garbage items, they win the game. A plus sign or similar indicator appears to signify their success.
- **Visuals:** The game environment includes elements like buildings, clouds, and a river, creating a visually appealing and immersive experience. The trash items are visibly different, making it clear which type of garbage needs to go where.

4.1.2 Public Safety Game

The Public Safety Game is an interactive puzzle game designed to educate children about environmentally friendly behaviors and safety. Here is an overview of how the game works:

- **Objective:** The player's objective is to solve a puzzle depicting environmentally friendly and safe behaviors. They start with an image showing environmentally unfriendly actions, and by completing the puzzle, they transform it into an image showcasing correct attitudes toward environmental conservation.
- **Gameplay:** The game consists of multiple screens. Screen 1 displays an initial image of a dirty city with garbage on the ground, a pedestrian walking in the street, and a car parked at a pedestrian crossing. This scene sets the stage for the player to recognize the need for environmental conservation and safety.
- **Transition Screens:** Screens 2 and 3 provide transitions to convey the idea of transitioning from an unsatisfactory environment to a clean and safe one. Screen 2 shows a child thinking about a clean and organized environment, while screen 3 depicts the child appearing sad, possibly in response to the environmental degradation seen in screen 1.
- **Puzzle Selection:** In screen 4, the player is presented with an image of a clean environment, with three squares in the center indicating the

number of puzzle pieces available (four, nine, and sixteen). The player can choose the level of difficulty by selecting the desired number of pieces for the puzzle.

- **Puzzle Solving:** Upon clicking one of the squares, screen 5 appears with the clean environment image in the top left corner. The rest of the screen contains a frame with the image in puzzle form. The player must put the puzzle together, using the reference image as a guide. To manipulate the puzzle pieces, the player can click on the turn icon and then click on the desired piece to rotate it into the correct orientation.

- **Winning Condition:** Once the player completes the puzzle, a plus sign appears to indicate that they have won the game. They can then choose to proceed to the next challenge (with a greater number of puzzle pieces) or exit the game.

4.1.3 Conclusion

These games serve as an excellent example of therapeutic games for children. They feature a user-friendly interface, simple tasks, and motivating gameplay. In addition, they incorporate more complex interaction systems than just pressing a button, which positively impacts the rehabilitation of children's hand motor skills. However, a drawback of these games is that they do not require the child to use both hands, which is not suitable for bimanual therapy.

4.2 Upper Extremity Rehabilitation Using Accelerometer Feedback on a Multitouch Display

This section is based on a study [1] by Dunne et al., which describes the development of a system for upper extremity rehabilitation in children with cerebral palsy.

The system comprises three main hardware components: a multi-touch display, inputs for tangible objects, and a wearable accelerometer. The multitouch display, a Microsoft Surface, is equipped with five internal cameras that detect reflections from infrared light on its 30" display, allowing for recognition of physical objects, finger-touch input, and specially designed fiducials or 'tags'.

The system utilizes Bluetooth to connect the Surface platform to a small accelerometer, which is integrated into a custom-made vest that the patient wears. This accelerometer measures trunk rotation, specifically focusing on trunk flexion, which indicates if a patient is leaning forward to compensate for the limited range of movement in the elbow and/or shoulder. The complete system used can be seen in Figure 4.1.

Figure 4.1: The complete system in use. The user is wearing the accelerometer and using tangible inputs while playing the "Butterfly" game, from [1]

4.2.1 Rehabilitation Games

The article [1] presents a variety of innovative rehabilitation games designed to engage and motivate children through interactive and therapeutic gameplay. These games are crafted to address specific motor and cognitive skills, providing a fun and effective way for children to participate in their rehabilitation. Below is an overview of the games featured in the article:

Find the Bone

Find the Bone is a fun and interactive game designed to engage children while also providing therapeutic benefits. Here is an overview of how the game works:

- **Objective:** The primary goal of the game is for the child to maneuver a bone to a dog using their finger, navigating through the game landscape. The challenge lies in avoiding other characters and obstacles scattered throughout the environment.

- **Scoring System:** Points are earned by collecting stars that are randomly placed on the screen. The therapist can set constraints to dictate the placement of these stars, ensuring that they are positioned in a way that encourages the child to move and explore the entire game landscape.

- **Customization and Adaptability:** One of the key features of this game is its adaptability to the motor ability of each child. Using tangible objects, such as hedges, the therapist can customize the location of obstacles in the game landscape. This allows the game to be tailored to the specific needs and abilities of each child, ensuring that it remains engaging and challenging without being overwhelming.

Spelling

In this spelling game (see Figure 4.2), the player's task is to correctly spell out the name of an animal shown in a bubble on the screen. Here is how the game works:

- **Objective:** The main objective is for the player to spell out the name of the animal displayed in the bubble using letter tiles scattered across the playing surface. The player must do this as quickly and accurately as possible.

- **Scoring System:** Points are awarded based on how quickly the player correctly spells the words and how many animals they spell within a certain time limit. This encourages the player to improve their speed and accuracy with each attempt. A scoreboard displayed after the game motivates the child to beat their previous scores and allows progress tracking over time.

- **Interaction Methods:** The game offers two different methods of interaction:

    - Tap with Wand: Players can select the letter tiles by tapping them with a "Wand" input tool, possibly a stylus or a designated touch tool.

    - Toss Gesture: Alternatively, players can throw the letter tiles at the onscreen target using a tossing gesture. This adds a physical and interactive element to the gameplay.

- **Therapeutic Benefits:** The game not only helps improve spelling skills but also encourages motor control and hand-eye coordination. By offering different interaction methods, the game accommodates various abilities and preferences, making it accessible to a wide range of players.

Figure 4.2: A screenshot of the Spelling game, from [1]

Catch the Butterflies

This game (see Figure 4.3) is specifically designed to address the rehabilitation needs of patients with paralysis on one side of the body. Here is how the game works:

- **Objective:** The main goal of the game is for the patient to capture butterflies in a virtual jar using bimanual input, requiring coordination of both hands. This activity helps in exercising and strengthening the affected side of the body.
- **Gameplay:** The patient controls a foam ball using their weaker hand, while the "wand" input tool, likely controlled by the stronger hand, is used to touch the butterflies and capture them. The patient must position the jar just below the moving butterflies and touch them with the wand to capture them.
- **Bimanual Coordination:** By requiring coordination of both hands, the game promotes the integration and synchronization of motor movements on both sides of the body, which is particularly beneficial for patients with hemiplegia.
- **Challenges and Feedback:** If the patient leans forward too much, the wearable accelerometer sensor triggers, causing the butterflies to fly away. Additionally, if the foam ball loses contact with the screen for too long, the captured butterflies escape from the jar. These challenges provide feedback to the patient and encourage them to maintain proper posture and focus on controlling the ball.
- **Therapist Customization:** Therapists have the flexibility to modify game parameters during the session to suit each patient's needs and abilities. For example, they can adjust the sensitivity of the accelerometer or alter the speed and location of the moving butterflies to provide an appropriate level of challenge.

Figure 4.3: A screenshot from "Catch the butterflies", from [1]

4.2.2 Conclusion

These games serve as a great example of therapy using a touchscreen device. Additionally, the example of bimanual interaction in these games will be utilized in the concept of a co-created application in this project. However, despite all their strengths, these games are designed for a specific device and involve the use of more complex equipment, which is a significant drawback.

4.3 Virtual Reality

Virtual reality is widely used in the therapy of people with cerebral palsy; an example of such use will be discussed in this chapter, based on the study [2].

In this study, participants were tasked with picking up and moving virtual objects to a specified location using both hands simultaneously (see Figure 4.4). The scenario and tasks were designed to simulate food preparation, such as placing a hotdog on a bun, meat on a dumpling, rice onto nori, and shrimp into a sushi roll.

Here is how the task was structured:

- **Task Variation:** To prevent boredom from the repetitive nature of the task, the objects were randomly varied every 5th, 7th, and 8th trial. This variation kept the participants engaged and maintained their interest throughout the task.
- **Bimanual Interaction:** Participants used both hands simultaneously to perform the task. When hovering over a food item with both hands, two "interaction spheres" were highlighted, representing the area in which their virtual hands could pick up the object using the controller's gripper buttons. This setup ensured that participants could interact with the virtual objects effectively and intuitively.
- **Grasp Control for Hemiplegic Participants:** For participants with hemiplegia, who may suffer from loss of grasp control, a grasp action

for each hand was automatically detected when the space of the virtual hand coincided with the interaction sphere of the object. This feature ensured that the object was not released until both hands reached the end goal position, allowing hemiplegic participants to complete the task successfully and comfortably.

Figure 4.4: Orthographic view of the virtual scene as seen in the development environment, from [2]

This study is a good example of how serious games can be used in bimanual therapy, but the key problem with this solution is that it requires expensive and complex equipment to be used.

4.4 Conclusion

The examination of current therapeutic games for children with cerebral palsy reveals both strengths and limitations in existing solutions. Although touchscreen-based games offer accessibility and educational value, they often lack bimanual interaction crucial for comprehensive motor rehabilitation. More sophisticated systems, such as those that utilize multitouch displays and wearables, provide customizable gameplay but suffer from high cost and complexity. VR solutions show promise in offering immersive therapy experiences, yet their expense and technical requirements pose accessibility challenges.

In conclusion, while existing solutions contribute valuable insights, there is a clear need for more accessible, cost-effective, and engaging therapeutic tools. The proposed solution in this work aims to address these shortcomings by developing a game that prioritizes affordability, ease of use, and bimanual tasks to enhance the rehabilitation experience for children with cerebral palsy.

Chapter 5
Engine Selection

The prototype of the game was developed using .NET Multi-platform App UI (MAUI). Later, a decision was made to change the development environment, which led to the final application being developed using the Unity engine. This chapter will provide a more detailed rationale for the choice of development environment, as well as describe the advantages of Unity.

5.1 .NET MAUI

Based on the official Microsoft web page [3], .NET MAUI is a multi-platform interface for creating native mobile and desktop applications using C# and XAML.

.NET MAUI enables the development of applications that can be run on Android, iOS, macOS, and Windows using a unified codebase (see Figure 5.1).

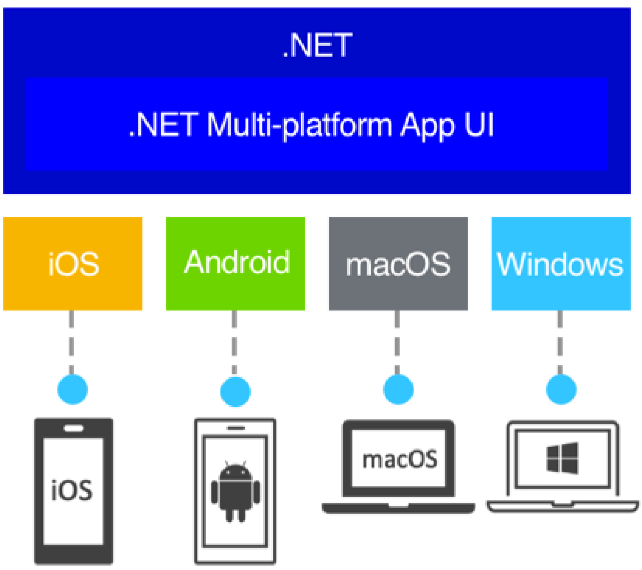


Figure 5.1: .NET MAUI supported platforms, from [3]

With .NET MAUI, you can create multi-platform applications using a single project, but if needed, you can add platform-specific source code and resources. One of the key goals of .NET MAUI is to enable the implementation of as much of the application logic and user interface layout as possible in a single codebase.

The .NET MAUI interface provides an API for various platforms for accessing native device functions. Examples of functions provided by the .NET MAUI interface for accessing device functions include:

- Access to sensors such as accelerometer, compass, and gyroscope on devices.
- Ability to check the device's network connection status and detect changes.
- Retrieve information about the device on which the application is running.
- Copy and paste the text into the system clipboard between applications.
- Select one or more files from the device.
- Securely store data as key/value pairs.
- Utilize integrated modules for text-to-speech conversion to read text from the device.
- Initiate authentication flows based on a browser listening for callbacks to a specific registered URL of the application.

5.1.1 Problems of .NET MAUI

The initial choice of .NET MAUI was not random. In one of the semesters, I needed to develop an application on this platform as part of the semester project for the implementation of user interfaces subject (B4B39IUR). It was decided to combine the semester project with a bachelor's project. As a result, the prototype of the app for children with CP was created. As a result of the development of the prototype, the disadvantages of this platform were identified, which contributed to the use of Unity in further development.

Main disadvantages:

- **Graphics:** .NET MAUI is not primarily designed for game development, so it lacks a built-in, powerful game engine.
- **Community and Resources:** Compared to some other game development platforms, the community and resources specifically for game development with .NET MAUI are less abundant. Which leads to slower problem-solving and development.
- **Limited Game Development Features:** .NET MAUI is not designed for game development. Therefore, it lacks some of the advanced game development features that specialized game engines provide, such as physics engines, particle systems, or built-in AI tools.

- **Personal reasons:** My limited experience with .NET MAUI significantly slows the development process and makes it considerably more difficult.

5.2 Unity

Subsequent work on developing the application took place using the Unity game engine. As written on the official website of the engine [26], Unity's real-time 3D development engine allows artists, designers, and developers collaborate to create amazing immersive and interactive experiences. Using Unity, it is possible to work on Windows, Mac, and Linux. As .NET MAUI, the Unity engine enables the development for Android, iOS, macOS, and Windows. Unity has a built-in Visual Studio integration with the C# API.

5.2.1 Advantages of Using Unity

After the development process was shifted to Unity, it became faster and more engaging, allowing us to focus not only on coding but also on creating more captivating visuals for the games. Here are the key advantages of developing using the Unity engine:

- **Community Support:** Unity boasts a large and active community of developers, artists, and educators, providing access to forums, tutorials, documentation, and online resources for learning and troubleshooting.
- **Visual Editor:** Unity has a visual editor, which is a user-friendly interface for designing scenes, placing objects, adjusting properties, and creating animations without extensive coding knowledge. This empowers developers to prototype and iterate quickly.
- **Rich features and tools:** Unity provides a wide range of built-in tools and features for game development, including physics engines, animation tools, rendering capabilities, and more. These features help to create high-quality games with relatively less effort.
- **Personal reasons:** I have already developed several games using this engine, and based on my experience, I can say that for me, the use of Unity significantly speeds up the game development process and makes it enjoyable.

5.3 The Unity Advantage: A Definitive Conclusion

In summary, transitioning from .NET MAUI to Unity was a good decision. While .NET MAUI offered initial promise, its limitations hindered the ability to create an engaging gaming experience.

The switch was driven by practicality and personal preference. In summary, Unity not only addresses the shortcomings of .NET MAUI but also elevates the project, enabling it to deliver an immersive gaming experience. Therefore, Unity emerged as the superior solution for the project's development.

Chapter 6
Concept

This chapter introduces the concept of a rehabilitation application with a game designed for children with hemiplegic partial cerebral palsy. The application aims to leverage tablet technology to provide an enjoyable and effective platform for pediatric rehabilitation. The user profiles include primary users, rehabilitation professionals, and parents/guardians. The domain description covers pediatric rehabilitation and the promotion of bi-manual interaction. The requirements, both functional and non-functional, outline the key features and characteristics of the application. Finally, an early prototype of an application showcasing a bimanual interaction game is presented, along with its evaluation using a cognitive walkthrough.

6.1 Application Overview

The following section provides an overview of the application, outlining its purpose, domain, and target user audience.

1. **Purpose:** The purpose of this application is to encourage young children to engage in bi-manual interactions using off-the-shelf devices like tablets. This application will consist of games, whose purpose is to increase the availability of rehabilitation options for children with motor impairments, providing them with an enjoyable and effective means to improve their motor skills.

2. **Application Domain:** The application domain of this project lies at the intersection of rehabilitation technology and interactive gaming. It leverages the accessibility and familiarity of tablets to create a user-friendly platform for pediatric rehabilitation exercises.

3. **Target User Audience:** The target user audience primarily consists of children aged 5 - 10 years who may require rehabilitation interventions for various motor skill challenges. Additionally, this application can be a valuable tool for healthcare professionals, such as pediatric therapists and caregivers, who are involved in the rehabilitation process. The application's user interface should be intuitive and engaging to ensure that it is accessible and enjoyable for the intended age group.

6.2 User Profile

This section outlines user profiles for the rehabilitation application, including primary users aged 5-10 years with limited tablet experience and specific motor challenges, rehabilitation professionals, and parents/guardians committed to supporting their child's rehabilitation journey through effective and accessible activities.

1. Primary Users:
   - Age: 5 - 10 years
   - Technical Proficiency: Limited experience with tablets
   - Motivation: Improve fine motor skills, coordination, and dexterity
   - Physical Condition: Hemiplegic cerebral palsy
   - Preferences: Engaging and visually stimulating content, responsive interfaces, and intuitive controls.
2. Rehabilitation Professionals:
   - Profession: Physical therapists, occupational therapists, or related healthcare professionals
   - Technical Proficiency: Moderate to high proficiency in operating tablet devices and familiarity with rehabilitation techniques
   - Motivation: Looking for innovative tools to enhance therapy outcomes for children with motor impairments
3. Parents/Guardians:
   - Role: Facilitators and supervisors of the rehabilitation sessions
   - Technical Proficiency: Basic to moderate proficiency in operating tablet devices
   - Motivation: Committed to supporting their child's rehabilitation process and looking for effective tools and activities.

6.3 Domain Description

The domain description refers to a detailed explanation or overview of the specific areas or fields that are relevant to a project or study. Here is the domain description of the described application:

1. **Pediatric Rehabilitation:** The domain of this project encompasses pediatric rehabilitation, focusing on children aged 5 to 10 years. This age group represents a critical developmental stage in which interventions can have a significant impact on motor skill development. The game takes advantage of standard devices, such as tablets, to create an accessible platform for participating in rehabilitation exercises. It incorporates

elements of interactive gaming to make the rehabilitation process enjoyable and motivating for young users. The games would offer a variety of exercises designed to enhance coordination, fine motor skills, and cognitive development. In addition, the application will provide features for progress tracking, allowing healthcare professionals and parents to monitor.

2. **Bi-Manual Interaction:** Bi-manual interaction refers to the use of both hands in a coordinated manner to perform tasks or activities. In the context of this project, the games would encourage children to interact with the tablet using both hands, promoting bilateral coordination and motor skills development.

6.4 Requirements

The application requirements came from an analysis of the needs of children aged 5 to 10 years who faced motor skill challenges. Designed to promote bi-manual interaction, the specifications aim to create an engaging rehabilitation application. They cater to individual user profiles, offer various games with immediate feedback, track progress visually, and provide customization options. The non-functional requirements prioritize usability, seamless performance, and engagement for a user-friendly experience.

6.4.1 Functional Requirements

Functional requirements describe the specific behavior, functionality, and operations that the system must perform.

1. User Management and Authentication:
   - F1.1 The application must allow users (children, therapists, and parents) to create and manage individual profiles with names.
   - F1.2 Therapists and parents should have the ability to monitor multiple child profiles.
2. Game Functionality and Feedback System:
   - F2.1 Present a list of available games.
   - F2.2 Enable interactive tasks and challenges that encourage bi-manual interaction.
   - F2.3 The application should provide immediate feedback during gameplay to guide the user's movements and actions.
   - F2.4 The game should include various interactive elements (e.g., buttons, targets, puzzles) that respond to the child's touch or gestures.
   - F2.5 A virtual reward system should be implemented to motivate and reinforce positive behavior.

3. Progress Tracking:
    - F3.1 Track and display user progress in a visual format.
    - F3.2 Therapists and parents should be able to access progress reports for each child.
4. Bi-Manual Interaction:
    - F6.1 Games shall be designed to require bi-manual interaction, utilizing both hands for activities like tapping, dragging, and tracing.

6.4.2 Non-Functional Requirements

Non-functional requirements define characteristics, attributes, and constraints that determine how a system should behave, including issues such as performance, reliability, security, and usability.

1. Usability:
    - NF1.1 The user interface should be intuitive and easy for children aged 5 - 10 to navigate.
    - NF1.2 The application should provide clear visual cues and feedback during gameplay.
    - NF1.3 The game's graphics and interactions shall be engaging and visually stimulating.
2. Performance:
    - NF2.1 The application should run smoothly on tablets with standard hardware configurations.
    - NF2.2 The application must adapt to the tablet's screen resolution.
    - NF2.3 Response times for user interactions should be almost instantaneous.
3. Engagement and Motivation:
    - NF3.1 Games shall incorporate elements (such as positive reinforcement, animations, and rewards) to keep children engaged and motivated throughout the rehabilitation sessions.
4. User Guidance and Experience:
    - NF4.1 All interactions should be designed to be easily accessible for users with varying levels of motor abilities.
    - NF4.2 The game interface should be intuitive and visually engaging, with clear instructions for the child to understand how to interact with the game.

6.5 Prototype

Based on the requirements as part of the semester project for the implementation of user interfaces subject (B4B39IUR), a prototype of the application was developed. It was developed mainly for Android devices using .NET MAUI. It was tested using the cognitive walkthrough method to identify weaknesses, which allowed further development of the application.

6.5.1 Overview

The main goal of this prototype was to create a game concept that would primarily encourage children to use both hands while playing. Additionally, it was necessary to create a menu that would allow adding user profiles so that multiple children could use the application using their profiles. As a result, the application consists of four parts:

Main menu

The main menu can be seen in Figure 6.1. By pressing the button labeled "Select child profile" (see Figure 6.1 (A)), one is directed to the selection menu. It is also possible to exit the game, by pressing the "Exit" button (see Figure 6.1 (B)).

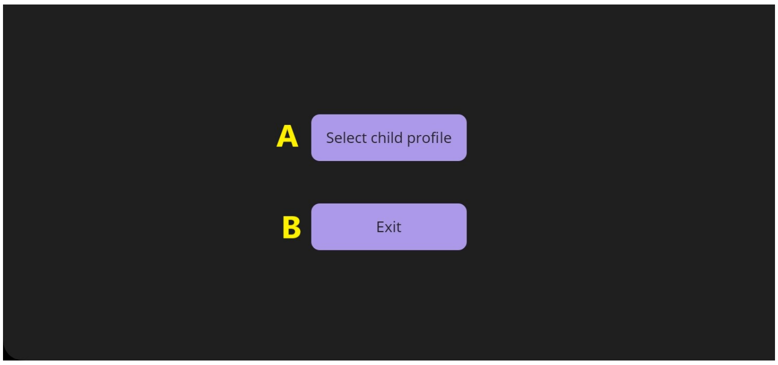


Figure 6.1: Screenshot of the main menu of the prototype application. A) Button to move to the user profile selection menu. B) Button to exit the application.

User profile selection menu

The user profile selection menu is shown in Figure 6.2. It allows one to move back to the main menu, by pressing the "Back button" (see Figure 6.2 (A)), add a new user profile, by pressing the button with the plus sign (see Figure 6.2 (B)), change existing profiles by pressing user's name (see Figure 6.2 (C)) and finally start playing using existing profile, by pressing the "Play" button (see Figure 6.2 (D)).

Figure 6.2: Screenshot of the user profile selection menu of the prototype application. A) Back button. B) Button to create a new user profile. C) Button to change existing user profile. D) Button to start playing using existing profile.

User profile creation menu

The user profile creation menu is depicted in Figure 6.3. It allows one to go back to the user profile selection menu, by pressing the "Back button" (see 6.3 (A)). The user profile can be saved by pressing the "Save" button (see Figure 6.3 (E)) and deleted by pressing the "Delete" button (see Figure 6.3 (F)). Before saving the user profile, it is necessary to fill in some fields, namely the input field for the user's name (see Figure 6.3 (B)), birthday selection field (see Figure 6.3 (C)) and gender selector (see Figure 6.3 (D)).

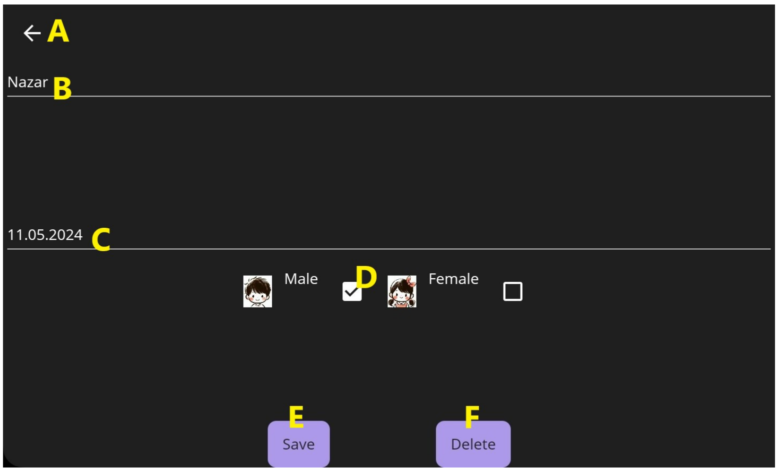


Figure 6.3: Screenshot of the user profile creation menu of the prototype application. A) Back button. B) Input field for the name. C) Birthday selection field. D) Gender selector. E) Button to save profile. F) Button to delete profile.

Game

As mentioned above, the primary goal of the game is to encourage the child to use both hands while playing. The developed game, depicted in Figure 6.4, effectively achieves this objective. The game aims to connect figures of the same color (see Figure 6.4 (D)) at a single point, and new figures appear on the screen every two seconds. It is not simply a matter of gripping one figure and transferring it to another; to register a connection, the child must simultaneously grasp both figures, thereby compelling them to utilize both hands during gameplay. At this stage, there was no emphasis on creating an attractive design, hence the game consists of primitive shapes without distinctive graphical elements. However, despite this simplicity, the game incorporates animation: upon successful connection of figures, they subtly enlarge and gradually become increasingly transparent, eventually fading away entirely. This subtle visual cue enables the child to understand that they are performing correctly.

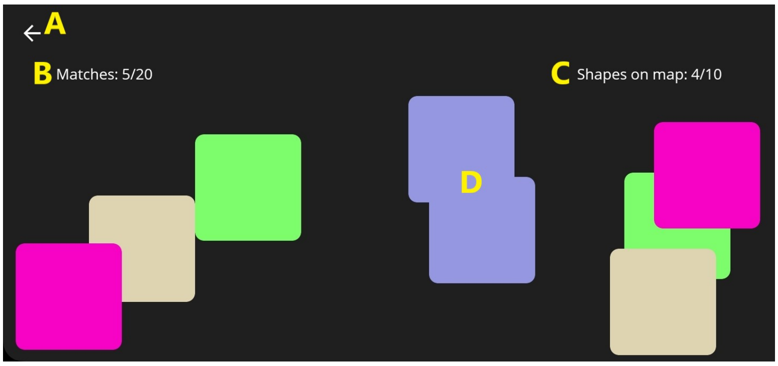


Figure 6.4: Game of the prototype application. A) Back button. B) A label that displays how many shapes need to match to win. C) A label that displays how many shapes are on the screen. D) Two squares of the same color that need to be matched.

In addition, the game features two labels to monitor progress. The first label (see Figure 6.4 (B)) shows how many figures have been connected and how many more need to be connected to achieve victory. The second label (see Figure 6.4 (C)) indicates the current number of figures on the screen and the total allowed. If the child connects the required number of figures, the game concludes with an appropriate victory message (see Figure 6.5 (B)). In contrast, if the number of figures on the screen exceeds the limit, the game ends and displays a message indicating defeat (see Figure 6.5 (C)). Following either outcome, the child is presented with three options: return to the user profile selection menu (see Figure 6.5 (A)), replay the game (see Figure 6.5 (D)), or exit (see Figure 6.5 (E)).

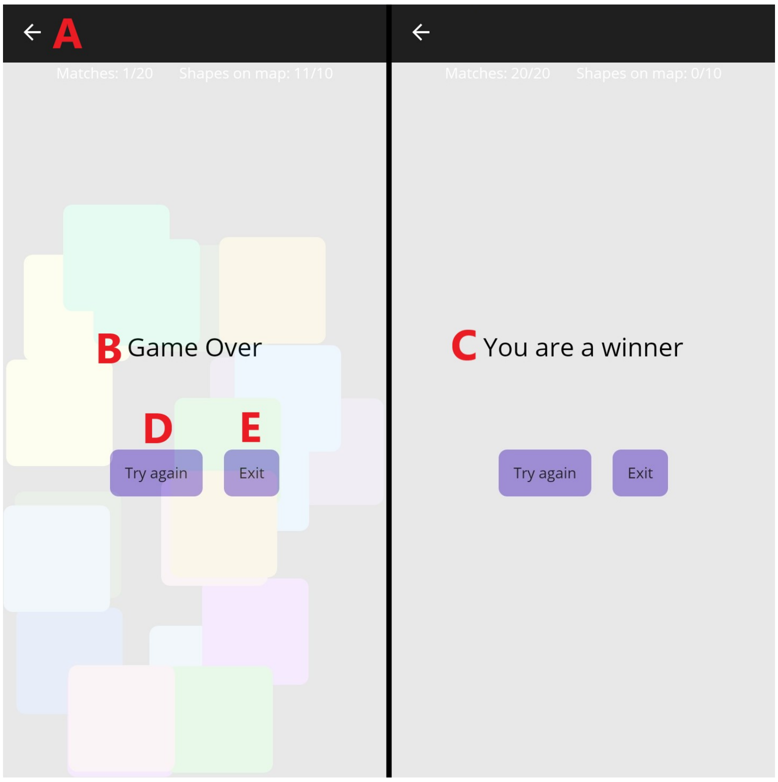


Figure 6.5: Screenshot of lose and win menus of the prototype application. A) Back button. B) Label that says you have won the game. C) Label that says you lost the game. D) Button to start a new game. E) Button to exit the application.

6.5.2 Evaluation

Since it was not possible to test the game in the target group of users, another testing method was chosen, namely the cognitive walk-through, which according to [27], is a structured approach to evaluating the usability of a product. It involves the tester, who is not a user, asking four simple questions about how a specific user journey is conducted.

A cognitive walkthrough starts by identifying the specific tasks that users are expected to perform. These are the tasks that will be analyzed for usability in the cognitive walkthrough. The assessor then performs each action in any given task process and asks the four questions for each action:

- Q1: Will users try to achieve the right result?
- Q2: Will users notice that the correct action is available?
- Q3: Will users associate the correct action with the result they are trying to achieve?
- Q4: After the action is performed, will users see that progress is made toward the goal?

After formulating tasks and questions, the assessor tries to simulate different users' behavior and predict their answers. Finally, by analyzing all of these answers, the strengths and weaknesses of the application are identified.

According to these steps, two parts of the application were tasted, namely the menu and the game.

Scenario: Parent / Guardian creates a new user profile, tries to change and starts the game

1. *Task:* Add new user profile.
   - Q1:
     - "No, user does not have any instructions."
   - Q2:
     - "No, because plus sign for adding new profile is relatively small and unnoticeable"
   - Q3:
     - "Yes, plus sign means something will be added."
   - Q4:
     - "Yes, as new menu will appear."
2. *Task:* Change created profile.
   - Q1:
     - "No, user does not have any instructions."
   - Q2:
     - "No, user will not understand that it is necessary to press the username, since it does not look like a button"
   - Q3:
     - "No, the action is not obvious."
   - Q4:
     - "Yes, as new menu will appear."
3. *Task:* Start the game.
   - Q1:
     - "Yes, because play button is on the screen."
   - Q2:
     - "Yes, because play button is big enough."
   - Q3:
     - "Yes, action is obvious."
   - Q4:
     - "Yes, as new game will start."

Scenario: Child playing a game

1. *Task:* Identify and touch shapes with the same colors.
    - Q1:
      - "No, because the game does not have any tutorial."
    - Q2:
      - "Yes, figures are big enough and clearly seen."
      - "No, because there are figures on the screen with slightly different colors, which is very difficult to notice."
    - Q3:
      - "Yes, the action is obvious."
    - Q4:
      - "Yes, because after this action the user can move the figures."
      - "No, more visual instructions needed."
2. *Task:* Connect figures.
    - Q1:
      - "No, because the game does not have any tutorial."
    - Q2:
      - "Yes, as the user can move the figures."
    - Q3:
      - "Yes, the action is obvious."
    - Q4:
      - "Yes, because after connecting the figures the game gives feedback in the form of animation."
3. *Task:* Estimate the number of pieces needed before achieving victory.
    - Q1:
      - "No, because the game does not have any tutorial."
    - Q2:
      - "Yes, since this information is written on the screen."
      - "No, the user cannot read and does not know numbers."
    - Q3:
      - "No, more visual instructions needed."
    - Q4:
      - "Yes, as this information is constantly updated depending on user actions."
      - "No, the user cannot read and does not know numbers."

6.5.3 Conclusion and Key Recommendations

Based on the cognitive walkthrough evaluation, it is evident that, while the prototype application has potential, there are significant areas for improvement to enhance the user experience, particularly for children with limited tablet experience and specific motor challenges. Here is a summary of the key takeaways and recommendations, which were taken in a count in further development:

- **Instructional Guidance:** Incorporate tutorials or guides within the application to provide clear instructions for each task or feature.
- **Clarify Interactions:** Ensure that all interactive elements are intuitively designed and distinguishable as clickable or touchable items.
- **Reduce Dependency on Reading and Numbers:** Minimize reliance on textual instructions and numerical information, especially for tasks aimed at younger users.
- **Consistent Feedback and Reinforcement:** Implement consistent feedback mechanisms throughout the application to reinforce user actions and provide positive reinforcement.

Chapter 7
Final Application Design

Based on the requirements outlined in previous chapters, as well as the shortcomings identified during prototype testing, the final version of the application for children with hemiplegic cerebral palsy has been developed. In this version of the application, the design has been completely changed to enhance interaction, making it more intuitive and visually appealing to children. Additionally, the application operates in landscape mode, maximizing the width of the screen, thus enhancing the user mobility in the first game. It is assumed that children's initial gaming experience will occur under the supervision of parents or guardians, enabling them to fulfill tasks presented to them during gameplay.

This application comprises three navigational menus, and a user profile creation menu, and also incorporates two games along with a menu that provides statistics for each of them. In subsequent sections, a more detailed description of these elements is provided along with the changes implemented compared to the prototype.

7.1 Menus

The application consists of three navigation menus and a user creation menu (see Figure 7.2), all of which allow to return to the previous one by pressing the arrow in the top left corner. To provide a more intuitive understanding of each button's action, a Diagram 7.1 has been created using the draw.io platform [28]. In this diagram, circles represent the various menus of the application, while rectangles symbolize buttons. The arrows visually depict the transitions between menus upon pressing the corresponding buttons, offering a clearer illustration of the application's navigation flow.

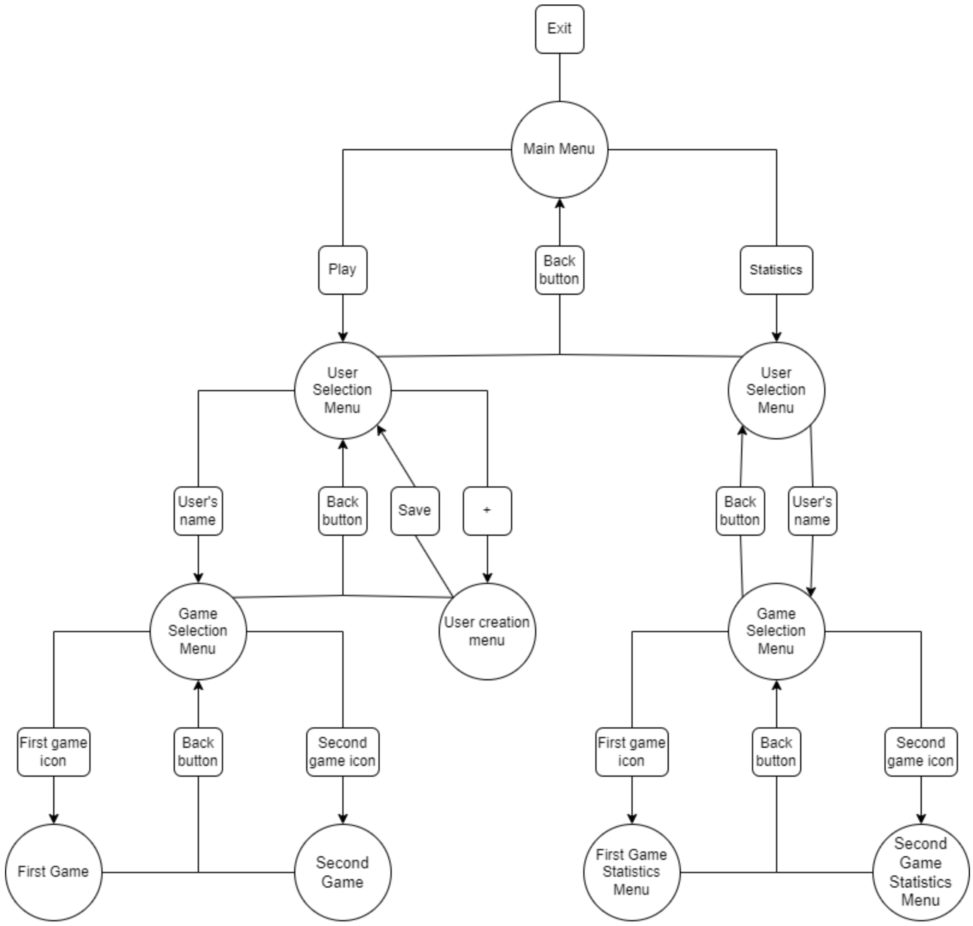


Figure 7.1: Diagram of navigation between different application menus

Almost all of the buttons in the application feature a consistent design, appearing as yellow rectangles of various sizes. In addition to the text, visual elements have been added to explain what pressing the button will lead to. The sizes and colors of all elements are carefully selected to ensure that they are distinguishable. However, it is still expected that younger users will engage with the application along with their parents or guardians as some elements require reading and writing skills. In addition, the language of the text has been changed to Czech to better align with the target user group. Here are all the changes, made in menus, compared with the prototype application:

Main Menu

Unlike the prototype, the main menu of this application (see Figure 7.2 (A)) consists of three buttons. This change is due to the addition of a feature that allows users to access their game statistics by pressing the "Statistics" button.

User selection menu

In the user profile selection menu (see Figure 7.2 (B)), all inconsistencies have been corrected. Specifically, the user's name is now displayed on the button, indicating its interactiveness. The application allows for the creation of up to five user profiles, and the button to add a new profile is now located at the place where the button with his name will later appear.

User profile creation menu

In the user profile creation menu (see Figure 7.2 (C)), the fields for the child's age and gender have been removed because they were deemed unnecessary. However, a new field for selecting the affected side of the body (left or right) has been added. This adjustment allows for customization of the first game based on these parameters.

Game selection menu

The game selection menu (see Figure 7.2 (D)) was added to accommodate the newly introduced feature of selecting two available games.

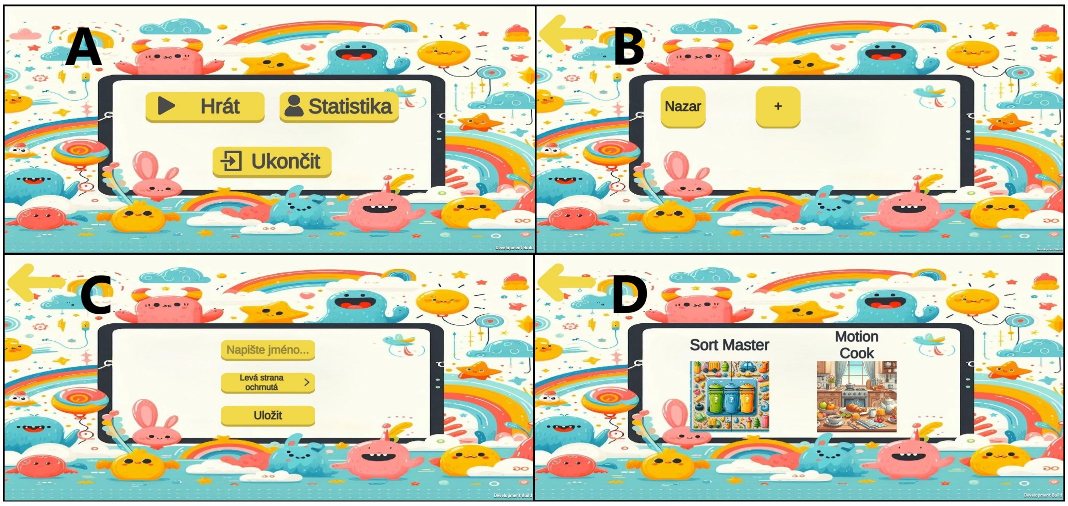


Figure 7.2: Screenshots of different application menus. A) Main menu. B) User selection menu. C) User creation menu. D) Game selection menu.

7.2 First Game

The first game, called Sort Master, was developed based on a prototype application, with its design and mechanics completely revamped while retaining the core interaction principles: connecting two objects at a single point using both hands. The objective of the game is to distribute the corresponding objects in containers, as described in more detail in Section 7.3.1. The game comprises a menu for selecting skins and difficulty levels, a menu with written game rules, and the game itself.

7.3 Game Menu

The game menu (see Figure 7.3) offers several options:

1. 1) Choosing or purchasing container skins and their corresponding contents is done by pressing arrow buttons located at opposite ends of the screen. Purchases are made using coins collected during gameplay. There are only two sets of skins available initially: skins with trash bins and skins with fruit and vegetable boxes. Fruit skins can be purchased by accumulating enough coins and pressing the button in the center of the screen (see Figure 7.3 (B)). This mechanic was devised to encourage children to spend more time in the game, extending their rehabilitation session, as collecting coins and buying new skins is an engaging process.

2. 2) The menu also allows one to adjust the difficulty of the game, which corresponds to the number of containers in the game: 1, 2, or 3 containers. Difficulty selection is made by pressing the "-" or "+" buttons at opposite ends of the screen.

Figure 7.3: Screenshots of different menu states of the first game. A) Screenshot of the menu of the first game with the purchased skin B) Screenshot of the menu of the first game with an unpurchased skin.

When the player selects a previously purchased skin, they can proceed to the game rules by pressing a checkbox button in the top right corner of the screen. Afterward, a menu with the game rules (see Figure 7.4) will appear, with the expectation that a parent or guardian will read and explain the rules to the child. After pressing the button on the right side of the screen, the game starts.

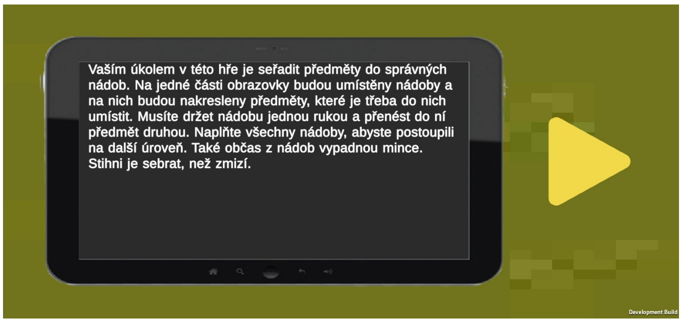


Figure 7.4: Screenshots of the menu with rules of the first game

7.3.1 Game Play

As previously described, the main mechanic of the game revolves around combining items at a single point, but alongside this, several other gameplay mechanics make the gaming experience more engaging and tailored for bimanual therapy. All text-based elements have been removed from the gameplay, and instead replaced with more visual cues, phone vibration, and animations to alert the user and provide feedback on the game. The game screen is divided into two parts (see Figure 7.5 (A)), which can be swapped depending on which part of the user's body is injured.

The part of the screen designed for the healthy hand resembles a green field upon which items appear at varying intervals. The user's task is to move these items to their corresponding containers on the opposite side of the screen. Items can be freely moved across the green field, but if released on the opposite side, they will return to their original position. The decision to make this part intended for the healthy hand was based on the fact that dragging items across the screen requires more physical activity and mobility.

The part of the screen intended for the injured hand consists of gray cells with containers. To transfer an item to a container, the user needs to grasp it with the injured hand; the container's image will change, indicating it is open for the item to be dragged into. Containers can only be moved within the gray-tiled area. When the correct items are placed in the container, they disappear and the container momentarily turns green. Attempting to move an unsuitable item into an open container will cause it to temporarily close and turn red, returning the item to its original position. To enhance the mobility of the injured hand, a coin-collecting mechanic has been added. When placing the correct item in a container, there is a 15% chance a coin will drop out, prompting the user to touch the coin to collect it before reopening the container. The appearance of a coin is signaled by phone vibration, and the container momentarily turns yellow.

When the required number of correct items is placed in a container, its image changes, indicating that it is filled with the corresponding items, accompanied by a phone vibration signal. The total filling of containers is indicated by a scale in the bottom left corner of the screen. When all containers are filled, the player wins. After winning, the player can choose to continue playing or exit to the game menu (see Figure 7.5 (B)). If they choose to continue, the difficulty of the game will increase, as detailed in Section 8.3.1.

Figure 7.5: Screenshots of the first game. A) Screenshot of the gameplay B) Screenshot after winning the game.

7.4 Second Game

The second game, called Motion Cook, is fundamentally different from the first and implements mechanics that involve interaction using the accelerometer, which potentially can significantly increase the mobility of the injured hand. The game is divided into two levels, each with distinct interaction mechanics.

7.4.1 Game Menu

The menu of the second game (see Figure 7.6) allows the user to read the rules of the game by pressing a button shaped like a question mark in the upper right corner and start the game by pressing a button in the center of the screen.

Figure 7.6: Screenshot of the second game menu

7.4.2 First Level

At this level (see Figure 7.7), the user will simulate cooking eggs. To start the game, they need to press buttons shaped like fingers on either side of the screen. If the user releases one of the buttons, the game will stop. This mechanism ensures that the child holds the tablet with both hands. Once the buttons are pressed, the user needs to shake the device in different directions, with the shaking direction indicated by an icon of the tablet in the bottom left corner. The direction constantly changes, making the game more engaging. In addition, the child must not drop the eggs from the frying pan which slide across it based on the tilt of the device screen. In the bottom right corner, there is a progress bar that informs the player about the readiness of the eggs.

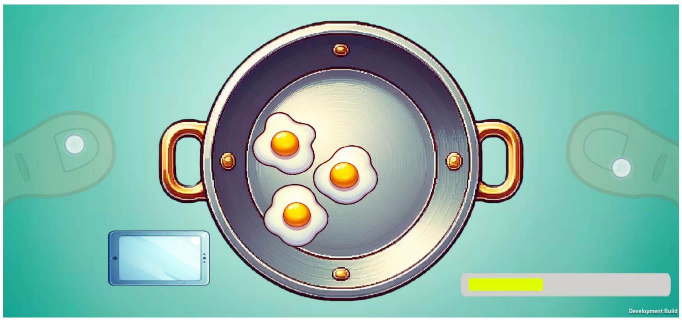


Figure 7.7: Screenshot of the first level from the second game

7.4.3 Second Level

In the second level (see Figure 7.8), the objective is to pour water from a pitcher into a glass. same as on the first level, the user needs to press buttons on different sides of the screen, and then tilt the device to simulate pouring water. Once the glass is filled, it will disappear and a new one will appear on the other side. The player should try to fill as many glasses as possible with the water available in the pitcher. When the water in the pitcher runs out, the game ends.

Figure 7.8: Screenshot of the second level from the second game

7.5 Game Statistics

As mentioned above, the application allows users to view the game statistics. The statistics menu (see Figure 7.9) consists of a grid with graphs of different colors, each corresponding to a level of difficulty or a level of the game. The vertical lines of the grid display the number of games. The points of the graphs on the vertical axis do not have a minimum or maximum value; the graph is plotted relative to these points. Statistics enable parents or guardians to track whether a child is making progress in the game or not.

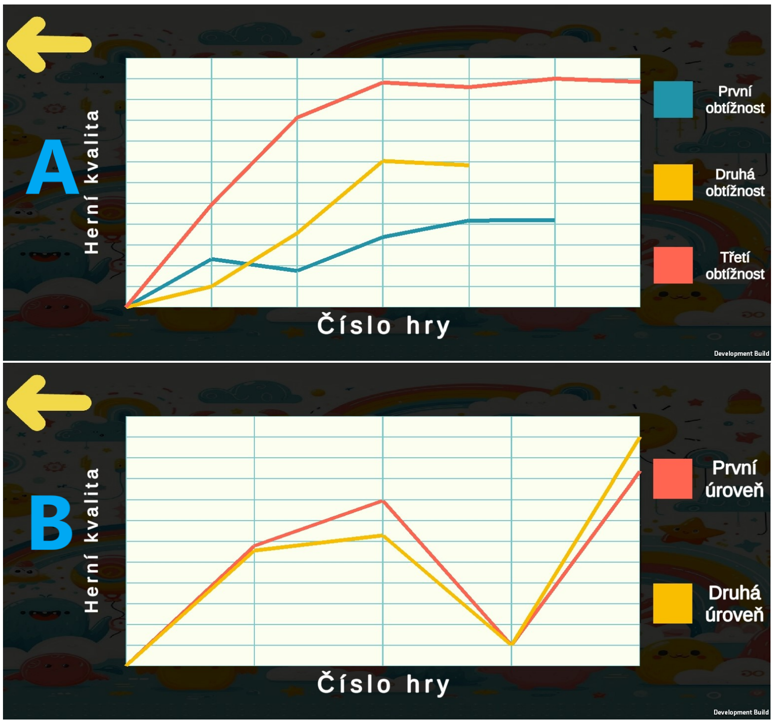


Figure 7.9: Screenshot of statistics of two games. A) First game statistics. B) Second game statistics.

Chapter 8

Final Application Implementation

This chapter provides a detailed overview of key implementation aspects of the application, developed using Unity version 2022.3.19f1, detailing the integration and optimization of various functionalities to achieve a seamless user experience. From touch recognition and accelerometer utilization to statistical evaluation of gameplay and the creation of engaging visual elements, each section explores the techniques and strategies employed to realize the application.

8.1 Track of touches

Touch screen recognition in Unity has proven to be a straightforward task facilitated by the utilization of properties and methods within the Input class [29]. Each Game Manager oversees this process, monitoring the increment in the value of Input.touchCount. Upon detecting an increase, it proceeds to compare the touch coordinates with those of each object belonging to a subclass of the Touchable class. If a touch occurs on an object, it is designated as _isTouched.

For each object that registers a touch, the Game Manager invokes the OnTriggerDrag() method, enabling the object to be dragged. This systematic approach ensures comprehensive tracking of all touches and objects affected by them.

8.2 Accelerometer

In Unity, working with the accelerometer is facilitated through the Input class and its properties - acceleration, and accelerationEvents. The accelerometer provides the linear acceleration of a device in three-dimensional space. The accelerationEvents property returns a list of acceleration measurements that occurred during the last frame, allowing for more precise handling by calculating the average value per frame.

The primary functions utilizing the accelerometer are defined within the Accelerometer class, which serves as the base for other classes employing these functions. The accelerometer is utilized for tasks such as moving objects based on phone tilt (e.g., simulating the movement of eggs in a frying pan), detecting screen shakes (resembling the action of frying eggs), and rotating objects (mimicking pouring water from a jug).

Object Movement

Object movement is executed through the Move(Vector2 direction, float speed) function, which is called every frame. This function receives accelerometer values and the object's speed, resulting in the object moving in the direction indicated by the phone's tilt.

Shake Detection

Screen shake detection is implemented using the Shaking(Vector3 acceleration, float shakeThreshold) function. The first parameter represents the accelerometer values in the current frame, while the second parameter denotes the shake sensitivity. A higher threshold value requires stronger shaking to trigger detection. If the accelerometer values along any axis exceed the sensitivity threshold, the function identifies a shake along that axis.

Object Rotation

Object rotation is achieved through the UpdateRotation(float value) function, where the accelerometer value along a specific axis (typically the x-axis in the game) is provided as input. The rotation amount needed for the object is then calculated using the formula below, where DeltaTime represents the time elapsed since the last frame. This formula determines the extent to which the object should rotate based on the accelerometer input.

$$RotationAmount = -value \times RotationSpeed \times DeltaTime$$

8.3 Statistics of Games

This chapter delves into the statistical evaluation methods employed in games, each with its unique parameters for assessing gameplay quality. In the first game, performance is scrutinized across multiple stages within a session, considering factors like time spent, mistakes made, and items transferred. Conversely, the second game evaluates performance at each level, emphasizing different metrics such as eggs saved or glasses filled, alongside game duration.

8.3.1 First Game Statistics

Evaluating the quality of a user's performance in their initial gaming session presents significant challenges. A single session in this game comprises multiple stages, each escalating in difficulty. Consequently, comparing a child's progress across sessions becomes complex; for instance, completing four stages in the first session but only two in the second session complicates performance assessment. However, a solution has been devised to mitigate this issue to some extent, despite its recognition as not being optimal.

Game Difficulty

The game consistently begins with a standardized level of difficulty, which is determined by the number of containers that require filling. This initial difficulty level is influenced by several parameters: the number of containers, the number of items to be transferred into the containers, the interval between the appearance of new items on the map, and whether the items will disappear over time, including the rate at which they vanish. The initial values for these parameters are provided in Table 8.1. Upon successful filling of all containers, the player advances to the next stage, which features slightly increased difficulty.

	One container	Two containers	Three containers
Number of items to be transferred	10	10	12
Interval between the appearance of items	2.5s	3.5s	5s
Whether the items will disappear	false	false	false
Rate at which items vanish	5s	5s	5s

Table 8.1: Initial difficulty parameters

The progression of difficulty of the session with one container is outlined in Table 8.2. These parameters were selected based on personal gameplay experience. While more precise tuning of these parameters would benefit from extensive testing, the current figures are deemed sufficient to maintain a balance between the game's challenge and its engaging nature.

	Interval between the appearance of items <= 2.5s	Interval between the appearance of items <= 1.2s	Interval between the appearance of items <= 1s
Number of items to be transferred	+ 3	+ 6	+ 6
Interval between the appearance of items	* 0.9	* 0.9	* 0.95
Whether the items will disappear	false	false	true
Rate at which items vanish (if value >= 2)	* 1	* 1	* 0.9

Table 8.2: Difficulty progression for one container

User's Performance Quality

The evaluation of a user's gameplay quality in this game is contingent upon both the time spent playing and the number of mistakes made. Given that the game comprises multiple sessions with progressively increasing difficulty, these parameters alone are insufficient for an accurate assessment. Consequently, it has been decided to evaluate the quality of each stage within a session individually, and then aggregate the resulting scores.

Each stage is independently assessed, taking into account the time spent on the stage, the number of items that need to be moved into containers, and the percentage of items correctly moved at that stage. The formula below integrates these parameters to provide a comprehensive assessment of the user's gameplay quality during a stage. By summing the scores obtained from all stages, a holistic evaluation is achieved, reflecting that the more stages a user completes, the higher their overall gameplay quality.

$$StageQuality_i = \frac{1}{\frac{TimeSpend}{ItemsToTransfer}} \times \frac{ItemsToTransfer}{Errors + ItemsToTransfer}$$

$$GameQuality = \sum_{i=1}^{n} StageQuality_i$$

8.3.2 Second Game Statistics

In the second game, statistical evaluations are conducted independently for each level, with distinct formulas utilized to calculate the quality of the game.

First Level

In the first level, the quality of the game is determined by two factors: the duration of the game and the number of eggs successfully preserved in the frying pan. The higher the number of eggs saved, the better the quality of the game. In contrast, as the time spent on the game increases, the quality decreases. Hence, the formula for assessing game quality in the first level is as follows:

$$GameQuality_{Level1} = \frac{SavedEggs}{MaxSavedEggs} \times \frac{1}{TimeSpend}$$

Second Level

In the second level, the assessment criteria change slightly to prioritize the number of glasses filled with water by the user. The more glasses are filled, the better the quality of the game. Similarly to the first level, the duration of the game inversely affects the quality rating. Thus, the formula for evaluating game quality in the second level is expressed as follows:

$$GameQuality_{Level2} = \frac{FullGlasses}{MaxFullGlasses} \times \frac{1}{TimeSpend}$$

8.4 Game's Visual Elements

Since the target audience of this application is children, it was important to create understandable and appealing sprites for the game. Due to the inability to draw, it was necessary to resort to using artificial intelligence to create images. All visual elements of the app, except for some buttons, were created using Microsoft's Copilot [30]. Even though creating images using AI may seem like a straightforward task, it is not always so. Sometimes, it can take a lot of time to create a suitable prompt, and at times dozens of images need to be generated to choose the right one. Table 8.3 consists of examples of prompts and sprites used in the final version of the application.

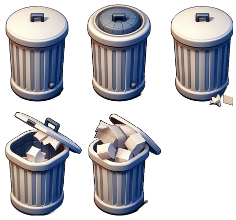
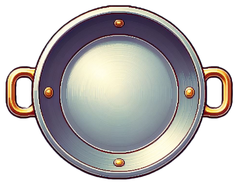
Prompt	Result
3D cartoony and smooth sprites for paper garbage cans in three states: closed, opened, and empty, and opened and full of paper garbage.	
Symmetrical top view of an empty pan with a handle for a game sprite.	
Gentle, soft, cartoony style icon for a children's game designed for children with cerebral palsy, conveying inclusivity and accessibility.	
Transparent empty jug, side view, symmetrical, as straight as possible, soft, smooth, cartoony.	

Table 8.3: Prompts and sprites

Chapter 9

Testing

This chapter delineates the evaluation process of the final application, conducted with live users. Unfortunately, it was not feasible to test the application in children with hemiplegic cerebral palsy. Instead, children within the target age group of the application were recruited for the test. Each child was accompanied by a parent during the evaluation, as the application is designed for collaborative use by both parties.

9.1 Overview

Before starting the test, each parent signed a consent form. This form succinctly delineated the objectives of the test and affirmed the anonymity of the participants. Once all requisite signatures were obtained, the participants proceeded with the test.

The test was carried out using a Huawei MediaPad T5 tablet. Three children of varying ages participated in the evaluation: a five-year-old, a seven-year-old, and a nine-year-old. The older children attempted to minimize parental assistance, while the five-year-old was fully guided by her parent. Each child was seated at a table facing the tablet, with the parent positioned to their left, reading aloud the tasks that the child needed to perform.

The testing procedure was documented using a mobile phone camera to facilitate a more qualitative analysis of the results. Positioned discreetly behind the participants, the camera ensured that their facial features remained obscured, thereby preserving their anonymity.

Each child had to complete the following tasks:

1. Open the application and create a new user profile.
2. Play the first game.
3. Play the second game.
4. Return to the main menu and navigate to the statistics menu.

The children were not limited by time and could play as long as they wanted.

9.1.1 First Participant

Gender: Female

Age: 5 years

Due to her young age, the first participant required parental assistance at various stages. The initial task posed difficulties as the location to create a profile in the main menu was unclear. This issue was resolved after selecting the "play" button. The second task also presented challenges; users were uncertain how to start the game due to the inconvenient placement of the start button and confusion caused by the "buy" label in the center. Eventually, the users navigated the interface and started the game. The parent read the rules aloud and the child proceeded to play without further difficulties, enjoying the game and using both hands. The third task encountered minor issues due to high sensitivity on the first level, which made it difficult for the child to shake the tablet. However, she easily managed the second level. The final task was completed without problems, but the statistics menu displayed no results as the child had only played each game once.

9.1.2 Second Participant

Gender: Female

Age: 9 years

As the oldest participant, the second child's parent was asked to refrain from offering assistance. She completed the first task quickly but struggled to understand how to enter her name in the user profile creation menu due to limited experience with mobile devices. The parent provided guidance. The second task was again problematic; the child found it difficult to comprehend the functions of the various menu elements and took a while to figure out how to start the game, with the parent also experiencing confusion. Once the game began, the child did not encounter difficulties, although the initial stages were too simplistic for her age group. The third task was completed without problems and the second game did not pose any challenges, with the child fully engaged and using both hands. The final task was completed without difficulties, but both the child and the parent were unclear about the meaning of the graphs in the statistics menu.

9.1.3 Third Participant

Gender: Female

Age: 7 years

In this case, the parent provided moderate assistance. The child completed the first task without any difficulties. The second task again presented problems; the child was initially unsure of the function of the arrows at the bottom of the screen but quickly figured out how to start the game, unlike the other participants. During the game, the child faced no difficulties, she was holding the container with one hand and dragging items into it with the other, occasionally releasing the container to collect fallen coins. The third task was executed without issues; the child held the tablet with both hands and played both levels. The final task was completed without problems, but as with the previous participants, both the child and the parent were uncertain about the significance of the graphs in the statistics menu.

9.2 Conclusion

The evaluation process of the final application, conducted with live users, provided valuable insights into its usability and functionality.

9.2.1 Test Results

By observing and documenting the interactions of three children with the application, several key issues were identified that need to be addressed to improve the overall user experience. Detailed findings from each task are presented below to pinpoint areas requiring modification and enhancement.

1. User Profile Creation:

    - The process of creating a new user profile was not intuitive, particularly for younger children.

    - Difficulty in locating the option to create a profile within the main menu.

2. First Game Menu:

    - The placement of the start button was not convenient, causing delays and confusion.

    - The "buy" label in the center added to the confusion, making it unclear how to start the game.

3. First Game Complexity:

    - The initial stages of the game were too simplistic for older children, leading to a lack of engagement.

4. Second Game Sensitivity:

    - The first level of the second game was overly sensitive, making it challenging for younger children to shake the tablet effectively.

5. Statistics Menu:

    - The statistics menu displayed no results if the game had only been played once, which was confusing.

- Both children and parents found the graphs in the statistics menu unclear and were uncertain about their significance.

By addressing these issues, the application can be improved to be more user-friendly, intuitive, and engaging for children of varying ages and abilities.

9.2.2 Future Improvements

Based on the feedback from the test, several modifications are necessary to enhance the intuitiveness and user-friendliness of the application. The primary focus should be on the review of the application menu, which was identified as the source of significant user difficulties. These revisions should include redesigning both the main application menu and the menu for the first game. The statistics menu should be improved with visual elements to increase its comprehensibility for users.

Regarding the games themselves, it is recommended to consult with specialists in the field of cerebral palsy during later stages of development. This will ensure that the application can effectively benefit children with cerebral palsy. In addition, incorporating customization of the game parameters to allow for adjustable difficulty levels will accommodate users of varying ages and abilities.

Chapter 10

Conclusion

The developed application for the therapy of people with hemiplegic partial cerebral palsy aims to meet the urgent need for rehabilitation, especially for children aged 5-10 years. Its unique approach to using easily accessible devices such as tablets sets this solution apart from existing serious games, which often rely on sophisticated technologies. The key findings and contributions of this work are summarized as follows:

1. **Define Specific Needs and Preferences of Target Users:** A comprehensive analysis of the target user group enabled the precise definition of the application requirements and the refinement of the target group to children aged 5 to 10 years. Consequently, both functional and non-functional requirements were formulated, ensuring the application is better suited for children with hemiplegic cerebral palsy.

2. **Conduct Comprehensive Analysis of Current Technologies:** The analysis of existing technologies highlighted the potential of serious games in enhancing rehabilitation outcomes for children with hemiplegic cerebral palsy. It identified gaps in current solutions, particularly the high cost and complexity, and the need for more accessible alternatives.

3. **Prototype Development and Implementation:** Two prototype applications featuring games for bimanual therapy were developed. The initial prototype facilitated a clearer articulation of the requirements for the games within the application and identified various weaknesses, thereby enabling their minimization in the final version of the application.

4. **Usability Evaluation:** Usability testing with participants confirmed the application's effectiveness and user-friendliness, supporting its potential for real-world application, but also emphasized its weaknesses for future development.

In general, the proposed application promises an innovative and accessible solution for the rehabilitation of people with hemiplegic partial cerebral palsy, especially children. By combining technological advances with a deep understanding of neuroplasticity and user needs, this project has the potential to have a significant impact on the quality of life of its target group.

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