Designing a Smartphone Exergame for Children with Cerebral Palsy in the Home Environment

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ABSTRACT

Children with cerebral palsy must perform daily exercise which is a tedious and energy consuming task. Exergames can make this routine more engaging, which can increase the compliance of the patient. This research explores the feasibility of an exergame device called the Squid Monster. The device is the result of a research through design process, and it is designed to be played on smartphones in the home environment. It operates on the smartphone's integrated sensors and two external squeeze sensors, making it accessible and cost-effective. We conceptualize how the design can be supported using a machine learning adaptive difficulty system, aiming to increase flow and therapeutic adherence of the device. Ultimately, guidelines are provided to designers for future work in this field.

CCS CONCEPTS

• **Human-centred Computing**;

KEYWORDS

Therapy, Cerebral Palsy, Play, Exergaming, Adaptive difficulty, Inertial Measurement Units (IMU), Home environment, Motivation

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1 INTRODUCTION

Cerebral Palsy (CP) is a group of disorders commonly symptomized by motor or cognitive impairment, ranging from mild to severe. One of the most common symptoms of CP is spasticity (70-80% of all cases [4]), which is an increase in muscle tone causing functional problems during everyday interactions. In order to increase the functionality of the spasticity-affected areas, patients are prescribed to do frequent therapeutic exercises, which tend to be boring and repetitive. Adhering to these therapeutic regimens can be a challenge, as they are time and energy-consuming. Exergaming in healthcare is defined as turning (therapeutic) exercise into a game to make it more engaging. One common target group for exergames are patients with CP. The exergames are often prescribed to these children to lessen the burden of physical therapy. By gamifying these therapeutic exercises, adherence to the therapy can be increased significantly [11].

One major challenge is to maintain the motivation of the patient to play exergames for longer periods of time. Multiple models of motivation can be used to inform exergame design decisions to try and maintain motivation for longer durations. Popular models include the Self-Determination Theory (SDT) [7] and Flow Theory [5, 6]. Both models of motivation have similarities as well as nuanced differences. One re-occurring theme is the notion of providing the optimal challenge tailored to the individual's capabilities. This poses a challenge when designing exergames for patients with CP, as the optimal perceived challenge can highly differ due to the variability of capabilities per individual. Therefore, there is a need for in-game mechanisms that tailor the difficulty according to the competence of the player.

There are already existing methods of Dynamic Difficulty Adjustments (DDA) implemented in a variety of exergames [2, 8, 9, 14, 19]. These methods vary in their approach in terms of what data is used as well as which mechanisms (i.e., statistics, algorithms) are used to perform the adjustments. More sophisticated DDA-mechanisms include the use of machine learning models that use kinematic sensor data to assess performance and adjust the difficulty accordingly [14]. The latter mechanism especially shows potential in exergaming, as kinematic data can be used to stimulate or assess the proper execution of the prescribed therapeutic movement, which could increase the efficacy of the treatment.

Movement classification using gyroscope and accelerometer sensor data has become a promising direction for exergame design. These sensors, also known as Inertial Measurement Units (IMU's), have become ubiquitous in everyday smartphone devices. Therefore, integrating exergames on a smartphone, combined with a movement classification machine-learning model, could add therapeutic value in a clinical setting and particularly in the home environment due to the accessibility and transportability of the smartphone device. Previous research has shown the potential of measuring refined motor capabilities using an external IMU whilst also making dynamic difficulty adjustments [13]. Our study takes this concept further by exploring the possibility of integrating a machine learning based movement classifier that can classify specific movements using the smartphone's integrated IMU's. This poses the question of how to design smartphone exergames consisting of a machine learning based movement classifier and a dynamic difficulty adjustment mechanism which can be played in the home environment.

This paper aims to present the design process which resulted in the final design called the Squid Monster. We explore the feasibility of this smartphone exergaming device and conceptualize how the integration of a machine learning based movement classifier with difficulty adjustment could support its effectiveness. A Research through Design approach was followed leading up to the final design, including a user study to test the interaction and experience of the prototype.

2 RELATED WORK

2.1 Exergaming

Cerebral Palsy (CP) is a group of disorders that is caused by brain damage during the first year of life. CP is commonly symptomized by a wide variety of physical or cognitive impairments depending on the localization of the affected part of the brain. The most prevalent symptom of CP is spasticity [4]. Spasticity is an increase in muscle tone caused by damage to the motor cortex. This neurological disorder results in various motoric challenges, ranging from gross motor activities such as walking to fine motor movements like writing. These impairments can limit the person's ability to interact with objects, which is one of the strongest predictors of limitation in everyday activities [15].

In order to increase motor functionality in children with CP, it is recommended that the child performs approximately 60 minutes of therapeutic exercise five days per week [20]. It is estimated that the non-adherence to prescribed therapeutic exercises for people with CP is almost as high as 50 percent [16]. But the causes of failure of adherence are not well documented or understood [10, 16]. What is known is that motivational factors are at play that results in non-adherence [17]. Exergames have been a viable option to increase the motivation of patients to perform therapeutic exercises. Studies have shown that gamification of the exercises can improve the compliance, motivation, and engagement of the patient in both the clinical and home environment [11]. However, the initial increase of motivation tends to decline after a short duration, which poses the challenge of maintaining motivation over a longer period [19].

2.2 Motivation

A common model to address these motivational challenges is Ryan and Deci's Self-Determination Theory (SDT) model [7]. The SDT is a general theory of human motivation that distinguishes different types of motivation, ranging from extrinsic to intrinsic motivation. Ryan and Deci propose three needs that can be used to optimize (intrinsic) motivation. These are autonomy (sense of being engaged in an activity based on personal choice), competence (the optimal perceived challenge), and relatedness (feeling of connection to a social context).

A motivational model commonly used in game research is the flow theory by Csikszentmihalyi [5, 6]. Flow is a state of mind defined by complete and voluntary absorption into an activity, such as gaming. Csikszentmihalyi mentions that to achieve a state of flow, three conditions must be satisfied: having a clear goal, receiving detailed feedback and having an optimal balance between challenge and skill.

Ryan and Deci referred to the flow experience as the prototype of intrinsic motivation itself [7, page 260]. The divergent factor between the SDT and flow theory is the feeling of connection to a social context, which is not present in flow theory. As both theories consist of overlapping traits and distinct differences, it poses the question of which theory should be used when addressing motivational challenges. One condition to enhance motivation, which is present in both theories, is the notion of succeeding in a task that provides the optimal challenge. However, designing an exergame that consists of an optimal perceived challenge can be difficult, as patients can vary a lot in their physical or mental capabilities. Therefore, the need for personalization is evident, which was also one of the findings in the research of Cisneros et al. [3]. Exergames should consequently allow for personalization mechanisms that specifically adapt the game's difficulty to the player's competence.

2.3 Adaptive difficulty

Most videogames frequently have built-in functionality to adjust the difficulty of the game manually. These settings allow the user to switch between fixed difficulty levels from easy to hard. However, when designing exergames for a target group like children with CP, these generic difficulty settings will often not suffice due to the highly heterogenous nature of the disorder. Therefore, it is necessary to have Dynamic Difficulty Adjustment (DDA) mechanisms so a state of flow can be achieved.

Multiple DDA-mechanisms in serious games have been explored in previous research [2, 8, 9, 15, 18]. DDA-mechanisms consist of two parts: A performance evaluation and an adjustment mechanism [1]. The performance evaluation refers to a calibration mechanism that assesses the player's ability at the start of playing and adjusts the baseline difficulty accordingly. The latter part dynamically adjusts the difficulty over time.

DDA-mechanisms often use in-game performance statistics of the player to make difficulty adjustments, such as the obtained score in the game or the time it takes to complete a specific task in the game [18]. Some exergames also use physiological data to define the difficulty, such as heart rate or cadence [12]. There are also exergames that use machine learning models as their DDA-mechanism, incorporating kinematic data from devices such as the Kinect (Microsoft Kinect) and movement data gathered by inertial measurement units (IMU) [15]. Using kinematic data shows a lot of potential when designing exergames for children with CP, because the data can be used to analyse the correct execution of the movement, which could enhance the efficacy of the exergame.

As smartphones with integrated IMU's have become ubiquitous in most households, it has become an interesting domain to design exergames for. These exergames can potentially be played in the home environment in a low accessible manner, possibly lowering the burden put on therapists. Previous research has shown that IMU's can be used to assess the fine motor capabilities of children as well as dynamically adjust the difficulty [13]. This research takes it a step further by exploring the potential of using data of the integrated IMU´s of a smartphone device and use it to classify specific hand movements trough machine learning. By doing so, the motoric capabilities of the player can be assessed and difficulty adjustments can be made accordingly. As this approach uses the execution of the movement as its input, it can potentially enhance medical efficacy when compared to mechanisms that use variables such as in-game statistics as their input.

3 METHOD

A Research through Design (RtD) process was conducted. This project builds on the lessons learned of the Magic Monster prototype, part of a research effort around Smart Toys by *anonymized for review* including several industrial partners such as IJsfontein Playful Learning and Philips in the Netherlands. The Magic Monster consists of a smartphone application and a cuddly smartphone casing. It motivates children with CP to do a magic trick in the home environment. In order to complete the magic trick, the children are required to perform a dorsiflexion movement with their spasticity-affected hand, which is a common therapeutic movement whereby the back of the hand is tilted backwards. A machine learning movement classifier was used to differentiate dorsiflexion movement from other hand movements using the data of the integrated smartphone's IMU's (gyroscope and accelerometer) as input. By doing so, the system is able to assess the motoric capabilities of the child, and modify the difficulty of the game through rule-based adjustments. During the testing of this design on the target group, the children with CP often performed the exercise without using the spasticity-affected hand. This led to the new iterations of the design that are presented in this paper with the aim to give less room for cheating possibilities.

Three major iterations on the design were completed during the process. After each iteration, a test was performed to assess the interaction. The first iteration was tested on university students. A semi-structured interview was conducted with a physiatrist of Roessingh Rehabilitation Centre (Enschede, the Netherlands) as well as a paediatric physiotherapist from Dolium Health Centre (Eersel, the Netherlands), concerning the second iteration, which was subsequently tested on four children (11 – 17 years old), assessing the interaction and experience. The final iteration was tested on three children with CP at the Roessingh Rehabilitation Centre (Enschede, The Netherlands). These participants consisted of one male (6 years old) and two females (7 years old), all classified with hemiparetic CP GMFCS level 2, with the male participant having mild cognitive impairment. This use case was conducted aiming to explore the interaction and experience of the final prototype, and how a machine learning based movement classifier could support it. During the case study, observations were made by the researchers and the attending occupational therapist concerning the interaction and experience. Quantitative sensor data of the flex sensor, gyroscope and game context variables were gathered for later analysis.

The final game was designed while keeping the possibility of adding a machine learning movement classifier component with a difficulty adjustment mechanism in mind. The original Magic Monster application contains an AI-architecture that can recognize specific hand movements and contains an adaptive difficulty system (Figure 1). This system uses mobile sensor data collected using the accelerometer and gyroscope in the phone to recognize these movements and assess the current skill level of the user. The aim is to incorporate a similar system into the new version of the Magic Monster application as proposed in this study. There are three sensors of relevance: the accelerometer, the gyroscope, and the squeeze sensors that are incorporated into the handles of the toy. The data collected using these sensors can be used to assess the skill level of the player and increase or decrease the difficulty as needed. For example, if the player is performing well, the threshold for squeezing can be increased to coerce the player into squeezing harder. While such a system is not part of the current application design, the new design was created while considering the possibility of adding such a system to the application in the future.

4 RESULTS

4.1 Insights from the Research through Design process

Two iterations preceded the final concept. A shape exploration during the initial phase of the process, followed by interaction testing on students, led to a steering-wheel shape design. It was found that this shape afforded a natural dorsiflexion interaction. When the user would steer to the right, a dorsiflexion movement of the wrist of the right hand was observed, and vice versa when steering to the other side. However, testing on students showed that the steering interaction was often performed to one preferred side, rather than in both directions. This was undesirable due to the

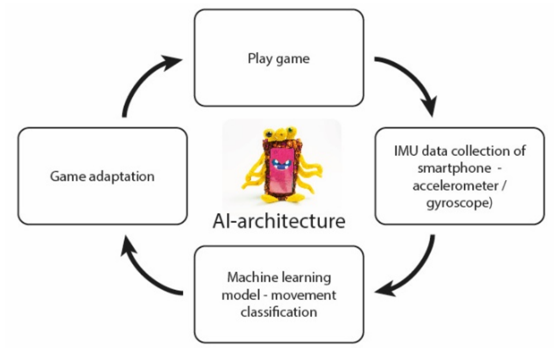

Figure 1: Diagram of the AI-architecture of the Magic Monster

possible cheating possibility for children with CP, allowing them to avoid performing dorsiflexion movement with the spasticity-affected hand. The design was also held in alternative ways, which was undesirable as it affected the interaction. To stimulate steering in both directions, an interactive bilateral LED-strip was added to the casing. This strip corresponded with coloured bombs on screen, indicating the user to steer the bombs towards the LED-strip with matching colour, stimulating bidirectional steering in the process. Flex sensors were added to the prototype's handles to ensure the device would be gripped correctly. These flex sensors were also used as an additional game input, stimulating flexion of the fingers which serves as an extra therapeutic element.

The second iteration which consisted of a steering wheel shape with integrated flex sensors, was discussed with the aforementioned medical experts. Both mentioned that the design did not necessarily stimulate dorsiflexion but rather a supination movement of the hand, which is rotating the forearm so that the palm of the hand faces upwards. Both medical experts mentioned that this movement could also be therapeutically beneficial for children with CP, as their spasticity-affected hand and forearm is often positioned in a pronated position, which is the rotation of the forearm with the palm facing down. By regularly performing the supination movement, which is opposite of the characteristic pronated position, functionality of the hand can be increased. Both medical experts mentioned that the squeeze interaction is particularly valuable when the child would be prompted to exert a controlled amount of force, as this would represent functional grip interactions performed during everyday activities. Squeezing too hard should be avoided because this can trigger spasms. Lastly, the physiatrist mentioned the potential of a game element which combined the squeeze interaction and steering motion, which would stimulate more complex movements.

The second iteration was tested on children without CP. The test showed that the children performed a supinating movement during the steering interaction. However, the coloured bomb metaphor corresponding with the bilateral LED-strip needed extra explanation from the researchers before the participants understood the meaning. The participants were also able to perform the squeeze interaction, but it also required a brief explanation before the in-game metaphors became clear. Thus, the narrative was revised for the last iteration, with the aim of making the interaction more intuitive.

4.2 Final design

The final design (Figure 2) consists of a steering wheel shaped phone casing that affords a supination as well as a squeeze interaction. The user can slide in the smartphone and run the Squid Monster application. When playing the game, bananas fall down the screen according to the orientation of the gyroscope. The player must steer the monster to ensure that the bananas fall into its mouth, stimulating a unilateral passive supination movement. Occasionally, the arm of a monkey appears on the left or right side of the screen and tries to grab the banana. This metaphor stimulates bidirectional steering, as the monkey alternates between the left and right side.

After eating five bananas, a blender shows up on screen. The user can then squeeze the handlebars to make a smoothie. When applying moderate pressure, the bilateral LED-strips gradually turn green, and the blender starts mildly shaking on screen. After applying moderate pressure for a couple of seconds, points are gathered, and the squeeze interaction is completed successfully. When applying too much pressure, the LED-strips gradually turn red, and the blender starts shaking rapidly. This causes the blender to overheat, resulting in a failure of the squeeze interaction after a couple of seconds. The dynamically changing colours of the LED-strip are also shown on screen on the blender itself.

Lastly, two manual difficulty adjustments could be made in the settings menu. These included the frequency of the monkey appearing as well as the required pressure range to complete the squeeze interaction.

4.3 User study

The user study was conducted with three children, two girls of 6 years old and one boy of 7, all three GMFCS level 2. Due to technical difficulties, the results of one participant were excluded. The remaining participants were able to successfully perform the steering interaction. However, some compensation strategies were observed. These strategies mainly consisted of exaggerated shoulder and torso movements. Supination movement of the wrist was observed but it did not exceed the neutral position.

All participants had initial difficulty with applying the right amount of force when performing the squeeze interaction. However, progression was observed. After four squeeze events, both participants were able to reduce the squeeze duration by half compared to their first squeeze interaction.

The quantitative data that was collected showed substantial interpersonal differences between the two participants. The squeeze interactions of the first participant were performed twice as fast on average compared to the squeeze duration of the second participant. It should also be mentioned that the second participant received some help from one of the researchers in order to exert the right amount of pressure on the sensor in order to complete the interaction.

Both participants were observably engaged when playing with the Squid Monster. The metaphor of the monkey induced a sense of rivalry for one of the participants, which increased the competitiveness of wanting to beat the monkey. However, the blender

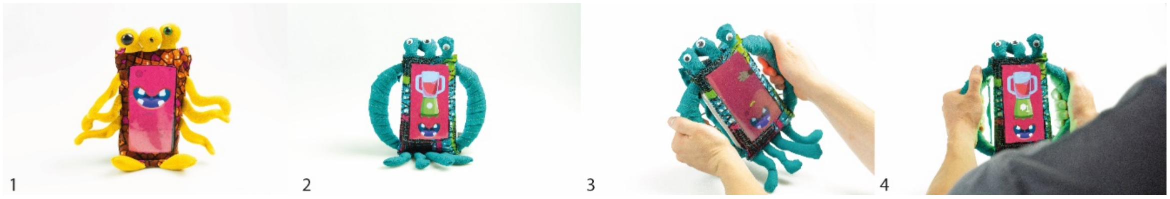

Figure 2: (1) The Magic Monster, (2) the Squid Monster, (3) Steering interaction, (4) Squeeze interaction

metaphor needed some explanation by the researchers before the participants understood the interaction.

5 DISCUSSION

This study explored the feasibility of a smartphone exergame in the home environment and how a machine learning based movement classifier with difficulty adjustment could support its effectivity. Based on the insights of the semi-structured interviews and the observations made during the user study, it was found that the interaction with the Squid Monster prototype showed therapeutic potential. However, the need for difficulty personalization was apparent due to the measured interpersonal differences of both participants. Multiple iterations were made regarding the in-game metaphors but in the end they still required explanation, highlighting the challenge of designing in-game metaphors that are intuitive for the player and the importance to include the player in the process.

Unsurprisingly, different interaction patterns were observed during the user study compared to the previous interaction tests done on students and children without CP. During the user study, the intended supinated position of the spasticity-affected hand was not observed when performing the steering interaction, but instead a neutral position was achieved. The attending occupational therapist mentioned that this was typical, as the natural supination range of motion of the hand of the participant does not exceed beyond the neutral position. According to the occupational therapist, reaching this neutral position should be therapeutically beneficial for the child. This finding is a possible sign of the efficacy of the smartphone exergame. However, compensation strategies of the shoulders and torso were also observed when performing the steering interaction. The compensation movements helped achieve in-game objectives but were undesirable from a therapeutic point of view. Both findings emphasise the potential of the integration of a machine learning based movement classifier, as it can differentiate compensation strategies from the desired supination movement.

The squeeze interaction has therapeutic potential based on the insights gathered from the interviews with the medical experts. However, the user study showed that its current design was too challenging for the target group. The substantial difference in performance between both participants when executing the squeeze interaction emphasised the heterogeneity of the motor capabilities of the target group. These interpersonal differences, which are in accordance with the findings of Pinos Cisneros et al. [3], highlight the need for a dynamic difficulty adjustment system.

Over the course of the RtD process, in-game metaphors were frequently altered based on the insights gathered from testing. During the user study, the metaphor of the steering interaction did become clear after a brief explanation, especially when it was mentioned that the monkey was evil. However, the blender metaphor needed a more extensive explanation. The main difference between the monkey and blender metaphor is that it is more clear for the player what needs to be done in the run up to the event in the former, whereas the latter mainly provides feedback during the interaction. In case of the monkey metaphor, the user can see the arm and can reason in the run-up to the event that it must be dodged. Subsequently, the shape of the design allows for a natural steering interaction to do so and there is a clear connection between what needs to be done in the game and the affordance of the physical prototype. The blender gives less signs of what needs to be done in the run-up to operating it, and it isn't evident that the squeezing of the handlebars correlates with operating the blender. In this case, the user mainly resorts to trial and error to find out what the goal is, receiving feedback after the deed is done. Giving feedback in the runup to an event, also known as *feedforward,* is desirable as it provides a clear goal to the user, which is one of the determining factors of achieving flow [5, 6]. This feature is also of particular importance when designing exergames for the home environment because there is no attending professional that can give an explanation.

For future iteration, in-game metaphors with feedforward mechanisms should be further explored. Designers should aim for a unity of the narrative (metaphors) and interaction (affordance) as they provide a clear and natural goal, which is one of the predicting factors of flow. We propose that the machine learning movement classifier combined with a dynamic difficulty adjustment mechanism should also be added to this unity. The model should be trained to classify specific hand movements using the data of the smartphone sensors. In doing so, the system can determine whether the player is performing the required therapeutic movement correctly. After the movement is classified, the system should nudge the player into a more desired execution of the movement. These rule-based nudges should be part of the narrative and supported by in-game metaphors consisting of feedforward elements. By doing so, the optimal challenge as well as a clear goal can be provided to the player, whilst supporting medical efficacy in the process.

Overall, the interviews with medical experts and the user study showed positive signs in terms of therapeutic efficacy. However, due to the small number of participants and the short duration of the user study, no conclusive remarks can be made. Research concerning the technical feasibility needs to be explored further, to see if the aspired AI-architecture can be implemented on smartphones. Lastly, this study mainly focused on overlapping characteristics of Flow Theory and the SDT. Other possible predictors of motivation like the relatedness domain of the SDT, or other theories not included in this study, need to be further explored.

6 CONCLUSION

This research explored how to design smartphone exergames consisting of a machine learning based movement classifier and a dynamic difficulty adjustment mechanism which can be played in the home environment. The small user study showed signs of engagement and interaction patterns which are therapeutically beneficial. However, nothing conclusive can be said about these findings due to the small amount of participants. nonetheless, even in such a small group, results from the study emphasize the need for personalization of exergames due to interpersonal differences. Implementation of a machine learning based movement classifier could potentially compensate for the heterogeneity of the target group using dynamic difficulty adjustments tailored to the player. We propose that this system should be in unison with the narrative and interaction, so a state of flow can be stimulated through feed-forward mechanisms whilst simultaneously aiming for therapeutic efficacy. More research needs to be done on how this unity would function practically, and its technical feasibility of integrating it into smartphones of the home environment.

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