Digital Games for Physical Therapy: Fulfilling the Need for Calibration and Adaptation

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ABSTRACT
With the advent of computer games involving the movement of the player's whole body or body parts, an opportunity arises to develop games for people with motor disabilities. In this paper we present four minigames developed for people suffering from spasticity and loss of motor control. We thereby focus on the input devices, sensor signal processing and mapping of players' actions on events in the game. In order to adapt the game to the player's motor skills and goals, specific attention should be paid to calibration procedures and adjustable parameters. We illustrate how this can be done and simultaneously, we demonstrate the feasibility for the development of digital games for physical therapy with currently available commercial input devices.

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ACM Classification Keywords
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General Terms
Algorithms, Design

INTRODUCTION
In the past decade, there has been an apparent shift in the way computer games are controlled: from classic game controllers with joysticks and buttons to controllers including sensors like accelerometers, gyro sensors, webcams, IR cameras, microphones and touch screens. Instead of fine motor control skills with hands and fingers, players need to move their arms, legs, head, or their whole body in order to play a game. Well-known commercial examples are Nintendo's Wii remote, Sony's EyeToy, and Microsoft's Kinect. Many games have been successfully developed for the consumer market, in other words, for normal people looking for fun, active entertainment. However, this evolution has also opened opportunities for developing games for people with motor disabilities. Tiresome exercises that are often needed to recover from injury or to (partly) overcome the limitations of motor disorders, can now be incorporated in computer games, thereby offering a more motivating environment.

Target group: spasticity
This paper presents the development of four minigames that were especially designed for people with motor disabilities, and more specifically spasticity. Spasticity is a motor disorder defined by involuntary muscle contractions, due to lesions in the central nervous system, that regulates and coordinates muscle tone [14]. It is a symptom of a number of conditions such as cerebral palsy, Multiple Sclerosis (MS), spinal cord injury and acquired brain injuries including stroke. Spasticity can result in uncoordinated gait, stiff body posture and shortening of range of limb movement.

Games for physical therapy
The first line treatment for these types of motor disorders is physical therapy, focusing on stretching and strengthening of muscles. These exercises have the ultimate goal of maintaining and/or increasing the range of motion, preventing deformities and contractures, increasing muscle strength and enhancing coordination of movements, in order to maximize comfort and optimize mobility of the patient.

As with any therapy, success depends for a large part upon the dedication of the patient and his/her motivation to actively partake in the physical exercises. These factors determine the quality of the exercises and augment the

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quantity of physical therapy. Although patients often look forward to spending time with the therapist [2], the actual motivation for executing repetitive, tiresome, and boring exercises is not always present. Therefore, combining these physical exercises with the immediate and intrinsic motivation associated with a game [15] can be beneficial.

In this paper, we report on the development of four such minigames that can be used during therapy sessions. These games aim to extend the player's range of motion, and to increase their ability to make controlled movements. Additionally, we focus on how to ensure that proper calibration and adaptation accommodates a wide variety of players. When designed properly, these computer games will result in the improvement of the quality of life of the players.

Related work

During the past few years, games for physical therapy have gained increasing success, perhaps inspired by the Wii console, its Wii remote and its balance board. Indeed, the current commercial sensors and input devices, open source software libraries and development kits, have lowered the threshold for designing physical games. Nevertheless, designing games that map the 'physical exercise' to a 'fun goal' is not a straightforward matter. Several research projects have taken a similar endeavor of designing physical games.

Burke et al. [5] developed several games with webcams and Wii remotes for people recovering from stroke, and illustrated the importance of meaningful play and challenge. Decker et al. [8] proposed a game with the Wii remote as pointing device for wrist rehabilitation. Other researchers developed games for therapeutic purposes with other input devices, such as haptic gloves [12,13], robotic devices [7] and pen-like haptic devices [4].

Perhaps, most relevant to our work is that of Alankus et al. [1] who developed minigames for stroke rehabilitation, for use at home. As input devices they used standard Wii remotes and webcams. Their games show some similarities with the games presented in this paper. One of their conclusions was the need for the games to be adaptable to the player's abilities and goals. This paper specifically addresses the issue of adaptability and illustrates how this can be implemented.

With this research project, we aim to build on the lessons learned from previous research projects and contribute to the growing body of knowledge of game design for physical therapy. More specifically, we developed games to treat spasticity, for use in therapy sessions. In this paper we focus on the design and implementation of the actual interaction. We describe how the sensor data are *calibrated* and mapped to events in the game. Additionally, a detailed description is given of how we ensured that the therapist can *adapt* the parameters of these mapping algorithms, in order to fit the game to the player's abilities and the therapist's goals. However, we will start by summarizing our design method and motivating why calibration and adaptability are key factors of games for physical therapy.

DESIGN METHOD

In order to design and develop the games, we relied on a participatory design method over a period of 18 months, involving three physical therapists and four occupational therapists from four different institutions: two schools for special education, one clinic for Multiple Sclerosis patients, and one centre that organizes leisure activities for people with mental and physical impairments. User tests were performed in the institutions, with therapists and their clients. In total 21 persons from the target group participated in the design and evaluation process: thirteen children between 9 and 13 years old, three younger adults of 16, 25 and 37, and five older adults between 50 en 69. The etiology of the children and the younger adults varied substantially, but all suffered from limited motor control, caused by disorders such as cerebral palsy, spinal cord injury, or hereditary muscle deterioration ailments. The older adults were all Multiple Sclerosis patients.

1. Workshops

At the start of the design process, we organized workshops with therapists and their clients during which we played commercially available games. Among the games that were tested were Wii Sports, Mario Kart, Sonic and Mario at the Olympics, Dancing Stage: hottest party, Wii Fit and Rockband on Nintendo's Wii console, and the standard EyeToy games on the PS2 console. During these workshops we discussed the appropriateness of games and the observed player motions for physical therapy.

During the next stage, we discussed with therapists which movements they would like to train using games. The goal was to translate these movements to game actions, in such a way that correct movements are rewarded in the game. Rather than adapting existing games we chose to create new games, partly through brain storm sessions with patients and therapists. We decided to design and develop four different minigames that train on different muscle groups and typical patterns for spasticity.

2. Low-fidelity prototypes

For each minigame, first a low-fidelity (lo-fi) prototype was developed and tested. The focus of such a lo-fi prototype is on the monitoring of the players movements and the mapping to game events, such as the actions performed by a game character. Appropriate sensors were chosen and calibration procedures and signal processing algorithms were developed and tested. Graphics were kept simple (see Figure 4 and Figure 6) and no cognitive challenges were included. With the low-fidelity prototypes we checked whether the games evoked correct movements. Many parameters of these prototypes were adjustable, and the purpose was to find out which parameters are the most relevant, and what their range should be.

3. High-fidelity prototypes

The high-fidelity (hi-fi) prototypes contain fully worked out graphics and additional cognitive challenges (see Figure 1 and Figure 5). As this paper focuses on the interaction between player and game, which was user tested with the lo-fi prototypes, we will not further detail the high-fidelity prototypes. However, as two games are already developed as hi-fi prototypes, relevant results will show up in this paper.

RESULTS – GAME REQUIREMENTS

From the first workshops, we found that existing commercial games are not suitable for therapy sessions, which is in line with other studies [9,10]. In general, these games are designed for 'normal' people not suffering from motor disabilities. Both gross and fine motor skills are needed to play these games successfully. Most of the players from our target group lack the skills to even finish the basic levels. The required speed and accuracy of execution is often too demanding. A related study emphasized the need for designing for slow fun for this target group suffering from spasticity [17].

We found that not only the difference in motor skills between normal players and the target group is substantial, but also the variation of the motor skills within the target group should be taken into account. Even intra-individual differences can be immense, e.g., patients with Multiple Sclerosis can suffer from relapses where performance temporarily deteriorates and necessary adjustments should be made easily. Therefore, each game should be adaptable to the current potential of the player and to the goals defined by the therapist. This was also concluded in the study of Alankus et al. [1].

Calibration

In order to optimize the 'fit' of the game to the patient, and taking differences in morphology of patients into account, a thorough but quick calibration procedure is indispensible [2]. Its main purpose is to measure the abilities of the player, such as the furthest desired positions of the limbs that are played with. Typically, the therapist asks or helps the player to take a certain pose, and the corresponding sensor values are measured. In addition, reference positions are taken and 'recorded' by the sensors. The calibration also ensures that player and sensors are positioned right such that all relevant player's actions can be monitored.

Adaptability

Additionally, game mechanics such as speed and accuracy should be easily adjustable and designed to accommodate for a wide range of skills. Each game algorithm is controllable by several parameters that can be adjusted by therapists. These parameters can be related to the mapping of user actions to game events, such as the sensitivity of the game character's motions to the player's motions, or are unrelated to this mapping, such as the allowed time to complete a task. Correct settings of these parameters will elicit a (motivating) flow experience in the game, forcing the player to perform at the edge of his/her potential, while successful play is still possible.

Game	Physical exercise	Sensors
Catching Dishes	Stretching and bending of the arms	Webcam
Collecting Eggs	Maintaining balance standing on one leg	Wii remote & MotionPlus
Preparing Recipes	Controlled head movements	Wii remote (IR camera)
Flying Dragons	Transfer of weight and balancing when seated	Balance board

Table 1. The four minigames with corresponding physical exercises and used sensor technologies.

Equipment and Development Tools

In order to promote the actual use of the game in a therapeutic context in a later stage, additional requirements are imposed. The equipment should be relatively inexpensive, easy to acquire, accurate and reliable. Therefore we opted for a standard laptop (Dell Latitude E6500) running Windows 7 as 'game console'. Software is developed using Unity's game engine in conjunction with MS Visual Studio. We chose commercially available input devices, such as the game controllers of Nintendo's Wii console, and a webcam. The Nintendo controllers include the Wii remote, from which we use the accelerometer data and the data from the infrared camera, the Wii MotionPlus, measuring angular rate around three axes, and the Balance Board, measuring force with four strain gauges. To communicate with the these controllers, the WiimoteLib library is used [16]. For the camera, we chose the built-in webcam of the laptop. We developed a plug-in for Unity, using OpenCV, to read out the camera's data.

RESULTS – THE FOUR MINIGAMES

Table 1 gives an overview of the four minigames, indicating the physical exercises and the sensor technologies that are used. In the next subsections we will describe the four minigames with focus on the analysis of the sensor data, the calibration procedure, the mapping to game events, the algorithm parameters that can be adjusted by the therapist and the observations from the user tests.

Minigame 1: Catching Dishes

Description

The first minigame (see Figure 1) requires players to stretch their arms in order to catch flying dishes at the edge of the screen and put them on a pile in the middle. The physical exercise focuses on the extension of the elbow and exo-rotation of the shoulder. Each dish is thrown quickly by a character in the center of the screen and then remains at its end position during an adjustable time. This way the player

Figure 1 The minigame ‘Catching Dishes’ is controlled by the player’s hand covered by a colored cloth. The player sees and controls a virtual hand on the screen (top left) to catch a dish (right to the virtual hand).

has enough time to reach for the dish, so a slow motion will suffice. Once a dish is caught, the player has to move his/her hand to the middle, in order to release to dish. This way the repetitive movement of bending and stretching the arm is continuously encouraged.

Analysis of sensor data

The webcam in front of the player is used to track the position of his/her hand. The player wears a colored cloth on his/her hand, to allow the software to track its position. The color tracking algorithm is based on the CAMSHIFT algorithm, for which an implementation exists in OpenCV [3,11]. We developed a plug-in for Unity, using OpenCV, that returns the <x,y> coordinates of the center of the colored cloth for each frame that is generated.

Calibration

During calibration, the camera data are directly shown on the screen (see Figure 2). First, the therapist adjusts the position of the camera and the player, ensuring that the player is always in view of the camera, also when his/her arm is stretched fully upwards or sidewards. Secondly, the color of the colored cloth is analyzed by the CAMSHIFT algorithm. Next, the therapist drags a green circle, using the mouse, to the position of the player’s shoulder (Figure 2). Finally, the player is asked to stretch his/her arm to the side

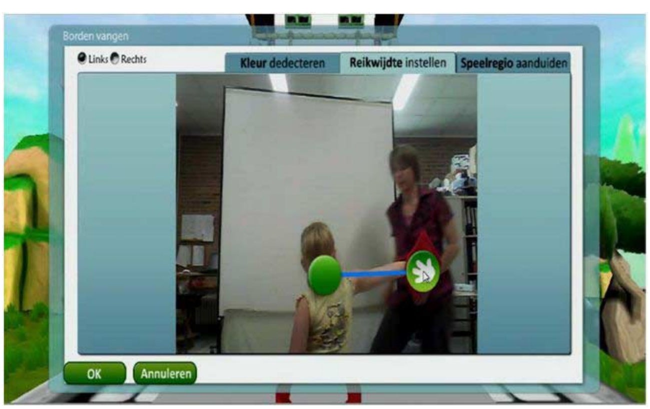

Figure 2 Calibration screen of Catching Dishes. The green circle has to be dragged to the shoulder position. The green circle with the hand indicates how far the arm can be stretched.

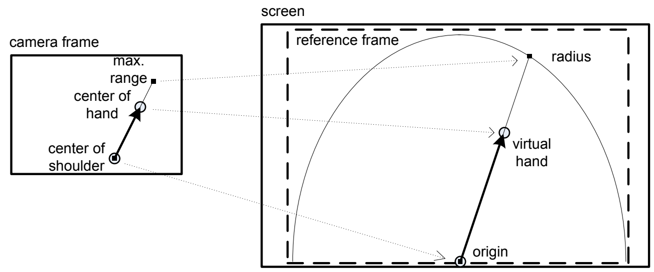

Figure 3 Mapping of the camera data (position of shoulder, hand and maximum range) to the position of the virtual hand on the screen.

as far as possible. The distance between the measured position of the hand and the shoulder defines a radius corresponding to the range in which the player’s hand can move.

Mapping to game events

During the game, the position of the player’s hand is continuously measured, and it defines the end point of a vector with its origin at the position of the shoulder (see Figure 3). For the mapping of the virtual hand on the screen, a reference frame with the same aspect ratio as the camera is used that covers as much of the viewable screen as possible. Within this reference frame, a half ellipse is defined that maximally fills this reference frame. Dishes will always appear at the edge of this ellipse. Now, the origin of the aforementioned vector is mapped to the bottom center point of the reference frame. The direction of the vector is preserved, and its length is scaled such that the maximum range, as measured during calibration, corresponds to the radius of the ellipse at that angle. The motivation for this scaling of the camera data is that the whole screen is used, even if the player has only a limited range to stretch his/her arm. Intermediate user tests revealed that a player has a tendency to stretch an arm further, if a dish appears closer to the border of the screen.

Adjustable parameters

A dish is caught when there is a collision between the virtual hand and a zone around the dish. The zone around the dish is a sphere in 3D space which radius can be set by the therapist (see the green circle around the plate in Figure 1). This way the accuracy of the desired position of the hand can be adjusted to the player’s abilities. A second parameter is the time the player has to catch the dish. During this time interval the dish will remain at its end position. On a separate screen the therapist can also select in which zones the dishes will appear.

Observations

User tests on the lo-fi prototype and the hi-fi prototype revealed that the software was able to accurately track the hand, even if the player moved rather fast. However, care should be taken that the player’s arm is never outside the camera’s view as this disrupts the tracking. Therefore, in the final version a loss of view will be indicated by a warning on the screen, and the request to point with the hand to the camera.

The difficulty is set by defining the radius of sphere around the dish that has to be entered by the virtual hand, and the time interval the dish can be caught. For any player, adjustments could be made such that the game was playable, i.e. that the players could catch at least some of the dishes. The therapists also confirmed that this is an appropriate way to adapt the game to the player.

Minigame 2: Collecting Eggs

Description

This minigame requires players to remain in balance standing on one leg in order to collect eggs by jumping from mountain top to mountain top (Figure 4). The game character will start a jump once the inclination of the player's thigh is above an adjustable threshold, and it will keep on flying as long as this threshold is exceeded. Once the inclination is below this threshold the character will land automatically on the nearest mountain top. The player collects eggs by landing on each mountain top supporting an egg.

Analysis of sensor data

A Wii remote with the MotionPlus extension is connected to the thigh of the leg to be lifted. In order to measure the inclination, only the accelerometer data of the Wii remote are used. The gyro sensor data of the MotionPlus are used to detect the direction in which the knee was moved during lifting: to the right, to the left, or forward, allowing the player to change direction (only in the hi-fi prototype).

Calibration

In order to calibrate the system, the player is first asked to stand on both legs. The inclination of the Wii remote is then measured, and will be used as the reference position. In this way, the Wii remote's y-axis – the axis along the length of the device – does not need to be aligned with the gravity vector at that position. Next, the therapist will ask the player to lift his/her leg to a desired position, and the

Figure 4 The minigame Collecting Eggs is played with a Wii remote on the upper leg. When lifted high enough, the game character will jump from mountain top to mountain top.

inclination will be measured again. The threshold value that will be used during game play is an adjustable percentage of the difference between the measured value at the lifted position and the reference position.

Mapping to game events

As mentioned above, this threshold should be exceeded to start a jump and keep on flying. In order to enrich the interaction, the angle of the inclination is also mapped to three other game events. First, the speed of the character will increase with higher angles. Consequently, there is the reward of faster play if the thigh is lifted higher. Second, the height of flying is proportional to the angle. Third, the arms of the character are more spread with a higher angle. Although these three additional mappings do not result in a higher game score, they improve the player's impression to have full control.

Adjustable parameters

Besides setting the threshold, the therapist can also adjust the difficulty level by changing the distance between mountain tops supporting eggs. Increasing this distance means that the player has to stay in balance for a longer time, making the game more difficult.

Observations

The physical exercise of standing on one leg (outside a game environment) is rather boring. With this minigame, it was apparent though how long the players could persevere playing the lo-fi prototype. This confirms the added value of a game in a therapeutic setting. Most participants could play the game, even with more difficult parameter settings. For one player the game was not suitable: he could lift his foot only a few centimeters from the floor, making it difficult to discriminate between a lifted leg and a supporting leg.

The therapists suggested possible extensions of the minigame. By attaching Wii remotes on lower leg and foot, a so called *triple flex* – a stretching of foot, knee and hip – could be monitored.

Minigame 3: Preparing Recipes

Description

This minigame requires players to sit still and move their head in order to select ingredients from the left and right side of the screen and throw them in the cooking pot in the middle (see Figure 5). The physical exercise focuses on a rotation of the head in a horizontal plane and/or bending forward of the neck. It is crucial that the head moves slowly and accurately in order to control the ingredient's position.

Analysis of sensor data

A Wii remote is connected to a hat worn by the patient. The infrared camera is used as a pointing device, just as in the standard Wii games. The LED-bar is positioned right above or below the screen. The coordinates of the LEDs in the

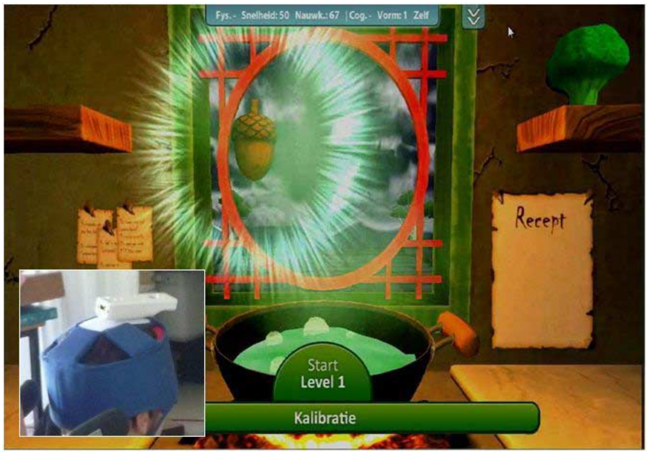

Figure 5 Preparing Recipes is played with the Wii remote on the head. The player controls the magic selection circle to catch ingredients and put them in the cooking pot.

camera frame determine the point on the screen the Wii remote is pointing at.

Calibration

For this game, the therapist only needs to ensure that the player and the hat are positioned right so that any position on the screen can be pointed at by moving the head.

Mapping to game events

Through the Wii remote, the player controls a 'magic' selection circle on the screen. When an ingredient is 'caught' by the circle, it will move along with the circle, as long as this movement is not too fast. The greatest challenge for this game was to find a way to force the player to move slowly. If the player moves too quickly or shaky, e.g. due to a spasm, the ingredient should drop and be caught again. This was solved by calculating for each new frame the new position of the ingredient according to the formula:

$$pos_{new} = pos_{old} + (pos_{target} - pos_{old}) * drag$$

in which pos_{new} is the new position of the ingredient, pos_{old} the previous position, pos_{target} the target position which equals the center position of the selection circle, and *drag* is an adjustable parameter. If the new position is not within the selection circle, the ingredient will drop.

Adjustable parameters

The *drag* factor, a scalar, plays a crucial role in the adjustment to the patient's skills. If this factor is 1, the ingredient is always at the center of the selection circle, at whatever speed this circle is moving. A small value increases the likelihood that the ingredient will fall out the circle in the new frame. So, at small *drag* values the player has to move very slowly. The second adjustable parameter is the size of the circle. A smaller size means that more accurate and controlled movements are necessary.

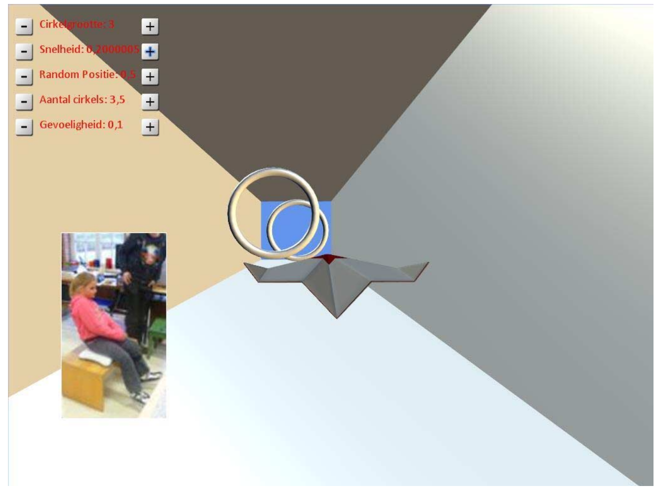

Figure 6 Flying Dragons: By shifting weight on the Balance Board, the player controls the dragon that has to fly through the rings.

Observations

The participants of the user tests were all dyskinetic cerebral palsy patients, since this game was specifically designed for this subgroup. Keeping their head in a stable position in the middle is very challenging for most of them. Occasionally, the therapist aided the player in maintaining a correct posture, e.g. by stretching the neck. In order to keep the game playable, the drag factor needed to be maximized, and a large radius of the selection circle was needed. However, therapists were very pleased observing that the players kept their head in a middle position during the game, which is already a successful result. Since these types of movements are trainable, the therapists believe that smaller parameter values could be used after sufficient practice time.

Minigame 4: Flying dragons

Description

This minigame requires players to change their balance in a seated position in order to fly on a dragon through the rings on the screen (see Figure 6). The physical exercise relies on a transfer of weight and balancing of the center of gravity, thereby strengthening muscles of the back and abdomen. The game character sits on a dragon and the player steers to left or right by changing his/her balance to left or right, and steers up and down by changing his/her balance forward or backward. The dragon's speed is adjustable, but remains constant during the game.

Analysis of sensor data

As input device the Wii Balance Board is chosen, which measures force in four positions using strain gauges. The WiimoteLib library returns the center of gravity of the forces on the balance board.

Calibration

Prior to playing the game, the player is asked to sit as closely as possible in an upright position in the middle of the balance board. The measured center of gravity will be used as the reference position during the game.

Mapping to game events

The deviations from the reference position in left/right direction (*dev.x*) and in forward/backward direction (*dev.y*) are mapped linearly to the rotational speeds (*yaw* and *pitch*) of the dragon in the 3D world, according the formulae:

$$yaw = dev.x * sensitivity$$
$$pitch = dev.y * sensitivity$$

Adjustable parameters

The *sensitivity* factor determines the difficulty level. As revealed by the formulae, a high accuracy is needed for precise control when this factor is high. The radius of the rings can also be adjusted by the therapist, increasing the necessary accuracy. The last factor that can be adjusted by the therapist is the dragon's speed. The therapists thus has three parameters to make adjustments to the player's skills and goals.

Observations

The therapists confirmed that playing the game was a good exercise, since the muscles have to remain tense during a certain time. Holding this tension is a challenge for most people from our target group, and the longer it has to be done, the more fatiguing it is. The slow action also gives enough time to react to the game events. Adjustments could be made for any player to make the game playable. The therapists also suggested to enable simplifications, such as the ability to only steer left/right or up/down.

DISCUSSION AND FUTURE WORK

Input devices

In order to promote the use of these physical minigames by therapists, we opted for commercially available input devices, such as the Wii controllers and a standard webcam. The user tests revealed that the reliability and the accuracy of these devices are sufficient for our applications. Obviously, the limitations of these devices were taken into account when designing the games. The most important limitations were the difficulty of measuring rotations in a horizontal plane with accelerometers and gyro sensors, and the limited viewing angle of the Wii remote's IR camera (for the Preparing Recipes game specifically). It is likely that more advanced input devices, such as a 3D camera, will enable a more detailed registration of the player's movement. However, the current high cost of hardware and middleware would impede widespread use.

Adaptability

The report of Alankus et al. [1] included several suggestions to improve the quality of digital games for people with motor disabilities, such as the importance of calibration and the importance of direct and natural mapping. The authors also included that it should be ensured that the full range of motions is used and that therapists are needed to determine the difficulty. We believe that these 'guidelines' are taken into account in our games. Through testing the lo-fi prototypes, the calibration procedure was optimized. The tests also revealed which parameters should be adjustable by the therapists and what range should be targeted at. Often initial settings still resulted in a too difficult game, again illustrating the importance of adaptability and of user testing.

A drawback of adaptability and calibration is that it takes time before an exercise can start. Since therapy sessions last typically around 30 minutes, including transportation to and from the therapy room, these adjustments should only take a few minutes. In case of our minigames, this requirement was always met. Calibrating and defining the parameters only takes 2 or 3 minutes.

Further steps

The next step is the development of four high-end minigames, including fully worked out graphics and menus, and cognitive challenges. Depending on the game, this challenge relies on e.g. visual discrimination, visual memory, spatial perception and mental rotation skills. Allowing the therapist to set these physical and cognitive challenges individually, allows for balancing a wide range of physical impairments and mental disabilities, ensuring everyone can experience flow and have fun [6]. The games will also be extended with an on-line database that logs all activities and performance of the users. The high-end games will be used during one year in all interested institutions, by the therapists during their therapy sessions. These ultimate user tests will allow a thorough assessment both by players and therapists and a thorough evaluation of the users' experience.

CONCLUSION

We presented four minigames designed and developed especially for people with motor disabilities, and illustrated the feasibility of using commercially available input devices as game controllers. User tests revealed that a reliable and natural mapping can be obtained. It is important however that the game parameters can be adjusted to the player's skills and development goals. For each minigame we illustrated how proper calibration and proper adjustment of the mapping of user actions into game events help to achieve this goal. We hope that this paper can inspire and help other developers to develop novel computer games for people with motor disabilities.

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