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Citation (APA)
Goderie, J., Alashrafov, R., Jockin, P., Liu, L., Liu, X., Cidota, M., & Lukosch, S. (2017). [POSTER] ChiroChroma: An Augmented Reality Game for the Assessment of Hand Motor Functionality. In *Proceedings of 2017 IEEE International Symposium on Mixed and Augmented Reality Adjunct* (pp. 115-120). IEEE. https://doi.org/10.1109/ISMAR-Adjunct.2017.44

Important note
To cite this publication, please use the final published version (if applicable).
Please check the document version above.

ChiroChroma: An Augmented Reality Game for the Assessment of Hand Motor Functionality

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ABSTRACT

For a better understanding of how different diseases (e.g. neurovascular diseases, neurodegenerative diseases, and musculoskeletal pain conditions) affect human motor function, a uniform, standardized and objective evaluation is a desirable goal expressed within the clinical community. We explore the capabilities of an augmented reality (AR) game that uses free hand interaction to facilitate an objective assessment of the upper extremity motor dysfunction. First, the design process of the game and the system architecture are described. Second, a study about usability of the AR framework and game engagement is presented based on an experiment we conducted with five patients and ten healthy people. Lastly, a short analysis of the accuracy of the hand data when participants performed "fingers tapping" gesture is done. The results of the study show that even though users experienced the system as physically and mentally demanding, it was engaging enough to make them complete the game. The study also shows that hand data captured is accurate enough to allow a high degree (95%) of pinching gesture recognition.

Keywords: Augmented Reality Games, Usability, Engagement, Upper Extremity Motor Dysfunction, Assessment, Parkinson's Disease, Stroke patients.

Index Terms: H.5.1 [Information Interfaces and Presentation]: Multimedia Information Systems—Artificial, augmented, and virtual realities; H.5.2 [Information Interfaces and Presentation]: User Interfaces—Interaction Styles.

1 INTRODUCTION

Disorders that impair the motor function may have a high impact on mobility of patients, affecting self-dependence and the ability to work and recreate. Ultimately, the result is the loss of quality of life [14], [18]. As an increasing number of people is affected by such disorders, the clinical community expressed the need for developing cost-effective assessment tools that allow for uniform and objective evaluation of patients who suffer from different motor dysfunctions. Currently, every medical discipline uses disease-specific clinical tests, which mostly involve subjectively scored assessment methods. Other assessment protocols are based on qualitative video analysis or cumbersome marker-based motion capturing. Variations in task and environment are further often not considered, although they are part of daily life activities.

In such a context, a virtual environment can offer the possibility to safely perform a diverse range of movements while interacting with objects of different shapes and sizes that can follow various trajectories. A virtual environment can be achieved using either Virtual Reality (VR) or Augmented Reality (AR). Each display technique has its pros and cons.

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VR has already proven to offer great opportunities for different purposes in various patient groups [4]: improve the gait pattern in patients with Parkinson's disease (PD); improve spatial perception in children with cerebral palsy; post-operative treatment of the hand; rehabilitation of stroke patients.

Placing patients into a virtual environment stimulates them to get immersed into the game while distracting the patient from their impairments and motivating them to perform at their best in the assessment. As shown by Arthur [2], when the field of view of a HMD is increased, the player experiences a more prominent game presence and the player's performance increases. Weibel and Wissmath [20] have shown empirically that immersion positively influences the player's enjoyment and performance. Other studies [16], [21] have shown that an immersive game experience can reduce a player's perceived pain or discomfort.

Although VR is an excellent tool for several purposes, the total visual isolation from the real world, with the patient having only mediated visual experiences may cause interference with their natural behavior. This disconnection with the real world, combined with a degree of input lag that is inevitable, often causes nausea during elongated exposure [6]. It is also possible that the patients lose their sense of balance, which limits the applicability to stationary or sedentary assessment criteria.

AR in comparison to VR allows the user to see the real world, with virtual objects superimposed upon or composited with the real world [3]. This unmediated contact with the real environment gives patients more presence compared to VR, which in turn can lead to more natural interaction behavior [10].

In order to perform movement tasks in the 3D space, patients should be able to perceive the correct 3D position of objects around them. For this purpose, a stereoscopic optical see-through (OST) HMD was a natural candidate for our system.

Nevertheless, OST AR encounters two major problems that are not a concern in VR or even in AR when using other display styles (e.g. monitors, projectors or Video See Through HMDs): the alignment of the virtual world with the real world and the limited field of view of OST-HMD.

Different AR systems have already been successfully developed for rehabilitation of motor function of the arm and hand, using a variety of interaction methods (e.g. (force feedback) gloves [15], [19], marker-based tracking [1], contact-less tracking [7], [13]) in different visualization styles (monitors, HMDs [7], 2D projections [10] in direct environment of the patient).

In our paper, the focus is to develop an OST AR game that would facilitate the objective assessment of a particular hand movement of patients with upper extremity motor disorders. We describe an AR game named ChiroChroma, which allows the player to colour-in a virtual 2D representation of an object using free hand interaction with a set of virtual components. After the user finishes colouring the 2D object it can be transformed into its respective 3D counterpart with which the user can interact. In order to complete the game, different hand gestures and postures are required. While playing the game, hand data captured by the contact-less sensor is recorded, to be analyzed at a later stage.

2 CHIROCHROMA – GAME DESIGN

ChiroChroma was developed in close collaboration with a movement scientist to identify which gestures are important to assess motor dysfunctions. Using the expert's input and the Unified Parkison's Disease Rating Scale (UPDRS) [17] a repeated finger-tapping/pinching motion was chosen for implementation and analysis.

The goal of the system is to collect hand data while the patient is performing the gestures required to play the game. It was designed as a game to make the assessment process more entertaining and less cumbersome by providing the patients with a captivating experience. The game should do so without obstructing their movement or losing their connection with the real world. To make the system usable by people with varying physical capabilities the therapist can modify certain aspects of the game with respect to the gestures.

The resulting game consists of three main components: the gameplay, the options, and the feedback view.

2.1 Gameplay

The gameplay consists of two phases. In the first phase, the player is given a 2D drawing subdivided into several areas that need to be colored. The second phase is an interactive phase where the user gets to perform a task with the 3D representation of the object they just colored in.

The scene in the colouring phase is displayed in Figure 1. It has five main elements, two buttons to navigate between the areas to colour, one slider to change the currently selected colour, one circle indicating the selected colour, and the 2D object. During this phase of the game the system collects data on the patient's hand motor functionality which can later be reviewed by the therapist.
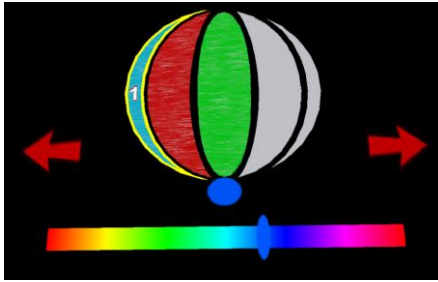

Figure 1: Coloring phase UI.

To make the game less physically demanding, the scene was positioned and scaled to be visible to the player with little movements of the head. Thus, the virtual scene with the size of approximately 50×40 cm was superimposed onto a table in front of the player (see Figure 6), using a marker.

To create a more robust experience, capable of handling unintended movements, the control elements (i.e. the buttons and the slider) were separated by making them gesture activated, meaning that the patient has to match the gesture to be able to interact with each object. These gestures are customizable by the therapist, as described in section 2.2. Having different hand positions to activate each game element also allows the testing of transitional gestures (e.g. opening/closing a hand), which are also part of the UPDRS [17].

Once the desired area and colour have been picked the user can start colouring the area. This is done by performing the pinching motion (i.e. moving the tip of the thumb to the tip of the index finger) repeatedly. The area is filled gradually based on how often the gesture was performed. Filling the area gradually is meant to make the patient feel as if they are really colouring something, which compensates for the non-intuitive nature of using a pinching motion for colouring.

After successfully filling the areas the user can initiate the second phase. The transition to this phase is set in motion by making the palm of the hand face the camera for 5 consecutive seconds. The overall idea of this phase is to entertain the player and make them feel as if the effort they put in during phase one was purposeful. Its unguided structure is meant to further disconnect the patient from the idea of being assessed, which might make the overall experience less burdensome.

In the second phase, the scene consists of the 3D version of the coloured object, a target, an attempts indicator, and a score indicator. The virtual scene is no longer registered in the 3D real space, being now positioned at a constant distance in front on the virtual cameras. The goal is to drag the object towards the HMD and release it. This will slingshot the object at the target, scoring points depending on the zone of the target that is hit. A hit is indicated by paint splatter in one of the colours of the object, as can be seen in Figure 2.
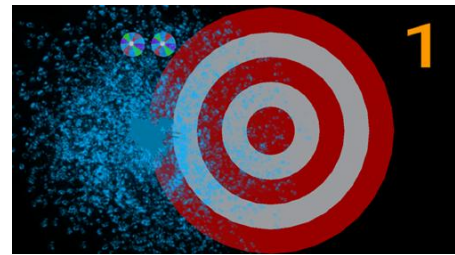

Figure 2: Interaction phase UI.

2.2 Options

The aim of the system is to assess a patient's physical capabilities, which can vary severely between patients. To accommodate for the varying capabilities of the patients it is important that the game is adjustable accordingly.

An adjustable game allows the therapist to add or remove some additional constraints which influence the game-play. Having the ability to tweak the game's parameter also allows the therapist to investigate the limits of a person's functionality by gradually increasing the difficulty. Finally, it makes it possible for the therapist to make small adaptations to the gestures that are being tested (e.g. whether to open or close a hand).

In the current system, the therapist is able to change the gestures that have to be performed in order to have the slider appear and the buttons activate, and to change the opening and closing distance of the pinch movement. Since the patients' capabilities can vary between their left and right sides, the settings can be set separately for each side (see Figure 3).
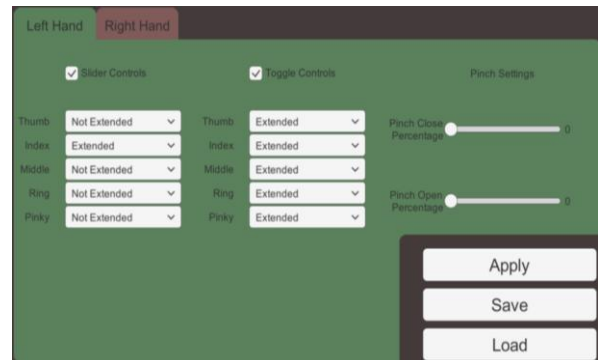

Figure 3: Options UI.

These changes can be applied while the game is in progress, making it possible to test multiple gestures during a single run.

2.3 Feedback

To facilitate easier assessment the therapist can load the data and see a graph of the data over time (see Figure 4). Currently the graph shows the pinch distance (i.e. the distance between the tips of the thumb and index finger) since this was the gesture we focused on. A graphical representation of the data can help the therapist in determining key elements of the movement, such as frequency and relative amplitude of the pinch.

A patient might show some movement characteristics that are not accurately presented in a graph (e.g. inability to move index finger independently from middle finger). This does not directly affect the pinch movement, but still is important information for the therapist. As such, a secondary feedback view is present where a 3D model of a real hand, projected from three sides (top, front, and side), is shown. The bones of this hand are moved accordingly with the collected data, showing a step-based representation of the movements over time.
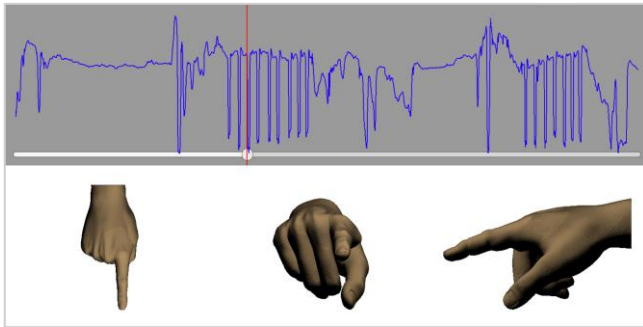

Figure 4: Assessment UI (Graph displays amplitude over time).

3 SYSTEM ARCHITECTURE

As a head-mounted display, the AIRO II OST-HMD from Cinoptics (2 OLED displays, each with a 1280×720 resolution, a 16:9 aspect ratio and ≈ 40° diagonal FOV) is used (see Figure 5). The HMD is fitted with a wide-angle SKYE camera (67.5° view angle) and on top a LeapMotion® Controller is mounted. The virtual scene's position is controlled from a single camera's point of view, which has to be translated to a stereo image for the left and right eye. Using the parameters of the HMD (screen width, screen height) and "average measurements" for humans (e.g. 64mm as distance between the user's eyes [8]) the position of these display cameras is determined.

Figure 5: Cinoptics AIRO II OST-HMD.

The game is implemented using Unity3D and is run on a laptop (Intel® Core i7-4900MQ CPU @ 2.80GHz, 16 GB RAM, NVidia® Quadro 2100M 4GB). To improve performance of the Leap Motion Controller the Orion beta SDK was used. This allowed for extended range and improved pinch recognition. The ARToolkit SDK was utilized to determine the relative position of the virtual environment. This was done using an 8×8cm marker

which was placed slightly above the users' point of focus and the centre of the interaction environment, effectively reducing the time it was obscured.

4 USER STUDY

To determine whether the described system was usable as a way to collect hand data, a series of tests with external people were organized. Additionally, the accuracy of the captured data was investigated.

4.1 Study Setup and Participants

The user study was conducted with two different user groups: healthy people and patients. While playing the AR game, the participants sat on a chair in front of a table (see Figure 6).

Figure 6: A PD patient during the experiment.

The tests with healthy people were organized to gather reference data for an objective performance measure. Another reason for these tests was to obtain a generalised opinion on the game. In total ten people (four male, six female) aged 23 to 61 (M=46 and SD=14.34) participated in this test.

The goal of the tests with patients was to determine to what extent people with varying severities of symptoms were capable of utilizing the system. A total of five patients (three PD patients and two cerebrovascular accident (CVA) patients) were asked to play the game, after which they provided feedback on the system. Based on the feedback the game was adapted between different tests, to make the experience more comfortable for the next patient. A total of three different versions were used during this phase, where no patient used more than one.

In both cases the user feedback was collected using 3 validated questionnaires: the In-Game version of Game Experience Questionnaire (GEQ) [12], NASA Task Load Index (TLX) [9], and System Usability Scale (SUS) [5]). GEQ and SUS are based on a 5-point Likert scale, and NASA-TLX on a 7-point scale.

4.2 Test Results

Data from the questionnaires provided some interesting feedback on users' experience during the game. For the healthy group, the results are presented statistically. Contrary, due to the limited size of the group overall observations are reported for the patients instead.

4.2.1 Healthy People

Based on the SUS criteria the system scored below the average of 68 with scores ranging from 40 to 80 (M=61.25, SD=13.28). Four out of the 10 participants scored the system above average,

suggesting that it has usable elements. From SUS, it became apparent that much improvement can be made with respect to 'willingness to use again' and 'ease of use'. Recurrent elements in the feedback were that the HMD was somewhat difficult to position correctly, especially for those who never used an HMD before, and that the virtual scene seemed misaligned to some degree, both affecting the ease of use. The reduced ease of use might also have negatively influenced how willing people are to use the technology again.

Analyzing the GEQ questions led to the following results for the 7 dimensions defined in [11]: the game scored high on 'sensory and imaginative immersion', 'competence', and 'positive affect', all with median [interquartile range] values 4 [3, 4]. Low scores were obtained on 'negative affect' and 'tension and annoyance', with 2 [1, 3]. Lastly, high scores were on 'challenge' 4 [3.75, 4] and 'flow' 4 [3.75, 5]. Overall this is a decent score which also indicates that significant improvement can be made with regards to 'challenge'. To create a game usable by most patients it could be necessary to reduce the challenge as experienced by healthy people to a low/average level.

The NASA-TLX scores, as displayed in Figure 7, show that the users did not feel raced or stressed and generally felt successful in performing the task required. It also indicates that they experienced varying levels of physical and mental demand while playing the game, ranging from very low to moderately high. This suggests that the game might be too physically demanding for patients.
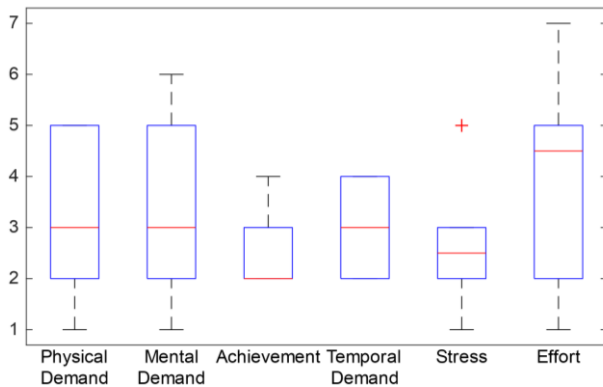

Figure 7: NASA-TLX questionnaire results of healthy group.

4.2.2 Patients

The purpose of the tests with patients was to improve the game by making it usable by people with varying degrees of symptom severity. This was mostly achieved by personally accompanying the patients during the test and identifying which game elements were lacking in robustness.

The tests showed that the elements most affecting robustness were the game controls (i.e. the buttons and slider), so most changes were made in this area, improving the overall user experience.

The SUS questions produced a higher lower bound (50) for the patients than for the healthy people (40), but still was considered below average by most of the users. The biggest contrast between the two was that the patients indicated that they were more willing to use the system again, but they also felt an increased need of having a technical person around to help them utilize the system.

The GEQ scores were comparable between the two groups, with the only difference being that the patients reported slightly higher values on 'challenge'.

When analyzing the NASA-TLX scores of the patients' tests similar results are obtained as with healthy people, with the

exception of the experienced level of physical and mental demand. With regards to physical challenge a clear divide was visible, some patients indicated that it was not demanding at all, whereas others found it very challenging, with no real in-between. The deviation in reported mental demand was much smaller with patients than with healthy people, as the majority reported to experience the game as mentally demanding.

4.3 System Accuracy

The accuracy of the system is an important factor for objective assessment. To see whether it is accurate enough, the collected data needed to be compared with the actual movements of the player. This was done by recording the playing hand using a camera, synchronizing the collected data with the video, and checking whether the virtual hand (controlled by the data) moved similarly to the real hand.

Over 95% of the pinches were detected correctly, and most of the ones that were not correct were caused by the user's hand not sufficiently facing the Leap Motion controller. It is possible that while performing hand gestures certain fingers are omitted from the sight of the LeapMotion. This causes artefacts in the virtual hand that do not match the real hand, but this does not influence the pinch distance measure, thus it does not affect accuracy.

5 Discussion

The SUS results of the tests with patients indicated that they were somewhat more willing to use the system again even though most of them experienced the game as more demanding than the people in the reference group. This could indicate that the system was well received as a potential assessment tool. The reported desire to have a technical person around could be related to the fact that the patients experienced the game as more mentally and physically demanding, but might also have to do with the higher average age.

Overall the tests showed that while the game is experienced as being mentally and physically demanding, the users were still heavily immersed into the game-play and were really determined to perform the tasks right and finish the game. This is very promising for the goal of eventually using the system to assess motor dysfunction. If the game can dynamically explore and adapt to the patient's capabilities the eagerness of the user to finish the game could result in a trustworthy objective assessment.

The experiences of healthy people might not fully represent those of the actual patients, as exercises often are less cumbersome and easier to perform for a healthy person than it is for someone suffering from a mobility-impairing disease. However, the results are useful to see whether an acceptable lower bound was achieved. If the game is too physically-demanding for healthy people, there is a significant chance it's not suited for people suffering from an illness that affects motor function. For this reason, the reference group tests should not be used to draw definitive conclusions on the system.

During development and testing two issues with regards to alignment were encountered. Firstly, it became apparent that the leap motion hand (i.e. the virtual hand) does not precisely match the user's real hand, both in position and scale. Secondly, the height of the scene in the current system is fixed, causing issues when dealing with varying environmental parameters (e.g. chair height, user's length, and user's posture). To fix these problems the virtual environment heavily overestimates the location of the hand, which makes sure that any user can play the game. However, it also means that for some users, or in some environments, it is possible to play the game without it exploring the users' physical limitations, which is detrimental to the purpose of the game. Another downside to overestimation is that one

cannot depend on precise interaction, limiting the possibilities in game design.

Our system detected 95% of the finger tapping motions correctly, while a camera might capture 100% of the pinches. However, having the digital data not only allows the assessment to be reduced to numbers, it also makes it possible to visualise the hands from varying angles, potentially revealing additional movement characteristics. This would otherwise require multiple cameras to capture the different angles.

6 CONCLUSION AND FUTURE WORK

In this paper, we described an AR game designed for assessment purposes of patients with upper arm motor dysfunction. We used contact-less hand tracking technology for interaction with the virtual content, which was displayed in an OST-HMD. Five patients (three PD and two CVA) and ten healthy persons participated in a user study, playing the game and providing us feedback to evaluate the current implementation of the AR system.

The usability of our AR system was mostly rated below average, losing most points on users' willingness to use the system on a regular basis. Additionally, its complexity and the reported desire to have an accompanying technical person negatively influenced the usability. The gameplay was experienced as both physically and mentally demanding, especially by the patients. Nonetheless, the users reported that they felt immersed in the environment and were driven to complete the game as intended.

The comparison between the virtual hand model and the real hand showed that the frequency of pinching is highly accurate, although the positions of the virtual fingers are not always following the real ones as not all fingers are constantly in the view of the LeapMotion controller.

The user tests also revealed that alignment is crucial for a robust experience, especially when dealing with users of varying heights.

Overall, the system yielded encouraging results towards achieving virtual-based objective assessments of motor dysfunctions.

As future work, it is important to investigate whether therapists can use it to draw objective conclusions, and to see if the game is extensible enough to create a sensible assessment program.

In order to achieve a robust tool, we consider improving the vertical scene alignment. One element that should be considered when attempting such an alignment is that the environment (either the virtual or the real one) needs to be adapted, as it is a liability to assume that the patient will be able to compensate for any misalignments.

The current system focuses solely on hand motor functionality; however, its general design idea makes it well suited to extend this to include other assessment elements as well. Additionally, the current game is focused around two gestures which are often used for assessment, which is generally not sufficient to lead to a complete assessment. To achieve this, it is essential to find the minimal subset of gestures required by the different medical professionals, and adjust/extend the game accordingly. And it is important to investigate whether the user data collected during playing such a game can be automatically analyzed to provide an objective scoring for different components of the motor function assessment.

7 ACKNOWLEDGMENT

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