Out of reach? – A novel AR interface approach for motor rehabilitation

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Abstract

Mixed reality rehabilitation systems and games are demonstrating potential as innovative adjunctive therapies for health professionals in their treatment of various hand and upper limb motor impairments. Unilateral motor deficits of the arm, for example, are commonly experienced post stroke. Our *TheraMem* system provides an augmented reality game environment that contributes to this increasingly rich area of research. We present a prototype system which "fools the brain" by visually amplifying users' hand movements – small actual hand movements lead to perceived larger movements. We validate the usability of our system in an empirical study with forty-five non-clinical participants. In addition, we present early qualitative evidence for the utility of our approach and system for stroke recovery and motor rehabilitation. Future uses of the system are considered by way of conclusion.

Keywords: Augmented Reality, Therapy, Physical and Motor Rehabilitation

Index Terms: H.5.1 [Multimedia Information Systems]: Artificial, augmented, and virtual realities; J.3 [Life and Medical Sciences]: Health

1 Introduction

Motor deficits of the arm resulting in diminished quality of life are reported for approximately two thirds of stroke survivors [1]. The incidence of stroke worldwide involves some 15 million people a year [2]. It is the major cause of adult disability, with a prevalence of estimated 30.7 million people of which 12.6 million suffer from moderate to severe conditions [3]. Meeting the needs of such a large population is extremely challenging. Conventional therapies such as physiotherapy can and do help to improve a stroke patient's motor skills for everyday life, but outcomes are dependent on the severity of the stroke and the extent of the impairment. The sheer numbers of post-stroke patients, and often an accompanying lack of home support, make it imperative that other approaches are developed that can assist with psychological as well as motor rehabilitation.

This paper reviews recently developed mixed reality technologies that are being used to treat patients with various upper hand and upper limb impairments, and particularly those experiencing the early stages of stroke recovery. The use of virtual reality (VR) and augmented reality (AR) technologies for therapeutic purposes is an exciting and increasingly rich area for researchers, who are keen to explore the usability and utility of computerised environments as clinical intervention tools in health care contexts.

Following a brief overview of these technologies and the studies they involve, we describe a novel system that combines physical and psychological rehabilitation possibilities for the treatment of upper limb impairments, using a simple game in a controlled AR environment. We have named the system *TheraMem*. The *TheraMem* system utilises AR and casual gaming to help motivate upper limb improvement by engaging both motor and memory capacity in the early stages of stroke recovery.

Quantitative and qualitative studies are then presented to evaluate the usability and utility of the system. The results are encouraging and are discussed in the light of other AR work that has been used to "fool the senses" for therapeutic purposes. Future uses of the technology are considered by way of conclusion.

2 Related work

The phenomenon of neuroplasticity (the brain's ability to adapt its functions and activities in response to environmental and psychological factors) is a growing area of research for both neurologists and psychotherapists [4,5]. Mirror Box therapy, for example, is an approach that was developed during studies involving phantom limb experience [6] which often includes pain [7]. By mirroring the healthy limb, and giving the visual appearance of two limbs moving, the idea is to "fool the brain" into seeing two hands moving [46], thereby reducing the pain in a once clenched phantom hand by effectively removing that perception [7]. More recently conventional mirror box therapy has been extended through the use of VR and AR environments [8].

A number of case studies have been undertaken using such technology to treat people with chronic pain [9-11]; complex regional pain syndrome [12], trauma injuries [13,14], severe burns [15] and enhanced motor output in patients with unilateral stroke [16-23]. The latter have become the focus of our work, because VR and AR game applications are currently providing innovative and potentially useful technologies, capable of combining with conventional physiotherapy and psychotherapy rehabilitation approaches to treat hand and upper limb impairments following cerebrovascular events.

Mixed reality systems are showing promise as useful tools for physical, occupational and psychological therapists, particularly in the area of post-stroke rehabilitation [1,8,24]. While such systems target different dysfunctions resulting from stroke (for example, upper limb hemiplegia (paralysis of one side of body) and paresis (partial loss of movement); hand function; finger flexion, speed and strength; hand-eye coordination; wrist flexion and extension; shoulder motor control; arm and torso movement and so on), they appear to be based on two premises about rehabilitation:

1. That repetitive intensive practice is required for behavioural motor plasticity;
2. That underlying neuronal cortical reorganisation can be harnessed to aid recovery.

Recently published reports on a variety of VR and AR systems have demonstrated promising but non-significant results in small sampled pilot studies [25]. These systems include those which incorporate haptic feedback from the hand via sensors mounted in gloves [16,17,26,27]; those which allow the user to view a representation of their arm and hand via a head mounted display [21]; video-capture virtual and augmented reality technology [28-30] and a system which provides multimodal feedback in the form of visual and musical feedback [31]. To facilitate engagement with the technology, computer games have been incorporated; playing these games with the affected arm and hand encourages repetitive motor task practice, which is thought to be necessary to stimulate neuroplastic changes [32-38]. The motivational aspects of computer gaming also allow for cognitive engagement and challenge [39]. A recent study with twelve post-stroke patients used a virtual reality gaming system and reported an "improved proximal stability, smoothness and efficiency of the movement path". [40]

Given the technological possibilities of VR and AR and the ethos of gaming to help motivate stroke rehabilitation, we began to develop the *TheraMem* system, which is described in the following section.

3 THE THERAMEM SYSTEM

TheraMem is a hardware and software system based on the following general assumptions:

a) The system can be used for physical functional and motor rehabilitation, in particular for after-stroke therapy.
b) A simple computer game approach increases user motivation and may change individuals' perceptions and beliefs about their impairments.
c) Controlled amplification of the movement of an impaired limb can lead to improvement of motor movement and in particular the range of reaching and selection movements.

The hardware concept described in [41] enables decoupling the capture from the display of the hands. This concept underlies *TheraMem*, since it provides a controlled environment in terms of: (a) (non-) visibility of the user's hands; (b) lighting; (c) background subtraction and (d) augmented visualization as well as interactive control. The system is illustrated in Figure 2.

The system described in [41] is mainly used for mirror-box therapy applications, distinct from *TheraMem*. However, we based our development on this approach and extended it with the essential elements for the research presented here, in particular (a) the development and integration of a game environment and (b) the development of finger tracking to be used to (c) amplify the visual hand movements.

The user sits in front of two black boxes with hands placed in the two boxes as shown. Curtains mask the actual hands, both while resting and during movement. However, the hands are displayed in an augmented way on the screen above the boxes so that the participant can clearly view them. An operator (therapist or experimenter) sits beside the user and can control various aspects of the system using a keyboard and mouse which are linked to a second monitor.

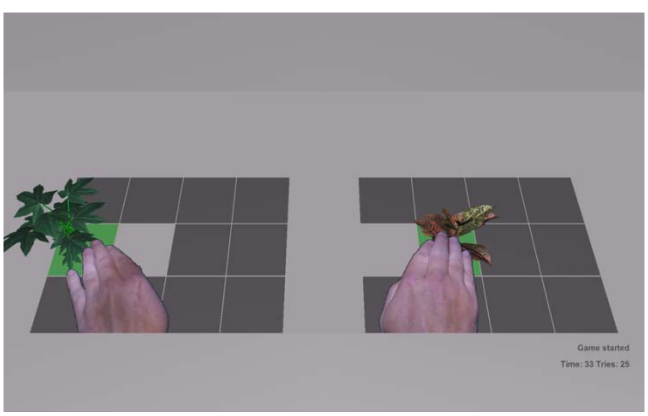

Figure 1: TheraMem screenshot - playing the virtual memory game

The user controls a virtual memory game using only the hands. In other words, no interaction devices are used. The game consists of two virtual boards with 12 (4x3) virtual cards (tiles) each. Tiles, colored in grey, are displayed "upside down" in the first instance in order to hide what lies "behind" them. By moving the hand(s) over the tiles, the user is able to activate a color change from grey to red. When the user places a hand over an individual tile and pauses for a short while, the tile flips over to reveal the content assigned to it (Figure 1). Moving the hand again returns the tile to its inactive (grey) state.

The content behind the tiles are 12 different 3D plant models, randomly assigned to each side of the system. When two identical plants (left and right side) are revealed, the tile board turns turquoise indicating a match. The matching tiles then disappear from the screen for the remainder of the game. Users are given the task of finding all 12 matching pairs. The number of attempts made to find matching pairs, and the time taken to activate them, are recorded and displayed on screen throughout the game.

Figure 2: TheraMem setup with user (left) and operator (right)

Apart from this standard mode of operation, the movement of the hands can be amplified for the left and right hands separately. Hence, a relatively small movement of the hand in the box can be displayed as a relatively large movement on the *TheraMem* board. We propose that this function supports the rehabilitation of motor movement skills. It occurs unbeknown to the user (participant) during a challenging and fun task which captures the user's attention. Less attention is paid to impaired movement, since the user focuses on the outcomes shown on the computer display.

The system architecture for *TheraMem* is detailed in the following section.

3.1 System Architecture

User hands are captured by two OTS USB web cameras inside the boxes. The two video streams are processed by the *TheraMem* application. The black box background is separated to extract the hand. Maximum finger position in the box (reach) is used to control the amplification of the displayed hand movement in a virtual 3D scene. The extracted hands are rendered on top of the virtual scene. The tracked finger (hand) position is used to trigger interactions with the virtual tiles. Both sides of the (single) 3D environment are displayed on the user's screen. Figure 3 presents a simplified schema of the architecture.

A standard, graphics accelerated desktop computer is used and two 22" LCD monitors provide a resolution of 1680x1050 pixels @ 60Hz.

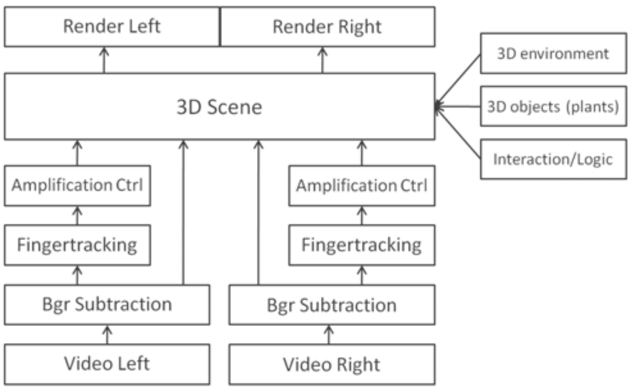

Figure 3: TheraMem System Architecture (simplified)

3.2 Hardware Box Setup

Two modified fiber-board boxes with a black finish were used to build the prototype. The front of the box was left open. A tailor-made curtain with a half length flap opening in the middle for the hands was fixed to the box with Velcro strips so that the height of the curtain could be adjusted (Figure 4).

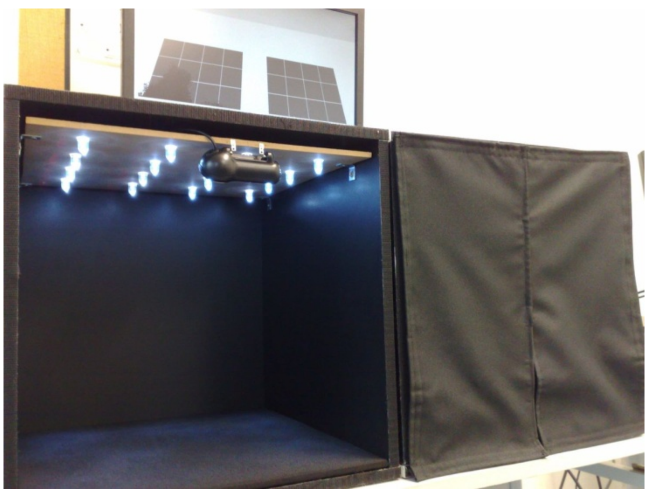

Figure 4: TheraMem box: left open, right closed with curtain

A wide-angle webcam is mounted to the top of the box in order to capture the interior. Lighting consists of an array of 4x4 high power LEDs – an optimized trade-off between brightness, diffusion and lighting characteristic to enhance the texture of the hand. The LED's are low voltage and low temperature. The floor of the box is covered by a wooden board tightly wrapped in pitch black, matte cloth. This setup allows for maximum control of the light for effective and efficient background subtraction.

3.3 Hand Extraction and Finger Tracking

The webcams capture the interior scene using 640x480 pixels at a frame rate of 30 Hz. In order to show the hands in the virtual environment, the hands must be extracted from the background. The black background is subtracted by brightness. No artifacts are normally visible and there is no noticeable delay or drop in frame rate. However, when there is a considerable opening of the curtain or the user's hands are very dark (skin color) some artifacts may be visible.

A four channel RGBA video stream is used where all background pixels are set to full transparency to give the illusion of the user's hand acting in front of the virtual scene (see Figure 5).

Because of the well controlled lighting conditions, it is possible to track finger position accurately. Each video frame is analysed using the OpenCV library to find the fingertip extremities. Only one maximum position of the fingers is needed to control the desired amplification effect. The video frame is searched up-down from left to right. Pixelwise comparisons of the RGB values against a pre-defined threshold for vertically neighbouring pixels lead to the computation of the maximum finger position (up-down direction in video coordinate system). This determined pixel position is computationally back-projected into the box space (result in x/y-centimetres). Both the camera (intrinsic) and the relation of camera and box coordinate systems (extrinsic) were calibrated in an off-line process using homogeneous coordinates.

The result is a projection matrix, which solves the calculation to determine the pixel position in the box space. We use a homography matrix which gives us the relation between the two spaces, assuming that the box space is flat. Usually the calculation of the homography matrix has to be done only once when the system is built. The computation of the projection matrix, i.e. the intrinsic and extrinsic coordinates of the camera, is based on Zhang [42]. We use a chessboard (the size of the bottom of the box) to get accurate results for the camera parameters. After computing the projection matrix, i.e. the intrinsic and extrinsic parameters combined in a matrix, the homography matrix can be extracted from the projection matrix by deleting the third column of the rotation matrix, which leads to a square matrix.

It is more accurate to compute the x/y-centimetres with the homography matrix than with the projection matrix. Because of the position and rotation of the video surface in the virtual environment (Section 3.4), another coordinate correction step is needed to align the visual with the actually tracked position of the fingertip. Given that the angle of view on the virtual box does not change, the rotated video surface can be seen as a distorted surface on the bottom of the virtual box, without the rotation. The goal is to fit the virtual box into the captured box on the video surface. This fit is achieved with another homography matrix, which has to be computed beforehand using at least four corresponding pairs of points. The corrected x/y value represents the maximum reach of the user's hand in the box environment and is used to control the interaction and amplification.

To test the accuracy of the finger tracking a virtual object, a sphere with a radius of 10 mm, was added to the scene. This object was moved accordingly to the finger movement within the plane of the virtual memory game. Even though there is a slight offset between the fingertip and the sphere developing when moving towards the plane borders (see Fig. 5), the fingertip was always within one half of the sphere, indicating a deviation up to 10 mm for the finger tracking. This accuracy was seen as sufficient because the tiles of the memory game do not require highly precise pointing to be activated.

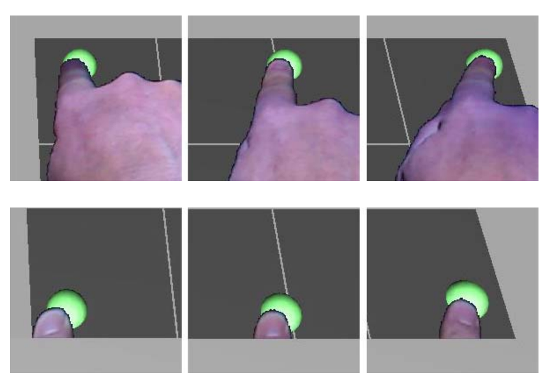

Figure 5: Estimation of accuracy of fingertracking.

There is no noticeable latency and we could measure a stable frame rate between 20 and 22 frames per second using the debug version of the system.

3.4 Augmented Reality Environment

The 3D scene consists of three main elements:

(1) The box environment defining the world coordinate system in which the basic geometry of the 12 tiles (per side) is rendered;
(2) The 3D objects (plants) to be rendered on pre-defined (randomized) tile positions;
(3) The two video planes showing the extracted hands as augmentations in the scene.

In addition, two grey faces function as blinds to restrict the user's view into the environment, according to the size of the video planes. (Figures 6 and 7)

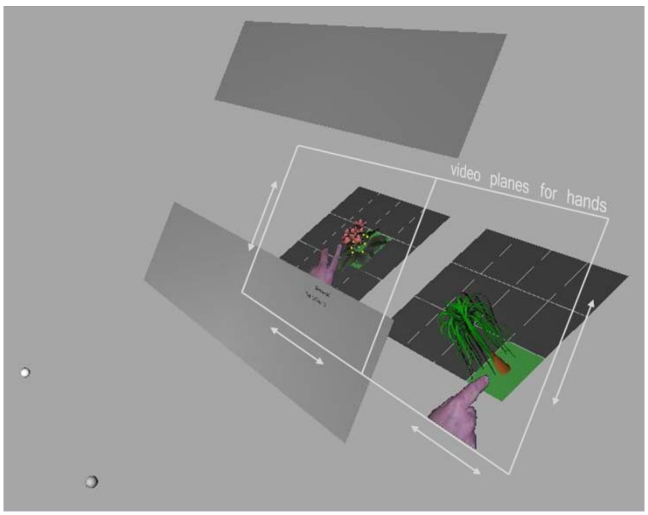

Figure 6: 3D Scene: Side Perspective (with plane illustrations)

The two video planes are placed in the front of the scene rather than the more usual back. Together with the background subtraction, this placement allows the hands to occlude the virtual scene.

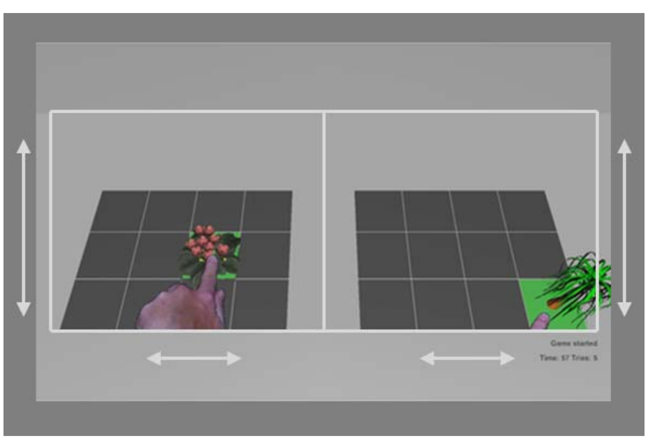

Figure 7: 3D Scene: User's Perspective (with plane illustrations)

The tiles are part of the box environment and rendered as grey squares in the first instance. If the determined fingertip position is within the limits of a particular tile, an action is triggered and the tile becomes red. If a tile stays activated for a brief moment, a pre-loaded model is switched on in the scenegraph as in Figure 7. If the plants on the left and right hand sides match, a "celebrate" action is triggered. All tiles subsequently change color and the two matching tiles are removed from the scenegraph rendering.

The 3D plant models were purchased from exchange3d.com as c4d files and had to be converted into Open Inventor objects. First they were loaded into *Cinema4D* (Maxon Computer GmbH) and exported as VRML 2.0 geometries. Right Hemisphere's *Deep Exploration* was then used to manually move the pivot points of the model and export them as VRML 1.0 models – a format equivalent to *Open Inventor*. A unified scaling (same size in virtual environment) was achieved by manually editing the VRML files. The resulting 12 geometry files are loaded on program start-up and managed in an *Open Inventor* switched scenegraph.

3.5 Amplification of Hand Movements

In order to implement the desired 'amplification' effect of the movement of the hands, the fingertip position was used to control the movement of the entire video plane in relation to the virtual environment vertically and horizontally. An amplification value controls the amount of plane movement in relation to the fingertip movement. If this value is set to Zero, the video plane stays at its initial position in virtual space. If an amplification value f is defined (f>0), the plane moves in its x and y directions: $s_{new} = s_{ori} * (f+1)$. This setting gives the impression of a "faster" moving hand and further reach in relation to the virtual board.

Because of the simple, but real-time efficient, way of determining fingertip positions (see Section 3.3), some jitter can appear depending on the color of the skin and fingernails and the position and orientation of the hand. This jitter can be filtered out by time-dependent averaging over a small number of video frames. Visual clipping of the hand around the wrist can occur due to the limits of camera capture, but this effect was unnoticed by users. The amplification value can be controlled independently for x and y for both hands separately. During informal testing, we established that a range of about 0.0 – 2.5 for the amplification value provided convincing results. In a clinical setting the appropriate value would be controlled by the therapist operating the system depending on the patient's condition and progress.

The *TheraMem* system is controlled with a graphical user interface on a second monitor (operator screen) by keyboard shortcuts and through an XML configuration file, loaded on start-up. The main interface functionality of the system is limited to (a) start a new game (randomized assignment of the 12 VRML models to the tiles) and (b) setting the amplification values for the left and right hands (usually by keyboard shortcuts selecting pre-defined value sets). A log file is written containing all interactions (including time stamps). The time elapsed as well as the current number of tries is displayed on the bottom right corner of the screen.

All main configuration parameters (e.g. amplification values, thresholds, game behavior) are externally stored in a readable XML file. Meaningful parameters were determined during system testing and iteratively refined. For instance the time for a plant to appear was set to 800ms and a threshold distance above which a movement of a finger should be considered as such was set to 2 millimeters.

4 USABILITY EVALUATION

After technically testing and bug-fixing the system, a usability test was designed, targeting the effectiveness, efficiency and satisfaction levels involved in using the system.

Questions used to establish the effectiveness of the system included: (a) Is the simple memory game playable? (b) Can all matching pairs be successfully located? (c) Is the game still playable if hand movement is amplified? (d) To what extent is amplification noticed by users and does this detract from the game?

Efficiency was determined by (a) the reaction time of the system to user interaction, (b) the reaching and selection performance of the system and (c) the time and number of attempts required to complete the task.

Satisfaction was determined by (a) the perceived ease and enjoyment of use, (b) the perceived effectiveness and efficiency of game play, and (c) the perceived comfort and level of mastery and control of the system.

4.1 Experiment Design

The experiment used two, subsequent within-subject, one-factor, repeated measure designs. The order of the within-subject conditions was randomized. Part B of the experiment was a slightly modified version of Part A. The goal of the experiment was to investigate the effectiveness, efficiency and satisfaction of the system [43].

4.2 Participants and Task

The participants were asked to play several rounds of the virtual memory game. The game was chosen because it: (a) can be used to evaluate reaching and selection performance, (b) is mildly challenging and therefore potentially motivating for patients in the early stages of stroke, (c) can be played by most age groups, (d) is not gender-specific and (e) is easy to learn and understand.

Forty-five participants (10 female and 35 male) took part in the usability study – 22 in Part A and 23 in Part B. Two participants (1 male and 1 female) were excluded because of vision and age eligibility criteria. The age of the 43 participants ranged from 21 to 69 years ($M = 37.8$, $SD = 13.5$).

Participants had no prior knowledge of the experiment. They were recruited from academic, administrative and technical staff and graduate students from different university departments. Participants were required to have normal, or corrected to normal vision to be eligible.

4.3 Conditions and Apparatus

Only movements of one hand were amplified because of our targeted application scenario of post-stroke rehabilitation which in general is characterized by unilateral impairments. Two independent variables were altered during the experiment: (1) the amplification value of the left hand as a within-subject condition and (2) prior knowledge about the amplification as a condition of Part B.

During Part A, the participants were not told about changes in amplification; they were simply informed that some technical changes were applied in between the rounds. During Part B, participants were explicitly told that their hand movements were amplified. They were not informed about which hand was being amplified or to what degree. In both parts (A and B), the repeated within-subject condition amplification value was altered in the same manner. Conditions 1 – 5 had the following factors assigned in randomized order: 0.0, 1.0, 1.5, 2.0, and 2.5. While in real-world use those amplification values would be tailored to the specific case and current condition and progress of the patient, we covered a very wide range of possible difficulties of hand movements using the set of amplifications defined here.

Two self-report questionnaires and an interview questionnaire were designed. In addition, semi-structured observations by the experimenter were recorded in a log book.

A *Participant Demographic Survey* questionnaire was administered to assess possible confounding variables like age, gender, handedness, and familiarity with the game. The *Post-Study Questionnaire* was divided into two sections. Section 1 aimed to elicit any perceived differences amongst conditions. Part 2 used 7-point Likert-scales to assess the usability of the system. The items were selected and adapted from IBM's usability satisfaction questionnaire [44]:

- Overall, I am satisfied with how easy it is to use this system (PS4)
- It was simple to use this system (PS5)
- I could effectively complete the tasks using this system (PS6)
- I was able to complete the tasks quickly using this system (PS7)
- I was able to efficiently complete the tasks using this system (PS8)
- I felt comfortable using this system (PS9)
- It was easy to learn to use this system (PS10)

A *Session Self-Report Sheet* was used to determine: (1) overall ease of use of the system; (2) difficulties in reaching the tiles; (3) difficulties in tile selection; (4) the timeliness of selection feedback; (5) the timeliness with which the 3D models (plants) appeared and (6) the perceived sense of enjoyment/fun experienced when using the system. In Part B, (4) and (5) were replaced with questions about the perceived speed of the right and left hands, when the participants had prior knowledge of amplification. The time taken and number tries involved in each round of the game play were also recorded.

For Part A, it was expected that:

- Participants would be able to complete the game successfully with or without amplification.
- Participants would notice and remark on the amplification.
- The reaction times of the system, the selection and reach performance and the overall usability would be rated clearly above midpoint.
- An increase in amplification would lead to an increase in the number of tries needed, but would lead to a decrease in ease of use, reachability, selectability, and sense of fun using the system.

In Part B, participants were given prior knowledge about amplification. Assumptions included:

- Participants would have the ability to rate the amount of perceived amplification.
- Game performance could strongly influence participant success, with quality and user ratings affected by a low number of tries and shorter completion time.
- System usability would not be affected by age.

4.4 Procedure

The experiment was conducted in a room where the system was the only equipment on show. On arrival, all participants were informed about: (1) the rehabilitative prospects of the *TheraMem* system; (2) the nature of the experiment, which was to evaluate its usability rather than therapeutic applications; (3) ethical approval and anonymity; (4) the experimental procedure, including reading an information sheet, signing a consent form, completing the *Demographic Survey*, and reading the task description. Questions about any aspect of the procedure were encouraged.

The experimenter explained the system set up, showed the content of the boxes (empty apart from camera and lights), and demonstrated how it works. Instructions were given to ensure the system was operated with a flat hand or index finger on the floor board of the box, rather than with the hands in mid-air. Participants were required to practice in a 'warm-up' round, where acceleration factors for both hands (and for x and y) were set to 1.0.

Once participants understood how to play the game, the procedure for 5 rounds of the game was explained. The amplification value was set according to the pre-defined randomization list and the game was initiated. During play, the experimenter logged any observations, including: (a) the occurrence of jitter or other artifacts, (b) the search strategy used by the participant under different conditions, and (c) any indicators of behavior due to different amplification effects.

Each round of the game lasted between two to four minutes. After completing each of the rounds, the participants were asked to remove their hands from the boxes. They were then asked to answer six *Session Self-Report Sheet* questions, using a scale from 1 to 10. In the process of asking the questions, the sheet was made visible to the participant so s/he could see how s/he answered in previous rounds to give a relative (differential) judgment.

Following the fifth round, the participants were given the *Post-Study Questionnaire* to determine if any noticeable differences could be detected, whether and what factors might have demanded their attention, and whether they felt distracted or maintained full concentration when playing. They were also asked about how the system changed across rounds.

Finally, the participants were informed about the actual difference between the conditions presented and were asked not to reveal this to their peers in the immediate future. They were also asked about their interest in receiving the results of the study and their willingness to participate in future studies. All participants were thanked and given a chocolate bar. In total, each session lasted for 30 – 45 minutes.

4.5 Results

Data from the five amplification conditions were subjected to a repeated measures General Linear Model (GLM in SPSS 18), using part of the experiment as an additional between subjects factor, and age as a covariate. Our analytic strategy was to check for linear and quadratic effects of amplification and their moderation by comparing the two parts (A vs. B) of the experiment. Thus, the analysis followed a 5 (amplification: within) x 2 (part: A vs. B, between) x age (covariate) design. Higher order polynomial contrasts (above quadratic) and their interactions were not of further interest. When single conditions were compared, these comparisons were based on estimated marginal means, using the degrees of freedom of the complete analysis, adjusting for covariates, and with p values corrected to avoid inflated Type I error (computed with GLM EMMEANS in SPSS using SIDAK correction). Handedness was not included in the analyses as the sample sizes of non-right handed people were too small. Effects that are not mentioned were not significant.

Experimenter-recorded ***time to completion*** showed a marginal linear increase with increased amplification: from 134 (SD = 18) sec at amplification 1 to 142 (SD = 22) at amplification 5, $F(1,40) = 3.4$, $p = .072$. Time also marginally increased with *age*, $F(1,40) = 3.68$, $p = .068$. The number of ***tries*** increased significantly and linearly with amplification, from 53.5 (SD = 8.7) to 55.6 (SD = 10.9), $F(1,40) = 6.75$, $p = .013$. This increase was stronger in Part A.

Ease of ***reaching, selecting, and general use*** was averaged for each condition and internal consistencies were high (all Cronbach's $\alpha > .80$). The effects of amplification on this score differed between conditions, as indicated by an interaction of the experimental part with the quadratic trend. Participants in Part A (not informed about the amplification) showed a quadratic trend such that experienced 'ease' was highest in condition 2 (moderate amplification), and similarly low in condition 1 and 5 (i.e. low and high amplification, respectively). For participants in Part B, who were informed about amplification, subjective 'ease' decreased with amplification, with conditions 1 and 5 differing significantly, $t(40) = 3.96$, $p = .003$. Nevertheless, scores were always well above the midpoint of the scale, as was the mean taken across conditions, $M = 6.9$ (SD = 1.52), $t(42) = 6.1$, $p < .001$ (Figure 8). Age was a significant covariate, with subjective 'ease' increasing with age, $F(1,40) = 4.50$, $p = .040$.

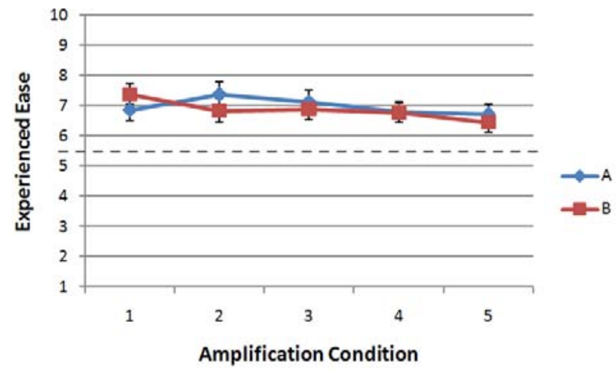

Figure 8. Averaged experienced ease of reaching, selecting, and use (Estimated Marginal M +/- 1 SE, range 1-10) depending on Amplification Condition and Information about Amplification (Experimental Part A: not informed, Part B: Informed); Scale midpoint at dashed line.

Enjoyment of the system showed an unmoderated quadratic trend, $F(1,40) = 4.93$, $p = .032$. More enjoyment was reported for medium amplifications than for very low or high amplifications. All scores were well above the midpoint, as was the average, $t(42) = 9.17$, $p < .001$ (see Figure 9).

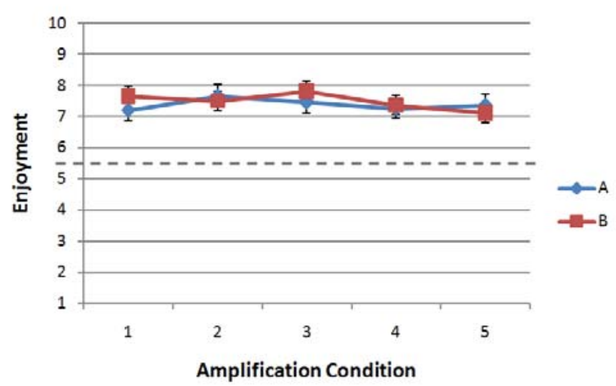

Figure 9. Enjoyment of using the system (Estimated Marginal M +/- 1 SE, range 1-10) depending on Amplification Condition and Information about Amplification (Experimental Part A: not informed, Part B: Informed); Scale midpoint at dashed line.

The main finding from these analyses is that both scores were consistently and significantly above the midpoint of the scale in all conditions (as illustrated by the error bars in Figures 8 and 9). We also found unpredicted quadratic relationships: 'ease' and 'enjoyment' not only decreased with increasing amplification (which was expected), but they were also lower for zero amplification. We return to this finding in the discussion.

In Part A, we also tested whether the experienced ***timeliness*** of the system was high and depended on amplification. The experienced timeliness of selection changes and appearance of new objects (plants) was assessed. When analyzing these changes in a 5 (condition) x 2 (aspect) repeated measures GLM, we found no significant effects; the effect of amplification was not significant, and the ratings did not differ for the two aspects. After averaging the two scores, the mean of timeliness judgments was 6.74, well above the midpoint of the scale (5.5), $t(19)=3.71$, $p = .001$, indicating that changes were experienced as 'timely'.

Answers to the 7 **satisfaction** items were analyzed separately and in combination. When analyzing the items separately, averages were significantly above the midpoint of the scale (4), all $t(42) > 5$, all $p < .001$ (see Table 1).

Table 1: Means, standard deviations and t-values for satisfaction components

Variable	*M*	*SD*	*t*
Satisfaction (average)	5.61	1.03	10.30
PS4	5.23	1.25	6.46
PS5	6.05	1.19	11.24
PS6	5.74	1.29	8.85
PS7	5.07	1.18	5.93
PS8	5.05	1.27	5.40
PS9	5.56	1.47	6.96
PS10	6.58	1.01	16.83

We also averaged the 7 items and tested them in separate analyses, depending on which part of the experiment participants were involved in and their age. Part A had no influence and age was a marginally significant covariate with a tendency for older participants to be more satisfied, $F(1,40) = 3.17$, $p = .083$.

In Part B, we asked participants to estimate the ***perceived speeds of the left and right hands***. Recall that we amplified movement of the left hand only; effects on the speed of the right hand are thus completely due to cognitive processes. We analyzed these estimates in a 5 (condition) x 2 (hand) GLM and found that with increased amplification, the perceived speed of the left hand increased, while the perceived speed of right hand decreased slightly. This finding was confirmed by a significant interaction of hand with the linear contrasts for these trends, $F(1,22) = 4.33$, $p = .049$; the linear trend was not significant for either hand on its own. At amplification 1, there was no significant difference in the perception of the speed of the left and right hands., but at amplification 5, the left hand was perceived to be faster than the right hand, $p = .043$. We surmise that attention is differentially allocated to the two hands, as suggested in [46].

4.6 Discussion

We tested whether participants were able to play a memory game in *TheraMem* without distraction, while varying amplification of the left hand movement. Some participants were informed about the amplification, and others were not.

Results suggest that the system was usable with subjective ease and satisfaction in all conditions, independently of the degree of amplification. We also found nonlinear effects regarding the differences between the amplification condition and the effects on perceived hand speed. All participants completed the task successfully (five rounds of memory game play), even with high amplifications of the left hand.

Efficiency measures for the system are supported by the questionnaire results. Perceived reaction times, reported ease of reaching, selecting and general use was above the midpoint. User satisfaction was measured with a reliable and robust scale [44], with participant ratings also clearly above the midpoint.

For amplification conditions, slight amplification was better rated than both higher amplification and no amplification, but only when participants had not been informed in advance. A possible explanation is that this amount of amplification was perceived as fast in terms of interaction speed, but not too disturbing in terms of decreased interaction quality (reach, select). It is also possible that an amplification of 1 did not result in a 1:1 scale representation of the real to augmented environment. Further testing is required to investigate this matter.

In Part B and when the perceived speed of the hands was assessed, not only did the left hand appear to accelerate with increased amplification, but the right hand also appeared to slow down. Studies with larger sample sizes are needed to investigate this more rigorously. Given differential deployment of attention to the hands, this effect also has implications for therapeutic practice that need to be further investigated.

The usability of the system was not only not impeded by age (consistent with our hypothesis), but actually **seemed to be enhanced** with age. Because our targeted population is rather mature this can be seen as a good result.

Even though we could not compare our system to an existing baseline, because our approach is novel and is intended to be used as an adjunct to existing methods, we could clearly demonstrate its general usability.

5 Utility Evaluation

Usability is a necessary but not sufficient prerequisite for the usefulness of a technology. We were interested whether scholars and students, clinical experts, and practitioners in physiotherapy would confirm our assumptions about how the system could be used in physical rehabilitation. We also wanted to explore other potential applications for the system. Hence, we participated in a 'hands on' workshop where physiotherapy students could use our system. Two group workshops were conducted with academic and practicing physiotherapists. Individual interviews were also conducted with seven experienced physiotherapists.

5.1 Student Evaluations

Student evaluations were undertaken as part of a post-stroke rehabilitation workshop that was conducted over one week. The workshop consisted of various supervised stations that introduced 100 third year students to equipment, technology and techniques that could be used in post-stroke rehabilitation, including mirror-box therapy, a Nintendo Wii game, a bimanual electronic device, a bimanual mechanical device, various manual games, and our *TheraMem* system.

Students worked in groups of three to five people and took turns to act as the "client", the *TheraMem* system operator ("therapist") and a note-taking observer. They were invited to fill in a brief questionnaire describing how they would:

(1) Explain the system to peers in a brief statement; (2) Envisage the system being used for motor rehabilitation and (3) Define a satisfactory outcome as a result of using the system in therapy. All and any other comments were also invited.

After four 2 hour sessions, 79 completed questionnaires were returned. Seventy six students described the system and game in a way that was clear and succinct. Ninety nine percent of the sample reported that they thought *TheraMem* could be a potentially successful adjunct therapy for motor and post-stroke rehabilitation.

Other anticipated uses for *TheraMem* included treatment of cognitive deficits, spatial awareness deficits, traumatic brain injuries, post upper limb surgery, agnosia (difficulty recognizing familiar objects or people), and physical neglect (e.g. ignoring one

side of the body). Observed and reported feedback was positive and encouraging:
"Best neuro lab ever!"; "It is so cool"; "Great fun."; "It's fun! Not boring like most exercises we give patients."

5.2 Group Workshops

Two one hour workshops were prepared involving a brief introduction to the *TheraMem* concept and system. These sessions included a PowerPoint seminar type presentation, a live demonstration of the system and the opportunity for the attendees to try *TheraMem* for themselves.

The first workshop involved approximately 20 people, including academic staff, postgraduate students, and clinical staff of the School of Physiotherapy. The second workshop was presented to six members of a professional 'Neuromuscular Special Interest Group'. The sessions were facilitated by three of the authors and were also voice recorded. The sessions were run discursively and participants were invited to give general feedback, their views on the utility of the system for post-stroke rehabilitation, and suggestions for the potential of *TheraMem* for wider use.

Responses were unanimous in agreement that the system could be used in the early stages of post-stroke rehabilitation, which is often when motivation and movement need to be actively encouraged. While the system is still a prototype, it was judged to be mature enough for use in clinical interventions. The game character could assist with the kind of continuous practice and repetition that is required for post-stroke treatment. People with early stroke can often move a little, but do not think they can. A small movement that is magnified may be stimulatory. However, some sort of (mechanical) support for the (lower) arm may be needed for our system, though if there is very little hand movement shoulder proprioception can be used instead.

Other potential applications identified by workshop participants included the treatment of cerebral ataxia, where patients could have their movements viewed on screen as slowed and less jerky by the system. Amplified hand movement can also show limited reach and extension as a much bigger movement in a virtual environment. Because the game element of *TheraMem* has a cognitive element, it could also be used by patients with cognitive deficiencies or disabilities. The current game may need to be modified for this purpose in terms of the number of tiles, colors, or objects shown. For instance, a very simple color matching game without any geometry was suggested for patients who are cognitively impaired. Patients with sensory deficiencies could be provided with acoustic and (passive) haptic feedback along with visual stimuli. An AR system that could provide adjunct support for everyday functional tasks such as gripping a ball, holding a cup or manipulating small objects was considered to be very desirable.

5.3 Guided Interviews

Seven experienced practitioners were individually interviewed by the first author. Their fields of practice included physiotherapy, neuromuscular rehabilitation, and rehabilitation medicine, with specializations in post-stroke rehabilitation and traumatic brain injuries (TBI), spinal cord injuries (SCI), chronic pain, hand therapy, prehabilitation (rehabilitation before surgery) and post-operative rehabilitation, including therapy with amputees. All of the interviewees were clinical practitioners with 2 to 30+ years of experience.

An *Interview Guide* [45] was prepared to ascertain:

- Whether the experts understood the nature of the *TheraMem* technology and how to use it as both client and operator.
- The rated usefulness of *TheraMem* for post-stroke rehabilitation and other possible applications.
- The technological and therapeutic advantages and disadvantages of the system.
- Future uses for the technology and future features they would like to see.

Having seen the system in operation some three weeks earlier, interviewees were sent the guide to help consider their responses. General impressions of the system were elicited at the outset of the interview, followed by a structured set of questions based on the guide. Each interview took between 30 and 60 minutes and was voice recorded.

All the interviewees reported that they understood how to use the system with would-be clients. They also indicated some enthusiasm for putting *TheraMem* to use immediately with actual patients. Functionality was reported as unproblematic and the operations of the system (GUI and keyboard shortcuts) were considered to be of appropriate and manageable complexity.

The application potential for *TheraMem* was highly rated, especially for post-stroke and general motor rehabilitation. Other named conditions with therapeutic potential included: ataxia (inability to coordinate muscular movement); complex regional pain syndrome; phantom limb pain; cerebral palsy (muscular impairment, speech and learning difficulties); Spinal Cord Injuries (SCI), Traumatic Brain Injuries (TBI) and cognitive disability.

A key advantage for *TheraMem* was seen to be its ability to achieve a therapist controlled neuroplastic effect though the amplification and mirroring of limb impairments. However, the mixed nature of motor and cognitive challenges built into *TheraMem* was considered as unlikely to suit all patients and conditions. The ability to handle real and virtual objects within the *TheraMem* space was rated as "highly desirable".

Suggested possible future enhancements for the technology were: the incorporation of more sense-related features (acoustic, tactile), cognitive therapy scenarios and the development of alternative games and AR environments. We are confident that further research will yield many further application possibilities.

6 Conclusions and Future Work

TheraMem is a novel system which combines Augmented Reality, a simple computer game, and spatial-visual decoupling of the user's hands for use in post-stroke rehabilitation. The system is considered to be mature and usable in the early stages of stroke recovery. The system also adds to the growing evidence that virtual and augmented technology can be used to "fool the senses" and to "fool the brain" with a (good) purpose. For example, Hoffman et al [15] explored the adjunctive use of water-friendly immersive reality to distract patients from their pain during wound debridement. Feintuch et al. [10] used their system to enable limb impaired patients to see themselves within a virtual environment. The impaired arm is replaced by a virtual arm. While making small movements with the paretic arm, the patient views an image that performs a healthy full range of movement using the virtual arm. Plastic changes in the brain are hypothesised as leading to reduced pain and improved limb function. Slater et al. [47] reported on how the normal association between touch and its visual correlate can result in the illusory perception of a fake limb as part of one's own body. An illusion of ownership of a rubber hand is commonly reported when touch is seen to be applied to the rubber hand, while felt synchronously on the corresponding hidden real hand.

Our own platform can be used to teach memory skills as well as an awareness of impairments. It can also potentially contribute to research that seeks to measure functional disabilities. Hence, encouraged by the feedback and support of our participants, students, colleagues, and experts, a clinical research phase has been initiated. This research has been approved by the national Health and Disability Ethics Committees (LRS/10/10/044). It is supported by the University of Otago Schools of Physiotherapy and Physical Education and a small number of local physiotherapy and psychotherapy practice offices. The importance of developing scientifically sound and effective procedures and protocols for this work cannot be overstated.

Perhaps the biggest challenge we have encountered to date has been to forge a single solution from a number of different but essential disciplinary inputs. These include integrating the application of a systematic psychotherapeutic approach to physical rehabilitation, an interactive, motivational and computerized game-based system, and the computerized support of well controlled and repeated physical rehabilitation tasks.

The therapeutic effectiveness of our approach needs to continue with the series of case studies we have launched, as a precursor to full and robust clinical trials. We look forward to reporting the outcomes of this work in due course. The future for *TheraMem* thereafter will depend on its efficacy in therapeutic practice and its usability and utility for the benefit of patients post-stroke or those with other types of limb impairment.

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