Augmented Reality

Visual manipulations 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 poststroke. Our Augmented Reflection Technology (ART) system provides an augmented reality environment that contributes to this increasingly rich area of research. We present the current set of technological capabilities of the ART system exemplified in two experimental laboratory studies as well as a prototype system built on top of ART which “fools the brain” by visually amplifying user’s 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 the first 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.

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.

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 our Augmented Reflection Technology (ART) system that combines physical and psychological rehabilitation possibilities for the treatment of upper limb impairments. Based on the ART we implemented our TheraMem system, integrating a simple game in a controlled AR environment. The TheraMem system utilises AR and casual gaming to help motivate upper limb improvement by engaging both motor and memory capacities in the early stages of stroke recovery.

Quantitative and qualitative studies are then presented to evaluate the usability and utility of the system followed by clinical case studies with volunteering post-stroke patients. 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]. The Mirror box therapy, for example, is an approach that was developed during studies involving phantom limb experience [6] which often includes pain [7]. Here, an optical mirror is placed vertically between the healthy and impaired limb giving the visual appearance of the impaired limb moving in a healthy way—the idea is to “fool the brain” into seeing two limbs moving [46], thereby reducing the pain in a once clenched phantom hand by effectively

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substituting that perception for example [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 and
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 feedbacks [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 for stroke rehabilitation, we developed the Augmented Reflection Technology system, which is described in the following section.

3. Augmented Reflection Technology system

Based on [41,48] we have developed an extended system which allows for a visual decoupling of a user’s displayed hands from their real hand, including different forms of visual manipulations. Instead of using direct line-of-sight AR (e.g. with video or optical see-through displays) we hide the user’s hands behind curtains, capture real-time video information, manipulate the video streams, embed them in a different environment and display the manipulated results on a computer monitor. This approach has some advantages over a head-mounted display system, namely:

1. It is more affordable and easier to use in a therapeutic setting since it has a lower degree of instrumentation, is more comfortable, provides a high display resolution, and does not require a tracking system.
2. The achievable overall background subtraction quality is higher. Because of the fixed real and virtual camera positions and the well-controlled lighting conditions robust hand visualisation is possible.
3. Compared to an optical see-through solution, the system allows for (a) fully opaque virtuality and reality overlay, (b) precise augmentation (fixed camera) and (c) can substitute different visual aspects for the purpose of decoupling.

The hardware setup of the system, which we refer to as Augmented Reflection Technology (ART), is presented in Fig. 1.

The client or user is placed in front of two black boxes that are equipped with curtains, lighting and off-the-shelf high-quality web cameras (left side of set-up). After placing their hands through the curtains, users can see their hands on the screen positioned on top of the boxes. An operator (therapist or experimenter) controls the system using a keyboard and mouse on a separate monitor (right side of set-up). The user cannot see her or his hands directly, except as mediated by the ART system and the operator. This set-up allows for a wide range of ways to control what is visible to the client. The kinds of manipulations that are possible are described in the following sections, with therapeutic applications of particular research interest.

3.1. Mirroring

The Mirror Box therapy can be simulated by ART in a video-mediated way. In optical mirror box therapy, patients place their impaired hand or limb behind a vertically placed mirror. By positioning the healthy hand or limb in front of the mirror and looking at the reflection, it is possible to create the illusion of two healthy body parts. This effect has been used therapeutically to mitigate pain and improve movement.

The ART system uses video streaming to record the healthy hand and display it on the monitor next to other (impaired) limb. We use the system to confuse the clients about which of their hands is being displayed, which hand is on which side of the screen and whether users are willing to take ownership of the hands they see. In empirical studies [41] we demonstrate that our system is able to “fool the brain” by having users take ownership for the hands on the screen. We can also swap and mirror either hand, thus enhancing the illusion. This effect cannot be achieved with an optical setup. The operator’s interface allows the manipulation of
(1) hand visibility (video image or blank), (2) projecting the hands on different sides of the monitor (left, right) and (3) mirroring the hands (none, left, right, or both).

3.2. Appearance

There is evidence that a manipulated presentation of one’s limb can influence the perception of an impairment or pain. For example, the perceived size of the hand can change the level of pain experienced in disorders such as phantom limb pain [51] and complex regional pain [52]. Using the graphics plane on which the hand is visualised, ART can create the impression of different hand sizes. It can also be used to modify colours. In complex regional pain, for example, the skin colour of the affected body part differs from that of healthy tissue. In the initial stages of the disorder the skin may simply be red, but changes to pale or livid colours in the chronic phase of the condition [53]. ART can change the colour and brightness aspects of the displayed limb to accommodate this kind of change. It can also create similar effects to the visual stimuli used by Moseley and Arntz [54] to influence pain ratings. For example, red cues evoked more unpleasant and intense pain than blue ones. Other spatial manipulations using ART allow the operator or therapist to actively move the client’s hand vertically or horizontally in addition to her or his own movements. Hence, the therapist can supplement movements of the impaired hand to progress therapy.

While they have not been implemented as yet, other useful movement manipulations could well include the amplitude of shake (e.g. for tremor treatment), the ability to change the pace and delay of hand or finger movements, the ability to accelerate or slow down particular movements and actions initiated by the client.

3.3. Environment

The way therapeutic progress is achieved is determined by the virtual (augmented) environment in which the client’s hands are operating. We support the loading of 2D images (background manipulation) or 3D models (scene manipulation). Fig. 2 shows the client’s view into the environment side-by-side with a system’s (3D) view of the scene. In the upper row, a blue pattern is used as a background image in combination with a computer-generated 3D grid. The hands are operating in front of the virtual content. For 3D model loading the 3D (physical) box space is remodelled and additional 3D elements are displayed, in this case using 3D models of a car and a cardboard box. Additional virtual blinds restrict the user’s view to the frustum given by the camera streams; that is, the virtual environment is shown only where hands can be displayed.

Both manipulations, image and 3D model, can be combined.

3.4. Sensory manipulation

The stimulation of sensory channels plays an important role in the therapy. The feeling of touch or being touched and the experience of different temperatures are used for therapeutic purposes. ART inherently supports some of these sensory features. Touching or stroking a client’s hand is possible because the boxes can be opened at the back, giving access to the therapist or operator. This feature also allows tangible objects to be introduced and grasped by the client. Tangible (real) and virtual objects can be combined, by showing a different textured surface in virtuality from the box itself to the colour of tangible objects in a way that hides or displays different aspects of their surface; for example, black surface parts become transparent, because they will be considered as background.

3.5. Ownership, immersion, presence

The degree to which a client can be immersed in the system and is intentionally confused about the ownership of her/his limbs is fundamental to our approach. Immersion, the technical aspect of manipulating one’s sense of being (partly) part of a virtual environment (presence), is influenced by factors like the size, position and resolution of the display(s), the presence and degree of visual and other sensory latency in display or the level of real-time interactivity of the system, which is often measured in displayed updates per second. The psychological sense of presence is determined by spatial presence, involvement and realism [49]. In addition, the sense of ownership of one’s limb can and should be manipulated in our scenario, either by arranging different display positions (e.g. left hand displayed at the far right) or by introducing foreign (e.g. experimenter’s hand) or artificial (e.g. rubber hand) limbs. Both can be displayed in reality (in the boxes) or virtually (photographed, recorded, virtual model). We are experimenting with these matters and are able to control some immersion factors by modifying the virtual environments, while keeping other factors constant (shadowing, resolution, etc.) and measuring ownership and presence by observation and self-report.

![Fig. 2. Client’s views (left) and 3D views (right).](image-url)
Multisensory (visual and proprioceptive) integration of conflicting perceptual stimuli [55], in our case of partial visual and spatial decoupling, impacts on existing or changing beliefs and affects ownership and the sense of presence both of which are measured in our proof-of-concept studies. While the spatial and visual decoupling is inherently kept constant, the real and virtual environments can be controlled (to a certain extent).

3.6. Measuring progress

It is important to be able to measure the movements of the client’s hands within the boxes and the virtual environment for:

- real-time feedback to the client about her/his progress,
- post-exanalysis of the client’s behaviour and progress by the therapist and
- scientific studies examining the underlying principles, theories and approaches used in this type of research.

ART provides different ways for enabling measurements. Different backgrounds, models and a grid can be loaded to quantify movements. For example, Fig. 16 shows a photographed, augmented grid environment with numbers which is used to determine the motor range and reaching performance of clients. In addition we allow for the recording and playback of video clips. We always record what is visible within the boxes and playback with or without augmentations, allowing for feedback and/or measurement.

4. Proof of concept studies

The following two non-clinical studies test the novelty aspects of mirroring, believability and augmentation. The first study uses real (tactile) augmentations, while the second uses virtual augmentations. The motivating research question for these studies is: will changes in the real or virtual environment change the way people are “fooled” about the system? In other words, will multiple, perhaps even conflicting, stimuli decrease a sense of ownership, immersion and presence? Will the decoupling (by way of relocation and mirroring) be noticed? Because of its therapeutic importance, we were also interested in changes in the perception of temperature by introducing real and virtual stimuli.

4.1. Play with water

In this non-clinical study, visual feedback as a form of non-virtual augmentation was combined with real tactile stimulation. Our interest was in evaluating how visual feedback in ART and in particular mirroring was perceived (if at all) and if it influences the perception of tactile stimulation.

Participants, who performed bimanual movements in water while observing the monitor, were analysed. We tested three visual conditions in fixed order: (1) no visual feedback (black screen), (2) correct visual feedback (left side of screen shows left hand, right side of screen shows right hand), and (3) mirrored feedback (right hand shown mirrored on left side and vice versa). The effects of water temperature with two conditions with same or different temperatures were assessed as well. Participant experience of believability and reported knowledge of mirror manipulation was elicited by interview at the end of the study.

4.1.1. Participants

A written consent was obtained from all would-be participants prior to the experiment. Twenty-four healthy right-handed participants (4 female and 20 male) were recruited through word of mouth and poster advertisements. All those recruited reported normal or corrected to normal vision and no acute or chronic pain in their arms or hands. Two participants were ultimately excluded from the data analysis, because one of them left before the end of the experiment and because of the consistent inability of the other to distinguish left and right, despite the "L" and "R" sticky notes on the screen. Pizza vouchers were provided as a reward for taking part in the study.

4.1.2. Apparatus

The ART system was slightly different from that used in the later TheraMem studies. The LED light was not required because enough light went through the light-permeable cloth covering the open back of the box.

Two water containers (34 cm x 23 cm) were filled with 4.1 l of water per trial. The containers were adapted to allow participants to comfortably place their hand in them (Fig. 3). Three containers were used in total. For the condition with same temperature, two containers with room temperature water were used whereas for the different temperature condition the container for the right hand was filled with water at approximately 45 °C.

Participants were asked about their temperature experience at 15 s and 45 s in each condition using the same question: “how warm do you feel your left [right] hand is?” Answers were invited using a rating from 0 to 10, with “0” indicating “almost freezing/as cold as I could stand” and 10 “almost boiling/as hot as I could stand”.

Having completed this task, participants were further asked:

1. What did you think was happening?
2. What was shown on the screens?
3. Did you notice there was mirror alteration going on at any time?
4. Did seeing the images on screen, as opposed to the blank screen, affect your temperature measurements?
5. In terms of the technology, and seeing the hands on screen, how realistic did you feel it was?

4.1.3. Procedure

Each participant undertook six trials of 1 min duration for each trial. The factors visual condition (none, vision and mirror) and temperature condition (same versus different) were changed between each trial. For visual condition, no vision involved a blank computer screen, and no visual feedback. In the vision condition, both hands of the participant were shown on the screen. In the mirror condition, participants were shown their own right hand plus the reflection of the right hand on the screen, giving the appearance of both the left and right hand. For the temperature condition, “same” corresponded...
with both hands being immersed in room-temperature water. Different corresponded with the right hand immersed in warm water and the left in room-temperature water. Each visual condition was displayed for 1 min and participants were asked for temperature judgements after 15 and 45 s.

Upon arrival, participants were seated in a room adjacent to the testing room in order to ensure they did not see the apparatus before the experiment. After a brief explanation, participants were asked to hold their hands out palms down and practice closing and opening them into a fist at a slow and regular pace. Participants were asked to remove any rings and watches and to put on a large gown that might influence hand or lower limb recognition.

Participants were then invited into the laboratory room and seated comfortably in front of the apparatus. The experimenter was located in a separate area and was not visible to participants, but could clearly hear the instructions that were given. Participants were instructed to place their hands through the curtains on the boxes and to completely submerge their hands in the water filled containers. A second experimenter stood at a comfortable distance behind each participant to monitor performance. For example, at any time during the procedure if the participant’s hand movements were out of synchrony, he or she was told to try and keep them moving together. Participants were also instructed to continue to make slow hand movements (open and closing of the fists) for the duration of the trial.

Between conditions, the participant was asked to leave the room and fill out a questionnaire. This occurred five times during the experiment, with questionnaires always given in the same order: affectometer A1, affectometer B1, K10, affectometer A2, affectometer B2. After the final condition, participants answered oral questions regarding the experiment. Finally, the manipulations used in the course of the study were described.

4.1.4. Analysis and results

A repeated measures ANOVA was conducted on the temperature judgements of all subjects, with temperature manipulation (same versus different for the two hands), vision condition (none, vision and mirror), hand (associated with temperature judgement: left, right), and time of rating (15 s and 45 s) as within-subjects factors. Corrected F-values were reported when appropriate for violation of the sphericity assumption.

The answers from the interview at the end of the study were coded and classified according the level of knowledge/believability that participants expressed.

The main effect of the vision condition was significant; $F(2, 42) = 4.438, p = .012$. As Fig. 5 shows, mean temperature ratings increased slightly from none (mean: 4.17) to normal (mean: 4.38) to mirrored (mean: 4.48) vision (collapsed across left and right hand). The contrasts for visual condition were analysed further and the contrast between no-vision and normal-vision was significant ($F(1, 21) = 5.136, p = .034$), as was the contrast between no-vision and mirror-vision ($F(1, 21) = 8.205, p = .007$). The values obtained when the hands were displayed are significantly larger than those obtained when no-vision was used. The contrast between normal-vision and mirror-vision was not significant.

Further analysis of the same temperature conditions showed an increase in both hand temperature judgements as a function of visual condition and revealed a significant effect with $F(2, 42) = 10.506, p < .001$. This effect was also significant for the left hand ($F(2, 42) = 6.560, p = .003$) and the right hand ($F(2, 34.661) = 9.423, p = .001$) alone in the same water. The linear contrasts for both ($F(1, 21) = 15.853, p = .001$), left ($F(1, 21) = 9.915, p = .005$) and right ($F(1, 21) = 12.464, p = .002$) were significant, indicating that even though the water was at the same temperature for both hands, visual condition significantly influenced temperature perception such that there was an increase from none to normal to mirrored visual condition. The differences as a function of visual condition, for both ($p = .798$) or single hands (left $p = .128$, right $p = .826$), in the different temperature conditions were not statistically significant.

Analysis of each hand separately with the other conditions collapsed showed significant effects for the left hand only. The effect for visual condition was significant with $F(2, 42) = 6.713, p < .003$ and the linear contrast was significant with $F(1, 21) = 9.189, p = .006$. The contrast was also significant between no-vision and normal-vision ($F(1, 21) = 6.553, p = .018$) and between no-vision and mirrored-vision ($F(1, 21) = 9.189, p = .006$). The contrast between normal-vision and mirrored-vision was not significant ($p = .148$).

The effects for visual condition for the right hand were not significant ($p = .232$); the contrast was not significant ($p = .066$) either.

The visual condition influenced temperature judgements. However, given that the effect for hands on the different-temperature condition was strongly significant ($F(1, 21) = 133.880, p < .001$), we cannot conclude that a temperature transfer between hands happened to the extent where the left hand reportedly felt as hot as right hand, despite the fact that only the right hand was immersed in hot water. We presume that the visibility of hands increases the perceived temperature, in conditions where the temperature is the same for both hands, or stays the same in all conditions.

![Image](Fig. 4. Participant during exposure.)

![Image](Fig. 5. Mean temperature ratings and standard error for visual conditions.)
4.1.5. Results of final interview

In the final interview only one participant correctly reported the nature of the manipulation. Eleven participants did not report an awareness of the manipulation. The remaining ten indicated that the experiment involved some kind of visual manipulation. When asked if they knew that some form of visual manipulation had taken place, (14%) reported noticing some form of mirroring, without being able to specify what it was. Three participants reported they knew that mirroring had occurred.

A one-sample T-test on the binary coded answers for the questions (1) if they noticed what was happening and (2) if they noticed any mirror alteration was performed. It was significant in both cases with (1) \( t(21) = -9.721, p < .001 \) (1) and (2) \( t(21) = -7.483, p < .001 \), indicating that overall participants did not know what was happening nor did they notice any sort of mirroring.

All participants reported that they considered the system to be realistic/ believable. However, no perceived temperature difference was reported. While the augmentation effect (the perceived temperature transfer) was not demonstrated, mirroring was clearly successful in confusing participants about which of their hands had been displayed.

4.2. Play with virtual ice and fire

This study investigated the use of virtual environments in influencing participants’ perception of their hands and also the effectiveness of mirror manipulation. In particular it sought to evaluate: (1) the usability of virtual environments in ART, (2) the temperature perception manipulation capabilities of two virtual environments, (3) the perceived presence and ownership of limbs displayed on the screen in virtual environments, and (4) the fooling effects of the combination of mirroring and virtual environments.

The ART system was set up to show the left hand on both screens, with the right side being mirrored. The participants were unaware of the mirroring condition. Two different textured environments were shown to the participants: the inner part of a big ice cube, just (virtually) fitting into the ART box, and a similar environment showing hot coal burning (see Fig. 6). We conducted a within-subject experiment with a randomized order of the two conditions.

We hypothesised: (1) that the participants would notice visual manipulations and voluntarily report on them, but (2) would be unable to describe what was going on (mirroring). In other words, hypothesis #1 tests for perceived inconsistencies while hypothesis #2 tests for mental model changes. We also hypothesised that (3) there would be a difference in temperature perception for the two (virtually cold and hot) environments presented, even if the actual temperature was always the same; (4) that participants experience ownership and presence of the hands displayed on the screen and (5) the perceived realism of the virtual manipulations would be rated clearly above mid-point.

4.2.1. Participants

Twenty-nine non-clinical staff and students from the University of Otago were recruited for the study, ranging in age from 19 to 54 years, \( m=29.03, SD=9.1 \). Twenty-five of the participants were male and three females. All participants reported normal vision or wore spectacles providing normal vision. None indicated health problems with their hands. Five participants identified themselves as left-handed.

4.2.2. Procedure and apparatus

A standard PC was used in combination with a 22 in. monitor for the study (1680 x 1050@60 Hz). The participants sat approximately 50 cm from the monitor. Each experimental session lasted for about 10 min. Participants were asked to remove any jewellery or accessories before they were seated. Virtual hot and cold environments were displayed and participants were asked to make slow grasping movements with both hands for about 20 s, a task that is also used in standard optical mirror therapy. After showing each environment, participants had to rate the temperature. The environments were shown in randomized order. After completion of this task, the participants were asked to fill in a questionnaire consisting of eight items which were modified versions of the I group Presence Questionnaire (IPQ) [49], using a Likert-like answer type format (from \(-3 \) to \(+3 \)):

- Q1. I had a sense that the hands displayed on the monitor were my own hands.
- Q2. The hands displayed on the monitor looked real to me.
- Q3. How real did the environment displayed in the monitor seem to you?
- Q4. I had a sense of acting in a virtual space, rather than operating something from outside.
- Q5. How much did your experience in the monitor environment seem consistent with your real world experience?
- Q6. In the computer-generated world I had a sense of “being there” (with my hands).
- Q7. I felt present in the virtual space (with my hands).
- Q8. I felt present in the laboratory environment (with my hands).

Participants were also asked if they had detected any mirroring:

- “I did realise that my hand was mirrored”.
- “If so, which one was mirrored? (“left”, “right”, “I don't know”)

Finally, participants were asked to comment on their perceptions in general, and on the experiment. All comments were recorded in writing.

4.2.3. Results and discussion

The data from the modified IPQ was significantly greater than 0 (one-sample t-test) in both ownership (combined average of Q1 and Q2) \( p < .000 \) and presence (Q4, Q6, Q7) \( p < .000 \), whereas the perception of reality (Q8) was not significant \( (p=.343) \).

A one tailed, one-sample t-test was performed on the 8 questions. The results for Q1 with \( t(28)=9.212, p < .001 \) indicate that participants’ perception of owning the displayed hands was significantly greater than 0 (Fig. 7). One-sample t-tests were also significant for Q2 and Q8 (both with \( p=.002 \)), Q4, Q6 and Q7.

![Fig. 6. Hot (upper panel) and cold (lower panel) environments.](image-url)
reality perception of the virtual environments. It may also relate to convincing enough quality, as reflected by the low and not significant reporting of perceived temperature. Neither the hot (don’t know’).

The results from both non-clinical studies demonstrate that the brain can be “fooled” using our system, even if the real or virtual environment is changed. This outcome is a necessary prerequisite for the introduction of visual and haptic augmentations for therapeutic purposes.

5. TheraMem system

Our TheraMem hardware and software system builds on the augmentation possibility within the ART system. It also utilises the property of a high degree of environmental control. Our main research interest is the practical utility of our technological approach for therapeutic settings. This requires a series of developmental steps: (1) implementation and constant re-developing the actual system and procedures, (2) testing of its usability and its underlying assumptions (“fooling” capabilities), (3) identifying and testing its utility for therapy and rehabilitation, and finally its practical application in clinical settings. Step 1 is described here. TheraMem is 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 an individual’s perceptions and beliefs about their impairments and
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 above 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 visualisation as well as interactive control. The system is illustrated in Fig. 8.

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 controls a virtual memory game using only the hands and no interaction devices. The game consists of two virtual boards with 12 (4 x 3) virtual cards (tiles) each. Tiles, coloured 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 colour 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 (Fig. 9). 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
5.2. Hand extraction and finger tracking

The webcams capture the interior scene using 640 $\times$ 480 pixels at a frame rate of 30 Hz. The black background is subtracted from the hands 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 colour) 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 Fig. 9).

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 $x$/ $y$ cm). 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 $x$/ $y$ cm with the homography matrix than with the projection matrix. Because of the position and rotation of the video surface in the virtual environment (Section 5.3), 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.

A sphere with a radius of 10 mm was added to the scene to test the accuracy of finger tracking a virtual object. This object was moved according 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. 11), 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.

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

5.3. 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,
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. (Figs. 12 and 13).

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. 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 Fig. 12. If the plants on the left and right hand sides match, a celebrate action is triggered. All tiles subsequently change colour and the two matching tiles are removed from the scenegraph rendering.

5.4. 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: \( s_{\text{new}} = s_{\text{ori}}(f+1) \). 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 5.2), some jitter can appear depending on the colour 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 behaviour) 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 800 ms and a threshold distance above which a movement of a finger should be considered as such was set to 2 mm.

6. 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 the following: (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.

6.1. 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].

6.2. Participants and task

The participants were asked to play several rounds of the virtual memory game, i.e. finding matching pairs of virtual plants. 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 females and 35 males) 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.

6.3. Conditions and apparatus

Only movements of one hand were amplified because of our targeted application scenario of post-stroke rehabilitation which in general is characterised 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, 2, 3, 4 and 5 had the following factors assigned in randomized order: 0, 1.0, 1.5, 2.0, and 2.5, respectively. 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.

6.4. 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; and (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...
Participants were required to practice in a ‘warm-up’ round, the floor board of the box, rather than with the hands in mid-air. Participants were thanked and given a chocolate bar. Each session and their willingness to participate in future studies. All participants were also asked about their interest in receiving the results of the study and their willingness to participate in future studies. All 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. Each session lasted for 30–45 min.

6.5. 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 analytical approach was to check for linear and quadratic effects of amplification and their moderation by comparing the two parts (A versus B) of the experiment. Thus, the analysis followed a 5 (amplification: within) by comparing the two parts (A versus B) of the experiment. Thus, the analysis followed a 5 (amplification: within) x 2 (part: A versus 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 SIDIK 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. There was no learning effect. The conditions have been pre-randomized. Experiment recorder time to completion showed a marginal linear increase with increased amplification: from 134 (SD = 18) s 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 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.

Fig. 14. 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.
timeliness of selection changes and appearance of new objects (plants) was assessed. When analysing these changes in a 5 (condition) × 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), indicating that changes were experienced as ‘timely’.

Answers to the 7 satisfaction items were analysed separately and in combination. When analysing the items separately, averages were significantly above the midpoint of the scale (4), all $F(1,40) > 5$, all $p < .001$ (see Table 1).

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 analysed these estimates in a 5 (condition) × 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].

### 6.6. 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.

It is also interesting to note that our research seems to support work on merging different sensory modalities [55]—human perception is a result of the brain processing sensory information coming from several different modalities. This includes vision and proprioception. If there is an ambiguous situation with mismatching sensory input the brain uses a maximum likelihood estimation model to resolve the situation and to form a more robust perceptual estimate. In the case of the ART system we believe the visual modality is dominating the proprioceptive modality and despite the actual movement being amplified the movement on the screen is perceived as what is actually happening.

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.

### 7. Utility evaluation

Usability is a necessary but not sufficient prerequisite for the usefulness of a technology. We were interested in 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. In addition, two group workshops were conducted with academic and practicing physiotherapists. Individual interviews were also conducted with seven experienced physiotherapists. Finally we present early findings and observations from our ongoing clinical tests with volunteering post-stroke victims.

#### 7.1. Student evaluations

Student evaluations were undertaken as part of a post-stroke rehabilitation workshop that was conducted over 1 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 the 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 h sessions, 79 completed questionnaires were returned. Seventy-six students described the system and game in a way that was clear and succinct, 95% 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 recognising 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”; “It is so cool”; “Great fun.”; “It’s fun! Not boring like most exercises we give patients.”

7.2. Group workshops

Two 1 h 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, colours, or objects shown. For instance, a very simple colour 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.

7.3. Guided interviews

Seven experienced practitioners were individually interviewed by the first author. Their fields of practice included physiotherapy, neuromuscular rehabilitation, and rehabilitation medicine, with specialisations 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 2–30+ 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 a client and an 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 3 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 min 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 seen was its ability to achieve a therapist controlled neuroplastic effect through 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 future research will yield further application possibilities.

7.4. Clinical feasibility study

The usability studies and feedback received from students and staff in physiotherapy gave us confidence that the ART system, and in particular TheraMem, can and should be used in a clinical setting. Consequently, we recruited five volunteer patients with different degrees and types of impairment as the result of strokes. The volunteers were invited to a series of four concurrent sessions to:

- a) assess their conditions with and without using our technology,
- b) expose them to the ART system,
- c) let them experience TheraMem as a therapeutic tool.

All sessions were led by a trained physiotherapist and assisted by an operator. Physiotherapeutic procedures were developed on the basis of best practice in post-stroke rehabilitation, taking into account the special nature and limitations of our system.
All the volunteers have completed either 2 or 3 1 h sessions to date. Our preliminary findings include the following:

(1) All participants were able to use the system and played the TheraMem game successfully in a reasonable amount of time (around 3 min) and with a reasonable number of tries (around 60).

(2) While the task was cognitively challenging for some it did not prove to be, as some professional practitioners claimed during the workshops and interviews.

(3) More severe physical impairments required assistive devices and procedures to be put in place. For instance, if a participant was unable to fully stretch an arm, a physiotherapeutic massage was provided and an elbow splint provided to allow for more arm control.

(4) TheraMem can be played either by just moving the hand, wrist and lower arm or by moving a stiff arm with the shoulder. Depending on the impairment, it is recommended that a wrist rather than a shoulder movement should be practiced.

(5) The way participants control their movements appears to be influenced by the way the curtains are fixed to the boxes. If we leave a 1/3 long opening, whole body or shoulder movements are provoked, while a small curtain slit motivates the use of wrist movements.

(6) During our usability studies with healthy subjects, we did not experience flaws in finger tracking because participants were instructed to either point at the TheraMem tiles with a finger or with a flat, straight hand. Some of the clinical participants were unable to position their hand and fingers in such a way. Fig. 16 shows an example of a clenched hand within the ART system. Here the finger tracking algorithm, which essentially calculates the maximum vertical position of skin coloured pixels in the image, does not work as expected—sudden jumps between tiles can be experienced which lead to seriously decreased gameplay performance and satisfaction. In one case we used a wooden implement (a tongue depressor) between the participant’s fingers as a pointing device.

(7) We need to develop different and better suited hand tracking approaches. Instead of relying on finger pointing we have to consider the whole hand as a pointing instrument, including a variety of different shaped hands and hand poses visible to the cameras.

(8) A similar difference between healthy and clinical subjects occurred with regard to the ability to hover over the (physical) board with one's hand. While the healthy subjects did not report on any difficulties, hovering over the tiles and pointing at them proved difficult for some of the clinical volunteers. Hence, when using more than just the hands to control the application, body weight was transferred onto the hand and with this caused friction between the hand and the (black) cloth in the box.

(9) Sometimes the Velcro sealed borders of the front opening had to be covered with duct tape, because of the uncomfortable friction on elbows or arms.

(10) For these and similar circumstances, we need to develop tailored assistive devices for lower arm and other support, which would allow those with different kinds of impairment to use the technology.

(11) All five participants asked for more diversity in the game itself after using TheraMem two or three times. Instead of just pot plants, they asked for a range of objects to be displayed, but not necessarily a different way to play the game. This request can and will be easily implemented.

(12) We are considering 3D model sets targeting different user groups in terms of age, physical and mental ability and personality type.

Before we exposed the participants to TheraMem, we let them exercise within the ART environment using different background images and models. As part of this work, we produced a background image with different fruits which was used to stimulate pointing movements. Participants had to point at matching pairs of fruits (see Fig. 17). In addition to preparing the patient on how to use TheraMem, this exercise also provided initial insights on the patient’s range of movement, hence providing the operator with a rough guide for optimal amplification settings.

Mirroring techniques were also used to "fool the brain" about the ability to move the impaired hand. Patients were able to perform symmetric movements in the mirror condition. By looking at the mirror image of their unimpaired hand, displayed as their impaired hand, they were able to move both hands in synchrony. Patients were asked to perform movements such as wrist extension, wrist flexion and wrist circumduction as well as finger flexion and extension. The actual observed movement in the impaired hand depended on the patient’s condition and ranged from a flicker movement to performing almost the full range of motion. Patients were highly motivated to perform the exercises.

The clinical outcomes of this on-going study will be reported elsewhere. A special therapeutic engagement questionnaire was developed which might also be used to contrast and compare the use of our technology alongside other techniques and instruments. Our early observations in using ART/TheraMem in a clinical setting are promising.

8. Conclusions and future work

TheraMem is a novel system based on the Augmented Reflection Technology which combines Augmented Reality, a simple
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References

[27] Schönhauer C, Pintaric T, Kaufmann H. Full body interaction for serious games 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 adjucive 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’s 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 computerised game-based system, and the computerised support of well controlled and repeated physical rehabilitation tasks. Our effective therapeutic approach needs to continue with ongoing case studies and ultimately full and robust clinical trials. We look forward to reporting the outcomes of this work in due course. The future for ART and TheraMem thereafter will depend on their efficacy in therapeutic practice and their usability and utility for the benefit of patients post-stroke or those with other types of limb impairment.


