# Manipulating the Experience of Reality for Rehabilitation Applications

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Fig. 1: Augmented Reflection Technology in use

**Abstract—Augmented Reality (AR) has the potential to change the way therapy and rehabilitation is understood and administered. It can be used to manipulate the experience of reality resulting in novel rehabilitative applications including but not limited to augmented mirror box manipulations. We present a conceptual framework for the effective use of AR in a therapeutic context developed around the aspects of belief, interactivity, predictability and decoupling. This framework is based on previous work in perception and emotion manipulation and is derived from and illustrated with a number of empirical studies. In particular we describe how our Augmented Reflection Technology (ART) system is able to manipulate the experience of reality in an effective way and how this demonstrates the potential of augmented environments to improve health and wellbeing.**

*Index Terms*—**Engineering in medicine and biology: Patient rehabilitation; Computer interfaces**

## I. INTRODUCTION

**A**UGMENTED ENVIRONMENTS have the inherent potential to confuse us about what we would experience as reality. They might combine the virtual and the real in a way that we cannot tell the two domains apart. This phenomenon has potential applications in e.g. industrial manufacturing, marketing, science communication, computer games or military simulations. Most relevant to our own research, augmented environments also offer great potential to study the brain's perceptual systems and how those might be capitalized on, to facilitate rehabilitation following brain-body trauma and/or chronic conditions. Based on our own and related work in the field, we define Augmented Reality as:

> **Augmented Reality (AR) is a concept and technology delivering a computer-mediated reality that enhances physical reality with virtual reality creating the user's experience of just one reality. AR manipulates the judgment of reality in a way that neither physical nor virtual reality alone can provide.**

Such manipulations can be used in the realm of physical rehabilitation and therapy to encourage and motivate, to guide and positively "fool the brain", leading to neuroplastic change. Neuroplasticity, the brain's ability to adapt its functions and activities in response to environmental and psychological change [1], is mediated by sensations, perceptions, emotions and finally beliefs [2]. This ability is exploited in neurorehabilitative practice to, for instance, manage phantom limb pain, treat stroke victims or deal with complex regional pain syndrome [3].

In this paper we present our approach which aims at providing an effective use of AR to manipulate the experience of reality for rehabilitation purposes, in particular for post-stroke therapy.

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We provide an extensive review of relevant literature in the field, in particular (computer and other) technologies using illusions with a rehabilitative purpose. Then we describe our Augmented Reflection Technology system in detail, present a number of empirical studies which were carried out during the last five years [2], [4]–[7] and finally derive a framework of factors for the effective use of AR.

## II. RELATED WORK

### A. Mirror Visual Feedback and Mirror Box Therapy

The phenomenon of neuroplasticity is a growing area of research for neurologists and psychotherapists, as well as psychologists investigating central processes [1], [8]. For example, Franz and colleagues Franz and colleagues have demonstrated a form of spatial coupling that occurs between the limbs of the body which results in a tendency for the limbs to move in similar (often mirror symmetrical) patterns [9]. Combining these findings, Franz and Ramachandran [10] tested amputees on a bimanual task to examine whether bimanual coupling occurs even if a limb is missing, by measuring movement output of a healthy limb during different conditions of imagined phantom limb movement. Indeed, bimanual coupling still occurred, suggesting that some forms of coupling depend on central, rather than peripheral or physical processes.

During these studies an initial reflection technique, now commonly known as the "mirror box", was developed [10], [11] and used to alleviate phantom limb sensations which often include pain [12]. A mirror box consists of an optical mirror placed vertically between the healthy and impaired limb, giving the visual appearance of the impaired limb moving in a healthy way. The observation of the mirrored healthy hand "fools the brain" into seeing two limbs moving i.e. bimanual coupling. This was demonstrated in Franz's lab as an initial proof of concept in a larger group of control participants who experienced enhanced bimanual coupling [13]. Our hope is that this form of illusionary movement also engages the brain's processes associated with the other (impaired) limb and thereby reduces associated pain or spatial and motor impairments.

Various forms of therapeutic applications using mirror visual feedback (MVF) have since been evaluated for the treatment of a variety of neurological disorders, including phantom limb pain [14], stroke [15]–[20], pain related to spinal cord or nerve injuries [21], following wrist fracture [22], fibromyalgia [23], complex regional pain syndrome (CRPS) type 1 [24]–[29] and CRPS type 2 [30].

Further support for the use of mirror visual feedback to influence processes in the brain was provided by recent publications. Bekrater-Bodmann, Foell, and Flor [31] reviewed the literature and found that complex chronic pain syndromes were often reported by patients who had illusory perceptions of the affected limb. These changes in body perception also indicate underlying alterations of the body representation in the brain and could potentially be corrected by using MVF which could lead to a reduction of illusory sensations as well as a reduction in perceived pain. Research by Hänsell, Lenggenhagerl, Känell, Curatolol, and Blankel [32] supported this. In their study, participants and a mannequin were simultaneously stroked; when participants observed the stroking of the mannequin, their pain tolerance levels were significantly higher compared to when participants were shown a white sheet of cardboard instead. In a similar way, Longo et al.[33] demonstrated that participants who observed their hand in a mirror experienced pain relieving effects, whereas when they observed a neutral object these effects were absent.

Recent applications using the MVF have also incorporated manipulations of tactile sensations through mirroring [34], an experimental possibility that could further extend the understanding about how visual and sensory sensations combine in the brain, and ultimately, advances in therapies implementing such approaches. However, given that experimental manipulations are rather constrained with the use of the standard mirror box (such as subject biases and expectations), it is rather difficult to test hypotheses about the precise nature of the observed effects.

Virtual Reality (VR) and Augmented Reality (AR) environments might help to overcome these limitations. Various systems were recently introduced to extend the use of mirror visual feedback beyond the capabilities of the conventional optical mirror box [35]–[39]. A number of studies have been undertaken with VR and AR-supported technology to treat people with chronic pain [40]; complex regional pain syndrome [41], trauma injuries [42], [43], severe burns [44] and to enhance motor output in patients with unilateral stroke [38], [45]–[50]. The latter has become the focus of our work, because VR and AR applications are currently providing innovative and potentially useful technologies, capable of being combined with conventional physiotherapy and psychotherapy rehabilitation approaches to treat hand and upper limb impairments following cerebrovascular events. Examples of these were covered in a recent review [51].

### B. Referred Sensations

Referred sensations (RS), or sensations felt on sites of the body which were not actually stimulated, have been studied in the context of mirror therapy since about 1996 [11]. However, initial studies were unable to induce referred tactile sensations between hands in healthy participants and concluded that the effects of referred sensations are unique to phantom limbs. Similarly Sathian [52] did not find contralateral referred sensations in normal subjects or in hemiparetic patients without sensory loss affecting the hand. In arm amputees however, Ramachandran & Hirstein [53] were able to elicit RS in 4 out of the 10 participants. In another study by the same first-author, it was reported that RS was evoked from the face to an amputated limb [54].

Several other studies have also demonstrated the presence of RS, for example in a post-stroke patient [55], in six patients with hands anesthetized by stroke or neurosurgery [52] and in two subjects with spinal-cord injury [56]. Studies on patients with CRPS type 1 have also shown evidence of referred sensations. In particular, McCabe et al. [57] reported tactile RS in 5 out of 16 subjects, with closed eyes, but not when participants had direct vision of the stimulated limb. Acerra &

Moseley [58] conducted a study with patients suffering from CRPS type 1 and used a mirror to superimpose the reflected stimulated image of the healthy limb over the affected one. They found that if areas of the unaffected limb were stimulated, patients could feel pain in the affected side if the corresponding area was affected by allodynia, and patients felt "pins and needles" or tingling if that side was affected by paresthesia. However, that study did not report whether patients experienced any RS on unaffected parts of their limb(s). In contrast Krämer, Seddigh, Moseley et al. [59] were not able to evoke RS in (non-CRPS) chronic neuropathic pain patients with brush-evoked pain (allodynia), using a similar method.

Takasugi et al. [34] assessed RS in two experiments with healthy participants. In the first experiment, 21 participants were queried about RS in their own masked hand behind a mirror, while observing the reflected image of their stimulated other hand (control condition) and then the reflected image of the stimulation of an assistant's hand (experiment condition). In the second experiment, with 16 participants, the hand of the assistant was replaced with a rubber hand (experiment condition) while the control condition was the same. The researchers were able to elicit RS in all conditions with the experimental condition significantly stronger than the control condition in both experiments. They also reported ownership feelings associated with the visual appearance of the hand in the mirror image in the experimental condition in all but one participant in the first experiment, and in all participants in the second experiment.

### C. Ownership and Rubber Hands

Research of perceived ownership of virtual or artificial limbs has also been the focus of various studies. Among others, Botvinick & Cohen [60] analyzed the Rubber hand illusion (RHI), i.e. the perceived ownership of an artificial hand which was simultaneously stimulated with a participant's occluded hand placed next to it. This study provided the basis for other studies. Pescatore et al. [37] and IJsselsteijn, de Kort, & Haans [61] successfully elicited the RHI in a real and a virtual reality setup. Durgin et al. [62] evaluated ownership in three different setups where the stimulation of the rubber hand was either observed directly or mediated through a camera and a projector, or the projected rubber hand was stimulated in front of the participant. In addition, different orientations of the rubber hand as well as the use of red laser light instead of the brush were evaluated. The study found that overall two thirds of the participants reported feeling somatic sensations from the laser light although no direct comparison of standard mirror reflections and video-mediated manipulations have been conducted such as those by Takasugi et al. [34], which were described previously.

A similar experiment as the RHI using a virtual reality setup [48] was performed by Hägni et al. [63]. They allocated their participants into two groups and instructed them to observe a virtual pair of arms. In group one, the participants were just told to observe virtual arms intercepting virtual balls; in group two the participants were asked to observe the virtual arms and imagine them as their own arms while they intercepted the virtual balls. While the participants observed the virtual arms, the right arm was unexpectedly stabbed and began bleeding. The results showed an increased skin conductance response (SCR) in both conditions but suggested that the participants in group two showed significantly a higher skin conductance response than the participants in group one. This showed that computer generated visual feedback combined with mental imagery may be enough to alter the ways in which the body is perceived.

Related to the RHI, which induces the ownership of a rubber hand instead of one's own hand, is the third hand illusion (THI). In the THI, participants experience an additional (third) limb to be part of their body. Halligan, Marshall, and Wade [64] were pioneers in this field of research. The researchers examined a patient who suffered from stroke, but after the stroke, the patient experienced a Supernumerary Phantom Limb (SPL) added to the body. The patient was adamant about owning three arms, without being able to explain how owning three arms was even possible. This was one of the earliest examples of perceived ownership of a SPL, even without a physical third arm being present. In a further investigation of SPL sensation caused by stroke, Khateb et al. [65] using brain imaging found that the imagination of moving the SPL actually caused activations in the brain in alignment with the experiences verbally reported by their patient.

Schaefer, Heinze, and Rotte [66] used brain imaging to investigate the THI with healthy participants. The THI was induced by connecting an artificial hand and arm to the body and synchronously stimulating both the actual hand and the artificial hand. They found that participants not only regarded the artificial arm as their own, but many also felt as though they had three arms. This was also reflected in the analysis of the brain images.

Ehrsson [67] further investigated the THI with two rubber right hands placed on a table in front the participants, while their real right hand was hidden under the table. The two rubber hands and the real hidden hand were brushed for two minutes. Most people thereafter described the rubber hands as part of their own body. These findings were also supported by the skin conductance responses on the real hand immediately after one of the rubber hands was stabbed with a needle.

Guterstam et al. [68] similarly performed a range of experiments related to the THI and evaluated whether the illusions still works in various visual conditions. In their study 154 participants were involved in 5 different experiments. In the first experiment they found that participants reported the strongest ownership in the condition where the anatomical congruent placed rubber hand was combined with synchronous brushing. This was also shown in experiment two where in conditions with synchronous brushing, the skin conductance response to an appearing threat was stronger. In experiment three and four they found that the replacement of the matching rubber hand (i.e. a right rubber hand for the right side) with a rubber hand on the other side or a rubber foot would decrease the illusion. This was shown in subjective reports of the participants (experiment three) and in the threat-evoked skin conductance response (experiment four). In the fifth experiment

the RHI was compared to the THI and they found a weaker sense of perceived ownership towards the rubber hand in the THI compared to the RHI, but a weaker sense of disownership towards the real hand and a significantly stronger feeling of owning two hands in the THI.

In another experiment, Newport, Pearce, and Preston [35] found that the illusion also affects accuracy on a subsequent reaching task. In their experimental condition, two moving virtual left hands were displayed in front of the participants, using their MIRAGE system. The brushing of the real hand was either synchronously displayed with one of the two hands or with both hands. They found that ownership was only reported of the virtual hand(s) if brushed synchronously. The error in a reaching task performed afterwards, without any visual feedback, showed that the reaching accuracy was influenced by the location of the virtual hand the participants took ownership of previously.

Additional investigations into this virtual hand illusion were carried out by Raz, Weiss, and Reiner [69] on whether haptic feedback as well as passive or active movement of the virtual arm during conditions, would increase the effects of perceived ownership. Firstly, they found that there was a stronger sense of perceived ownership during synchronous conditions when both the real hand and the virtual hand moved precisely at the same time or were stimulated by the same stick. Secondly, the researchers found that there was a greater sense of perceived ownership when there was haptic feedback given to both the real and virtual hand in synchrony.

An additional investigation into this virtual hand illusion was later carried out by Slater, Perez-Marcos, Ehrsson, and Sanchez-Vives [70]. They performed the virtual hand illusion by stroking the patient's real right hand and (in synchrony) an aligned 3D stereo virtual arm projected horizontally out of the participant's shoulder. The researchers found that in the group of 21 male participants, when the hand was stimulated in synchrony, there was a sense of perceived ownership. In contrast, no sense of perceived ownership was found in a group of 20 men tested in a control experiment in which stimulation on the virtual arm and real arm was not in synchrony.

Yuan and Steed [71] investigated whether this sense of perceived ownership was still present when immersing the user in a virtual reality environment. The user was asked to complete two tasks while seated at a real table, wearing a head mounted display, showing the virtual environment. The first task was to use a wand tracker to point and match picture locations on the wall in the virtual environment. In the second game, the user was asked to pick up a ball and place it into one of three holes highlighted on the table. A virtual desk lamp then falls onto the virtual arm or a virtual cursor arrow representing the participants arm. The results revealed a significantly higher SCR on the real arm when the lamp was dropped on top of it, compared to when the lamp was dropped on top of the cursor. This suggests that there was a sense of perceived ownership towards the virtual arm when immersed in the virtual environment.

Overall, the literature suggests that there is considerable potential to fool our perceptions about what is real and what is not. In particular aspects of sidedness and mirroring, despite the fact that a certain suspension of disbelief is required, show strong potential. Also, the introduction and positioning of object, real or virtual, might play a major role in manipulation.

### D. Virtual, Augmented and Mixed Realities in Physical Rehabilitation

Mixed reality systems are showing promise as useful tools for physical, occupational and psychological therapists, particularly in the area of post-stroke rehabilitation [48], [72]–[75]. 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. Two key premises about rehabilitation seem to have emerged:

1. That repetitive intensive practice is required for behavioral motor plasticity,
2. That underlying neuronal cortical reorganization 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 [76]. These systems include those which incorporate haptic feedback from the hand via sensors mounted in gloves [45], [47], [77], [78], those which allow the user to view a representation of their arm and hand via a head mounted display [39], video-capture virtual and augmented reality technology [48], [79], [80] and a system which provides multimodal feedback in the form of visual and musical feedback [81]. 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 [82]–[88]. The motivational aspects of computer gaming also allow for cognitive engagement and challenge [89]. 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" [90].

In summary, it has been shown that interactivity and repetitive practices, as well as the perceived ownership of limbs, are of considerable importance. An augmented reality system integrating different aspects of manipulative controls will be promising in delivering a new experience of physical (neuro-) rehabilitation.

### III. THE AUGMENTED REFLECTION TECHNOLOGY SYSTEM

This section reports on the development of the Augmented Reflection Technology (ART) system setup to test hypotheses about limb presence and perception, belief, and pain under laboratory conditions. The prototype developed for this purpose hides the user's hands behind curtains in boxes, lights and captures the movement of the hands inside of the boxes, processes and augments the resulting video streams and shows

the (manipulated) hands as part of a virtual environment on the screen sitting on top of the boxes (Fig. 2)



Fig. 2: ART system in use

## IV. HARDWARE

We are using a standard personal computer which is connected to our Augmented Mirror Boxes (AMB) and two screens: one for the experimenter or therapist, the other for the user or client (see Fig. 2). The video signals of the cameras built into our AMBs are connected via USB to the computer system. This setup allows for a decoupled capturing and visualization of the user's limbs and therefore for a maximum of controllability.

Each AMB consists of a wooden, black cubic box with inside dimensions 370 x 370 x 370 mm3. The front opening is covered with a black curtain; the back opening can be covered with black, white or translucent board. The ceiling of the box is covered with light emitting diodes (LEDs) for consistent and appropriate lighting. The LEDs are operated with low voltage and do not produce harmful temperatures; therefore the setup is suitable for experimentation and clinical use.

Off the shelf web cameras capture the content of the box. The cameras are mounted to the ceiling of the curtain side of the box and are facing downwards. Wide angle lenses with about 80 degrees of diagonal field-of view are used to capture a maximum of the space within the box. Logitech Quickcam Pro9000 cameras are currently used in our box setups.

A wide screen monitor is placed above the boxes for viewing by the user/client and a second standard monitor is placed beside the boxes and is visible only to the experimenter/therapist. The experimenter controls the application using a standard keyboard and mouse. A standard desktop PC (Microsoft Windows XP SP3) equipped with 4GB of RAM and a graphics board, which supports OpenGL 1.1, are used.

## V. USER INTERFACE

The main dialog window is operated by the experimenter/therapist. In preparation or during a therapy session *Presets* of configurations can be saved, loaded and edited. Four tabs divide the interface into *General* information about the system, a dialog to manipulate the *Views* of the left and right screen, adjustments for the two AMB *Camera*s (e.g. contrast and color settings) and controls to record and playback raw *Movies* for the therapist's later review of the therapy session. Fig. 3 shows the main dialog window with the *Views* tab, which is used here to introduce the main technical features of the ART system.



Fig. 3: ART system - operator's dialogue

All settings are implemented for the left view (left screen) and right view (right screen) and are separated into four sections to manipulate the *View* (e.g. mirroring), the *Spatial* arrangement of the video streams within the virtual scene (e.g. size of hands), the 3D virtual *Scene* itself (e.g. loading of virtual objects) and alternative 2D *Background*.

Mirroring one video stream in a way that the healthy hand is displayed for both views is the core functionality to simulate an optical mirror box. The default configuration displays the left video source within the left view and the right video source in the right view. But all other combinations are possible depending on the therapeutic use. The images reflect the current settings to help the operator to understand the chosen settings. With the radio button "No Camera" the assigned camera view can be set invisible.

The three sliders ("Horizontal", "Vertical" and "Zoom") in section "Spatial Manipulations" offer the possibility to change the position of the hand in the view relative to the virtual scene.

In a mirrored setup one and the same hand can be displayed differently for the right and the left view. The button "Set to Default" restores the view and no manipulations are applied.

With the controls in section "Scene Manipulation" a 3D grid and/or a virtual box models can be loaded as part of the 3D scene. These box models can be enhanced by additional virtual objects. "Transparency" can be used to adjust the transparency of the box model. This way the underlying background texture will appear and be part of the scene. Virtual objects within the box model are not affected by the transparency value. See the virtual JayTee package in Fig. 4.
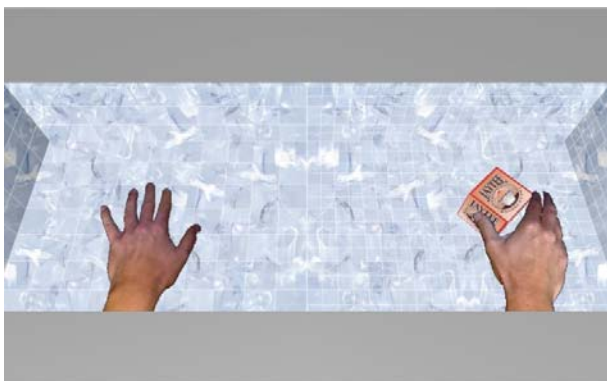


Fig. 4: ART system - left and right view with virtual 3d grid and additional objects

"Background Manipulation" allows for a selection of a background texture, which can be seen if there is no or a partly transparent 3D box model loaded. Some of the applications built with the ART system only use this 2D background to configure different scenes to suggest for example a hot or a cold environment.

## VI. Implementation

The implementation of the 3D scene is based on the Open Inventor scene graph. Video capture, processing and recording related functionality is implemented using OpenCV and DirectX. The core part of the system's implementation can be explained visually as shown in Fig. 5. Here the user's view of the two screens is displayed on left side of the figure. The right hand side of the figure shows the 3D scene as loaded in Open Inventor.
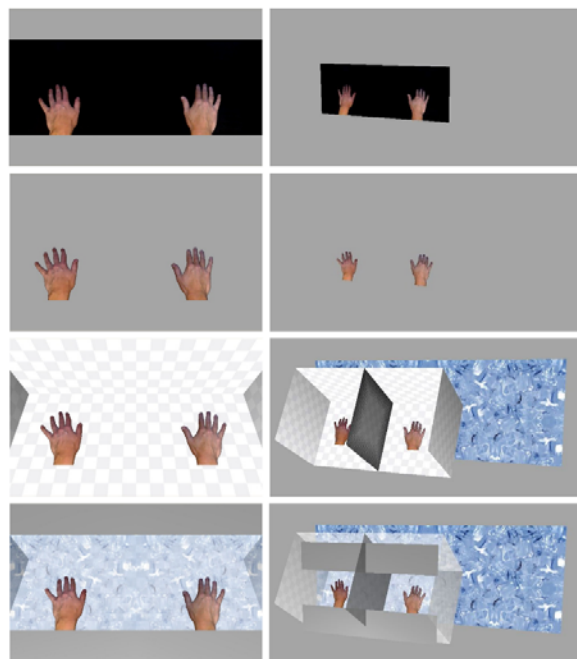


Fig. 5: User's and 3D screenshot views of ART system

The raw video is captured and displayed on two planes in the 3D scene graph (first row of Fig. 5). A simple background subtraction is used to render all black pixels transparent (second row of Fig. 5). The threshold for the value to define "black" can be altered in the user interface in the *Cameras* tab and needs to be adjusted for individual users/clients. This value is part of the preset configuration and can be saved and reloaded. Problems can occur under uncontrolled light conditions (e.g. curtain of box not properly closed) or for participants with darker skin color.

The video planes' position can be altered to adjust the size (movement orthogonal to the video plane) and position (movement in horizontal and vertical direction of the video plane) of the hand relative to the scene. This technique is also used for a virtual, real time amplification of the user's hand movement by adding an offset to the horizontal and vertical position of the plane.

Certain applications require the tracking of the fingertips calculating projected 2D finger positions in the virtual scene. These positions can be used to enable the user to activate certain virtual elements or allow the therapist to measure mobility improvements over time. The finger tracking component estimates the 5 uppermost positions of the hand outline after the background subtraction is completed. Most of the ART applications track one finger position only (the uppermost position) to allow pointing actions. For a detailed description of the finger tracking implementation and involved calibration issues please refer to Regenbrecht et al. [7].

Virtual models can be loaded to simulate the real boxes and include additional virtual objects. The virtual boxes are adjusted to match the size and perspective of the real boxes. They will occlude the virtual background texture (third row of Fig. 5). Models for additional virtual objects need to be prepared to match the coordinate system in terms of origin and size.

The background texture is mapped on a plane behind the box model and only visible if the box model is disabled or set partly transparent (see last row of Fig. 5). To restrict the view into the 3D scene according to the upper and lower edges of the incoming video stream we added "blinds" which are the foremost elements in the scene.

Fig. 6 summarizes the flow and the components of the ART system, starting with the raw video input, which is processed by the background subtraction module to feed the finger tracking component as well as to set transparency of the video plane in the 3D scene. The user interface can be used to configure the 2D (background texture) and/or 3D (virtual box and objects) content of the scene, which is rendered as part of the augmented environment.
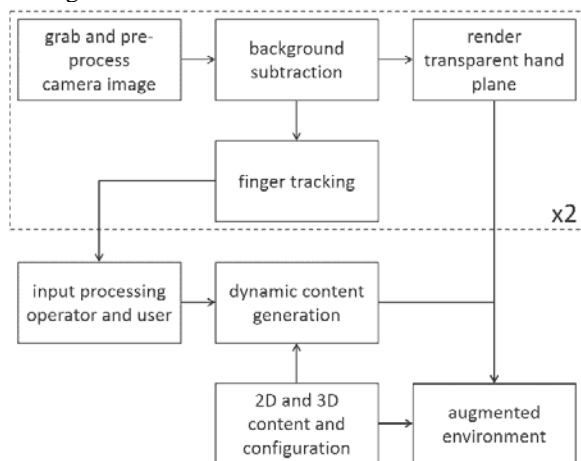


Fig. 6: Scheme of ART system

Our ART system provides us with a reliable platform to study and apply manipulations of the perception of reality in a wide range of controllable parameters. It is a powerful tool for the experimenter and clinician to fool users about what they believe is real. It enhances the physical space of our boxes with rehabilitation-relevant virtual reality so that the users can experience this space as one reality.

## VII. ART Studies

For the last five years we have been using our ART system in different configurations to examine the feasibility and effectiveness of video-mediated manipulation aspects of reality. In the following we give an overview of several empirical studies addressing different factors for manipulation. Those studies form the basis for the development of our derived factors for the effective use of AR in rehabilitation and therapy.

### A. Augmented Mirror Box

As a starting point we were interested in whether the ART system can be used as a replacement for an optical mirror box (OMB) and if it can even deliver alternative, additional features the OMB can't deliver. We were interested in the question whether our participants are able to correctly identify which of their hands is shown and in what location under different conditions. In addition to the obvious simple mirroring, which an OMB would deliver, we added conditions with one and two

handed mirroring and different forms of movements [2].

**Method**: Twenty-four participants took part in the within-subject study: 8 females and 16 males with an average age of 25.5 years (range 18 to 63).

The OMB was constructed by positioning a vertical mirror inside a black box of the same size as the boxes used for the ART system. The mirror covers one entire inner wall of the box. Both setups were placed adjacent to one another on a table to allow for direct comparison (see Fig. 7). All other environmental factors (e.g. lighting) were kept constant. Only the Augmented Mirror Box capabilities of the ART were used in this study.



Fig. 7: System used in Augmented Mirror Box studies

A Perception Questionnaire was used for the verbal administration after each trial, it contained a 9-point Likert-like answer format (from 1 as "Strongly Disagree" to 9 as "Strongly Agree") regarding Ownership, Agency, Spatial Presence, Perceived Realism and Appearance, Believability, and Perceived Difficulty.

A within-subject design was used with eight experimental conditions resulting from the three factors: System (OMB vs. ART) X Hands (one-hand vs. two-hands) X Movement (symmetric vs. arbitrary). Hands: For the OMB, the participants placed either one hand in front of the mirror and the other hand behind the mirror (in the neighboring box) or both hands in front of the mirror. With the ART system, both hands were placed in the boxes (left and right) and either one hand only (left) or both hands were shown on the monitor. Movement: The participants were asked to make symmetric movements with both hands opening and closing at a rate of about once per second. For arbitrary movements participants were able to try and test any movement they wanted within the box limits.

The order within the conditions was randomized and counterbalanced beforehand. After each trial, participants were asked to report on what they saw and their responses were written down verbatim by the experimenter.

**Fooling of sidedness**: Data from all 8 conditions and all 24 participants (192 trials) were analyzed. We were interested in comparing the setups in terms of their capacity to 'fool' participants about whether the reflected hand was actually their own, or was the other, non-reflected, hand. All user responses

across 192 trials (96 for AMB and 96 for OMB conditions) were analyzed and compared against the 'actual' condition.

The statistical analysis of the data indicated: that participants who used the ART system were more than 3 times more likely to get fooled than those who used the OMB; respondents who moved their hands symmetrically were about 2.5 times more likely to get fooled about sidedness than those who moved arbitrarily; and that the two handed displays were almost 3 times more likely to fool participants than those involving a single hand.

**Neglect of mirroring**: The second variable of interest was how often participants did not report mirroring of their hand(s) e.g. they did not report that their right hand looked like their left hand, i.e. it was horizontally flipped.

The statistical analysis suggested that participants who used the ART system were 3 times more likely not to report the visual manipulation compared to the use of the OMB. No significant differences were found for the type of movement and the number of displayed hands.

**Self-report**: Ratings for ownership, agency (feeling of being the originator of the movement), appearance as real and the color & size of the hand(s) were all rated clearly above midpoint on average (although ratings were lower for ART) and the difficulty to perform the task was on average clearly below midpoint, i.e. perceived as not being difficult. This shows that even though people were fooled they still perceived the hands as their own hands.

**Conclusion:** Findings confirm that our visually de-coupled and mediated mirror box technique is able to fool or confuse individuals' perceptions and beliefs. The ART produced strong results in this regard, particularly in the case of two-handed, symmetrical, mirrored movements, which form the basis for the therapeutic studies reported in previous work. The participants could predict what will happen on the screen based on their interactions with the system.

### B. Advanced Augmented Mirror Box

Using the same ART system as describe above we conducted a within-subject study with thirty participants and tested sidedness (left vs. right) x mirroring (mirrored vs. not mirrored) x information (participants informed about the type of manipulation vs. not informed). We used only the setting which was shown to be the most effective in fooling participants, namely symmetric movement with the display of two hands.

**Results**: We found that in conditions where there was no mirroring applied and the sidedness was not manipulated, most participants reported correctly about what actually happened. However, there was still a number of incorrect answers.

When mirroring was applied, regardless of the sidedness, most participants gave incorrect answers – the fooling of the brain appeared to be very effective.

Even when probing the participants on perceived mirroring and sidedness, most people failed to give correct answers.

**Conclusion**: In sum, the ART system seems to work as intended in that it does fool participants, as hypothesized. We also found that in case of doubt participants opted for the neutral condition (i.e. the normal position of their hands). They seem

to try to perceive what they believe: Mirroring seems unlikely and "everyone knows" that a left hand belongs to the left and a right hand to the right side. This study is explained in detail in Regenbrecht et al. [2].

### C. Therapeutic Game TheraMem

TheraMem [7] 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; 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 of movements. 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 (Fig. 8).
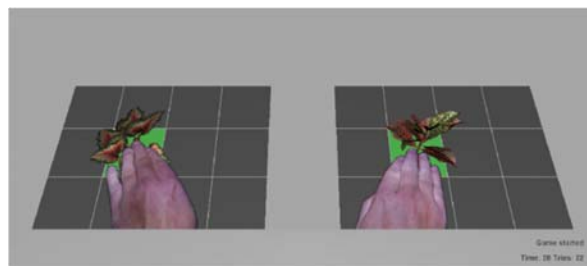


Fig. 8: Screenshot of TheraMem system in use

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. 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 unbeknownst 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.

We tested whether our 43 participants were able to play a memory game in *TheraMem* without distraction, while varying the 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, 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.

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 needs to be further investigated.

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.

### D. Hand Perception and Ownership

In a series of studies we've investigated how mirrored and non-mirrored hands are perceived, whether sensations or ownership can be referred and how the spatial perception of size can be manipulated.

To test the effectiveness of our ART system for referring sensations we replicated the original Rubber Hand Illusion (RHI) experiment. The main differences are (1) the visual and (2) spatial decoupling of the user's hands from what is presented. We were interested in whether the RHI still works. Fig. 9 shows our experimental setup.



Fig. 9: Rubber Hand Illusion experiment setup

The box in the middle is used for the rubber hand, and the other two boxes for the user's hands. In the video-mediated condition the user's left hand and the rubber hand are stroked simultaneously with a brush while the user is only observing the video images of the (real) right hand and the stroked rubber hand (Fig. 10).



Fig. 10: Video-mediated Rubber Hand Illusion

The results of this study with twenty-three participants suggest that there was a sense of perceived ownership in both the original Rubber Hand Illusion and in the video mediated Rubber Hand Illusion, even though the sensation was not as strong in the latter.

This result suggests that ART can generate a sense of perceived ownership during the Rubber Hand Illusion. These results support the findings of IJsselsteijn et al. (2006) which suggest that there is still a sense of perceived ownership towards a rubber hand, even when it is video mediated in a virtual reality or mixed reality condition. The findings are however not in alignment with the suggestions of Tsakiris and Haggard [91] and IJsselsteijn et al. [61] that the position and location of the rubber hand has a strong impact on the RHI - here we show that a certain displacement still produces the desired effects.

In another study we compared referred tactile sensations (i.e. the felt intensity of brushing of one hand on the other hand) and limb ownership, using an Optical Mirror Box (OMB) and our ART system [4]. An additional manipulations that could not be performed with a standard mirror reflection—the reversal of the spatial positions of the limbs—was investigated in an extra condition, to examine how far the perceived ownership effects could be pushed.

Results reveal that participants felt referred sensations in both the optical and the video-mediated setup, and that video-mediated manipulations of hand-position reversals, which is not possible with the OMB, produced equal to stronger effects.

Finally, we conducted a study with thirty participants to test whether the perceived size of the hand can be manipulated. By varying background images producing different forms of visual illusions of depth and size (see e.g. Fig. 11) we asked participants to report on the perceived size of their hands. It was shown that changing backgrounds influence how participants perceive their hands and that they continue to perceive ownership of their hands. This was also shown in another study [6], which evaluated the mirroring effect and perceived

ownership in virtual environments using the ART.



Fig. 11: Experiment on size perception

The ART system is able to manipulate the perceived size of users' hands by either directly changing the zoom factor (z position) or by changing the environment the users' hands are acting in. This has possible therapeutic applications as it was shown, for example, in pain management, that the size of the displayed limb influences the perception of pain [92]. Further studies are however needed to provide additional evidence though.

*E. Clinical Feasibility*

Following our studies with healthy control participants, we were interested in examining whether our approach and system are feasible in a targeted clinical context. First, feedback from approximately 100 physiotherapists, who evaluated the system in the role as a therapist and as a patient, was gathered [7]. This feedback was predominately very positive and encouraging. This was followed by a study with six patients suffering from chronic upper limb impairments after stroke who underwent therapy using the ART system four times each [5]. Observations and feedback from the patients, as well as data from two questionnaires - one for each patient and one for the therapist, were analyzed. Therapeutic exercises with ART's TheraMem, the mirroring capability, and a variety of features involving visual augmentations were conducted.

The analysis of the patients' feedback on the therapeutic exercises and the data from the questionnaires on the patients' experiences with TheraMem was positive. Findings confirmed that the use of the ART system in clinical settings for patients undergoing rehabilitation of upper limb impairments after stroke is feasible.

Exercising with TheraMem was well received by the patients and all of them were able to complete the games and at least once in a time below three minutes. However it must be noted that only three (the less severely impaired) of the six patients were able to play the game without the use of additional support devices.

The other patients needed additional support devices for two primary reasons: firstly, these patients had severe impairments and were therefore not able to keep their hands in the suggested position for TheraMem (flat on the floor of the box); secondly, again because of their severe impairments, these patients had

difficulty placing a hand and forearm inside the box and to keep it there. To overcome the first problem patients were asked to hold a pointing device in the form of a wooden stick in their hand; for the second difficulty patients were assisted with the use of an elbow-splint. It is suggested that both problems could also be overcome with (1) an extension of the finger-tracking algorithm implementation to track the entire hand and (2) by adding an extended arm rest in front of the box where patients can comfortably place their forearm up to the elbow, which in the current version has to be stabilized by the patient for each movement.

In the evaluation of the clinical outcome measurement, three out of the six patients showed (although small) improvements in their motor impairments. It is, however, too early to attribute these improvements to the use of the ART alone or to conclude that the use of ART is more beneficial for patients than regular physiotherapy.

In order to specifically evaluate the clinical outcomes, a larger-scale randomized controlled trial with more sessions and a longer intervention period is currently in preparation. In such a trial it might be expected that we will observe larger improvements especially for people who have had a stroke more recently.

In summary, the studies on the feasibility of ART with six patients demonstrated the potential of ART for stroke rehabilitation. The results obtained indicate a promising outlook for its future development and the application in clinical randomized control trials with more patients.

The following table summarizes the main aspects for "fooling" effectiveness as shown by our studies.

Table 1: ART effectiveness of "fooling"

| manipulation of | effectiveness |
|---|---|
| mirroring and sidedness | high |
| positioning and amplification | medium/high |
| size | low (future work) |
| ownership of own hand | high |
| ownership of rubber hand | medium |
| ownership of third hand | weak |
|  |  |
| clinical feasibility | positive |

## VIII. Reflections on the Effectiveness of Augmented Reality

After years of using our ART system in experimental and clinical studies and by observing and assessing users we revealed factors for an effective use of AR which seem to be common across all our therapeutic and rehabilitation applications (Fig. 12).
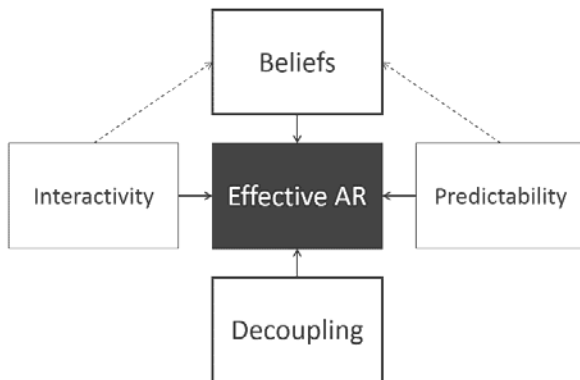
Fig. 12: Requirements for effective AR

### A. Beliefs

The user has to believe that the mediated experience is real. This requires (a) that the augmented environment is designed in a way that this can be believed, but (b) it is also based on the users' willingness to suspend disbelief. This phenomenon is well studied and known, for instance, for movies or virtual reality experiences - if one looks at the characters in a movie as actors or views at VR game objects merely as a sequence of rendered images no immersion or presence in the world presented can be achieved. In our mirror studies, for instance, this is the case if the mirror box user is unable or unwilling to neglect the fact that his or her hand is actually behind the optical mirror. This is possibly one reason why standard mirror box therapy has been found to work for a rather small percentage of patients. Our system of maximizing the "confusion" about which hand is displayed and in what position and orientation can be capitalized here in terms of possible therapeutic value. The users can't be entirely certain about what is displayed and therefore the system is supporting the suspension of disbelief. Decoupling (see below) plays an enabling role here and (manipulated) predictability and interactivity contribute to the users' current beliefs about the system and their perceptions and emotions.

### B. Interactivity

The system's interactivity is determined by its ability to respond to users' actions with real-time feedback. Users test and change their hypotheses and beliefs by interacting with the augmented environment continuously. During mirroring sessions users test whether their right or left hand is displayed by performing different or no movements. In TheraMem they try to reach certain tiles and constantly test their ability to do so. In our referred sensations elements they imagine the interaction of the brush with their hands (or their mirrored hands or the rubber hand). The users move their hands back and forth to test the scale and size of the environment and their hands. Interaction is a means for the users to understand the system - this is one of the main aspects to manipulating the judgment of reality.

### C. Predictability

The provision of a coherent set of (multi-modal) predictor patterns combining real and virtual elements is an inherent characteristic of an augmented environment. When interacting

with the AR system, can the user expect a predictable response from the environment presented? This does not necessarily mean that the augmented environment depicts or simulates the real world as can be seen in our TheraMem application. The tiles are turning around and are revealing 3D models - such a behavior is rather unlikely to happen in the physical world. However, our users accept (after a very short while) the system's response and adapt to it. Even the applied amplifications of the movements of the hands are perceived as predictable as long as they are consistent and coherent within the environment.

### D. Decoupling

The decoupling of the physical from the mediated domain is the main defining feature for the effectiveness of our ART system. The user's real, physical actions are virtually disconnected by introducing a barrier (the box and curtain) and reconnected in software by displaying the hands on screen again. Here, the manipulation of the experience of reality can occur. This is characteristic for other AR systems too. A video-see through head-mounted display decouples the real view from the mediated view. The interaction on a smartphone's touch screen decouples the real interaction from the augmented world. The quality of the reconnection, we could also call "seaming", determines the believability of the AR experience. How accurate is the overlay or substitution in the augmented environment? Is there any conflicting sensation or perception between real and virtual domains?

In addressing and combining these four factors effective augmented environments for rehabilitation and therapy can be built. We even believe, but still have to prove, that a rather immediate neuroplastic change can be provoked in using our approach: A commonly-held view is that early-formed or long-term sensory processes are responsible for neuroplastic change and this directly results in the brain's experience of ownership. Challenging this view, we propose that such changes are directly modifiable by our perceptions and beliefs in an immediate and rapid way. The (constructive) confusion of limb "ownership" arises due to (1) the brain's ability to adapt to environmental changes (immediate neuroplasticity); (2) the visual decoupling of perceptual from sensorimotor processes underlying limb representation and; (3) the passive and active interactions of one's real hands (body) and the external (or virtual) environment in a predictable way.

Augmented Reflection Technology delivers an experience and platform neither physical nor virtual reality can provide alone.

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